Joint Dual Photopeak Image Reconstruction in Lu-177 SPECT

2018 EANM

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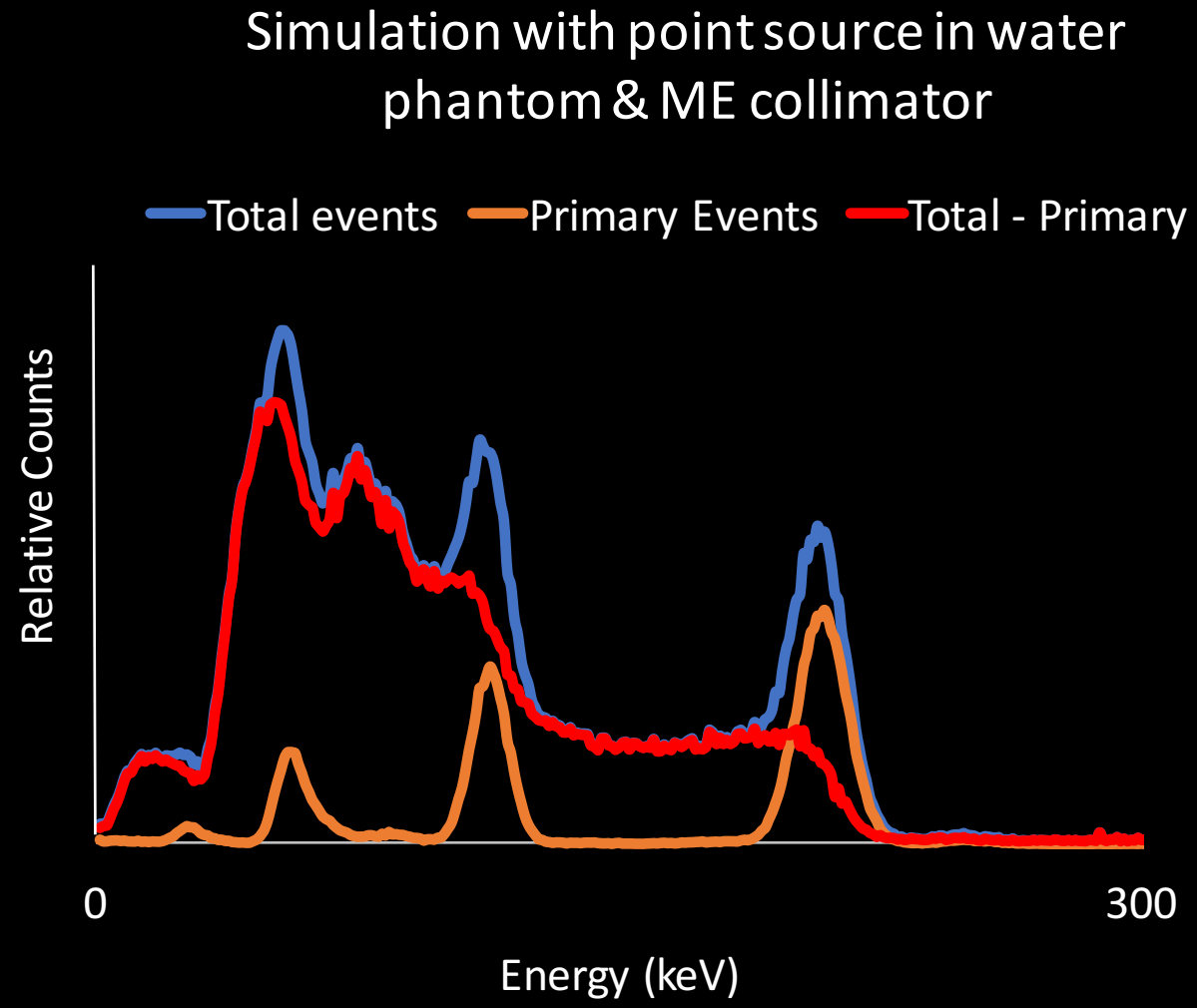
Energy Spectrum of ^{177}Lu

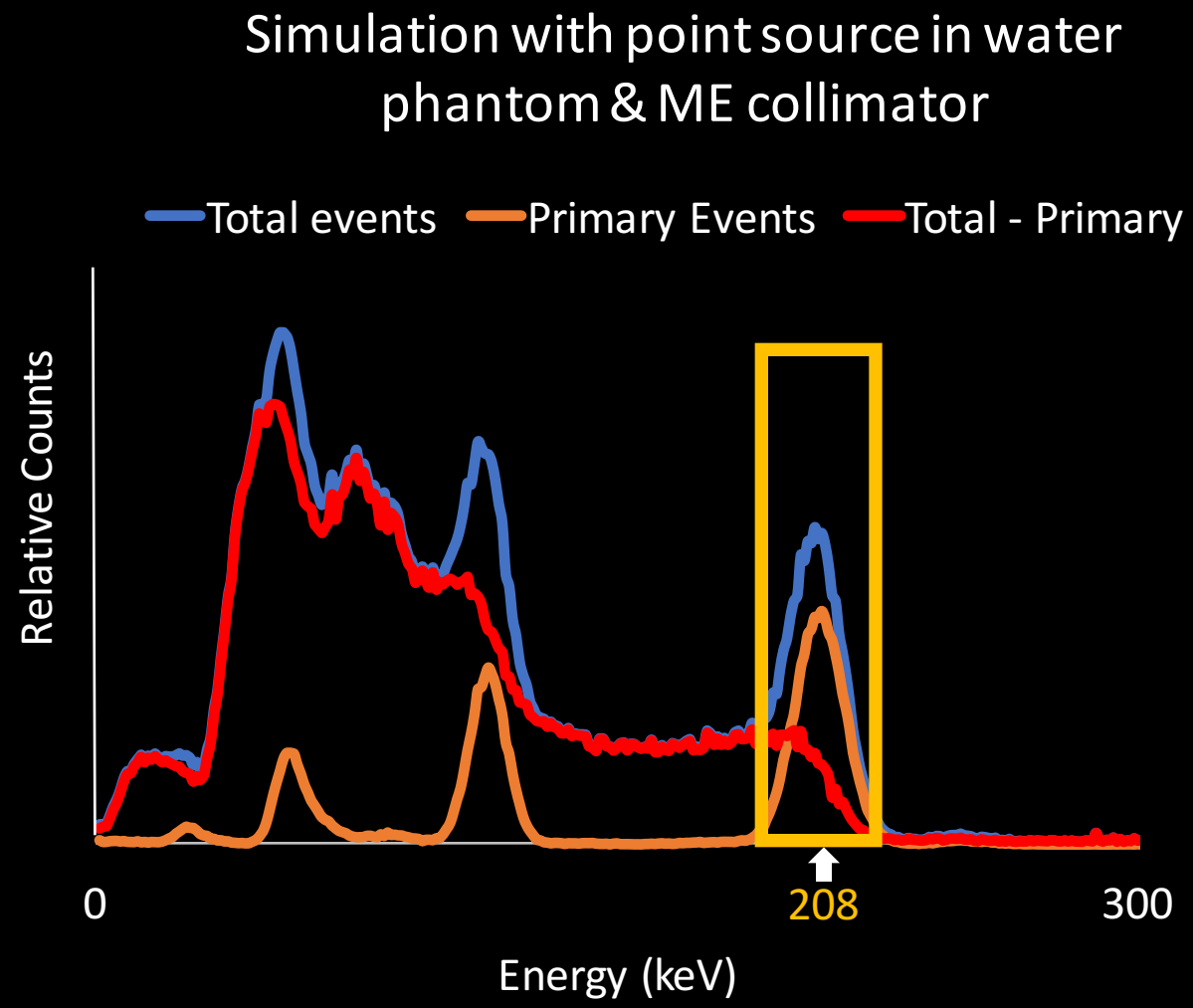
- ❑ General recommendation[1]
  - ME collimator + 208 keV
- ❑ Another option
  - ME collimator + 113 & 208 keV



1. Ljungberg et al. "MIRD pamphlet no. 26" J Nucl Med 57.1 (2016): 151-62.

Energy Spectrum of Lu-177

- ❑ General recommendation
  - ME collimator + 208 keV
  - → Clinically adopted option
- ❑ Another option
  - ME collimator + 113 & 208 keV

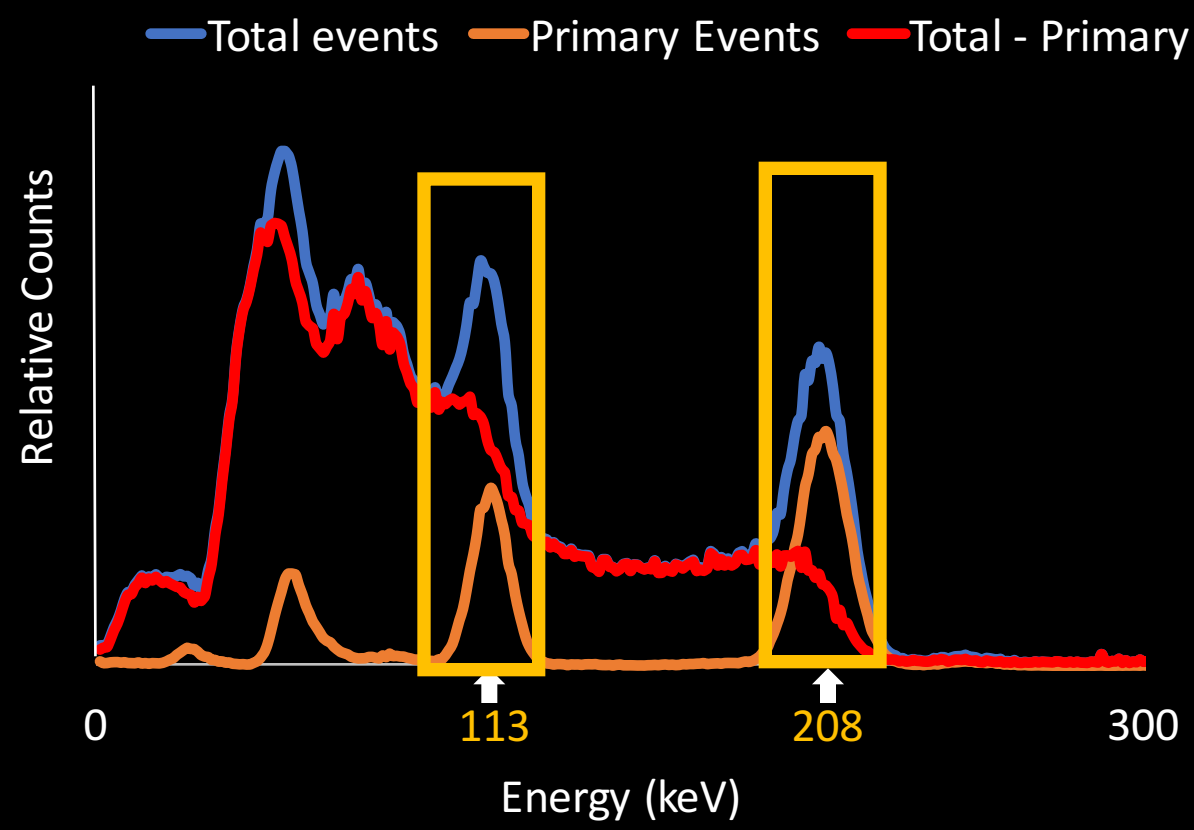


Energy Spectrum of Lu-177

- ❑ General recommendation
- • ME collimator + 208 keV
- ❑ Another option
- • ME collimator + 113 & 208 keV

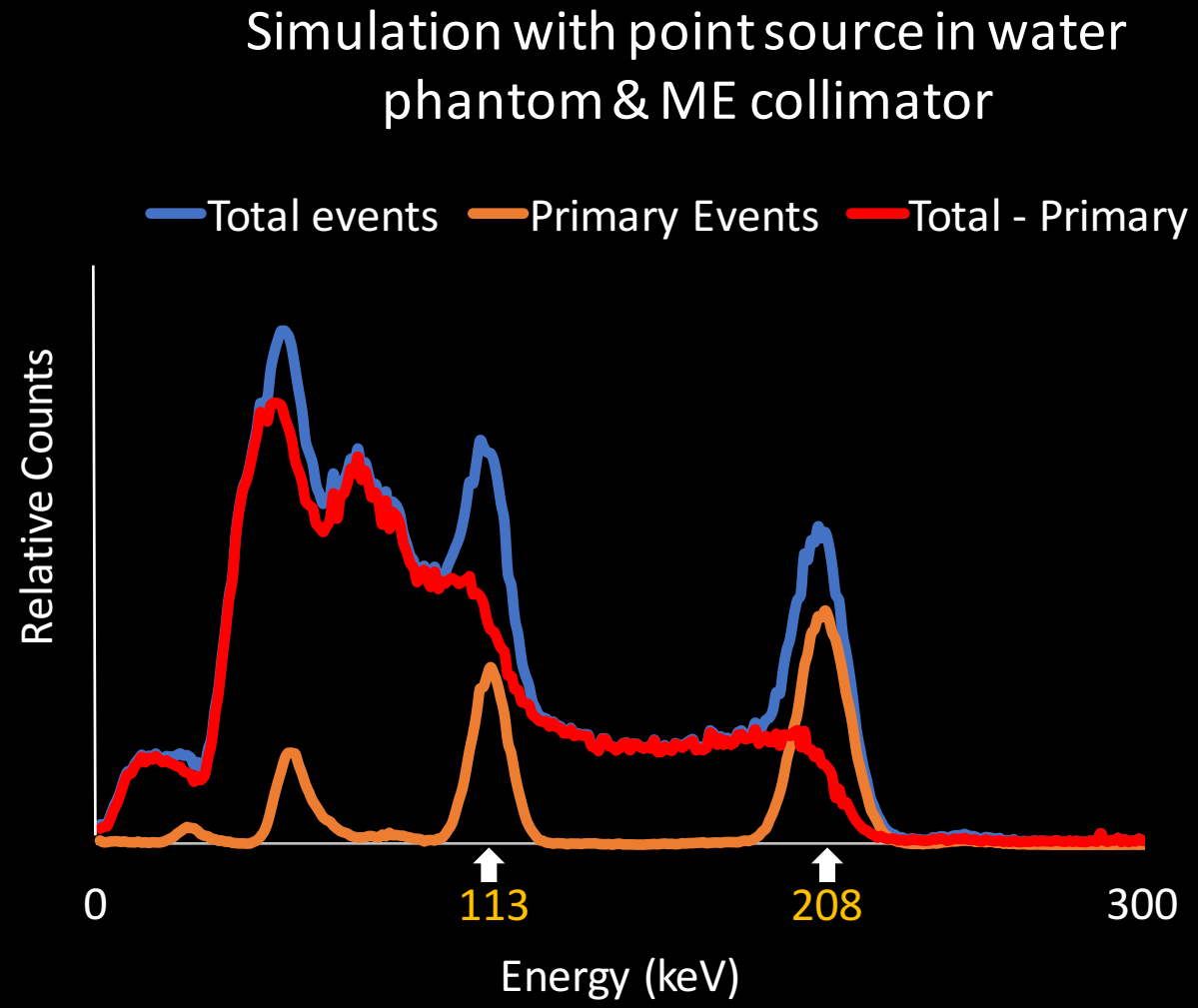
→ Good to use when # of counts is insufficient (imaging at later time point or pretherapy diagnostic imaging)

Simulation with point source in water phantom & ME collimator



Energy Spectrum of Lu-177

- Compared to 208-keV, 113-keV has
  - ~60% of Yield
  - ~70% Primary Counts (cps/MBq) for ME collimator



Options for using both photopeaks - 113 & 208 keV

❑ Two options

1) Reconstruct two images separately and make sum

$$y_1 \sim \text{Poisson}\,(A_1 x_1 + s_1),\ \hat{x}_1 = \text{argmin}_{x_1}\ f(x_1; y_1, s_1)$$
$$y_2 \sim \text{Poisson}\,(A_2 x_2 + s_2),\ \hat{x}_2 = \text{argmin}_{x_2}\ f(x_2; y_2, s_2)$$
$$\hat{x} = \hat{x}_1 + \hat{x}_2$$

2) Reconstruct one image jointly

$$y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} \sim \text{Poisson}\,(\begin{bmatrix} A_1 \\ A_2 \end{bmatrix} x + \begin{bmatrix} s_1 \\ s_2 \end{bmatrix})$$
$$\hat{x} = \text{argmin}_x f(x; y, s)$$

- $\boldsymbol{y}_1(\boldsymbol{y}_2)$ is main energy window and $\boldsymbol{s}_1(\boldsymbol{s}_2)$ is scatter energy window acquisition around 208(113)-keV
- $f(x)$ denotes negative Poisson likelihood function
- For scatter estimation, we used triple-energy-window (TEW) technique

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$$\hat{x} = \text{argmin}_x f(x; y, s)$$

→ More aligned with actual Poisson nature of multi-window acquisition

- $\boldsymbol{y}_1(\boldsymbol{y}_2)$ is main energy window and $\boldsymbol{s}_1(\boldsymbol{s}_2)$ is scatter energy window acquisition around 208(113)-keV
- $f(x)$ denotes negative Poisson likelihood function
- For scatter estimation, we used triple-energy-window (TEW) technique

What factors need to be considered for joint reconstruction?

❑ System Model

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} \sim \text{Poisson}\left(\begin{bmatrix} A_1 \\ A_2 \end{bmatrix} x + \begin{bmatrix} s_1 \\ s_2 \end{bmatrix}\right),$$

where

$$a_{ijk} = \alpha_k p_{ijk}\, g_{ijk}$$

a_{ijk}: element of system model (A_k) at i-th row and j-th column in k-th energy window

α_k : Relative camera detection efficiency $\times$ branching ratio

p_{ijk}: depth-dependent and energy-dependent effect of attenuation

g_{ijk}: depth-dependent and energy-dependent 3D-collimator detector response

Experimental setting

- 2 measurements + 1 simulation + 1 patient scan

I. Sphere phantom measurement (4 scans)

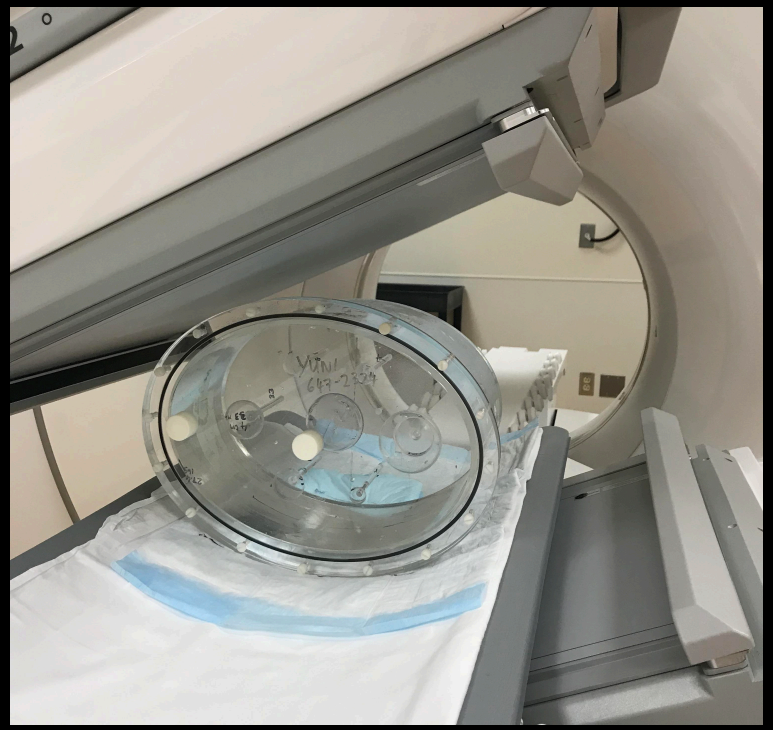
II. Liver-torso phantom measurement (4 scans with high/low-counts)

III. XCAT phantom simulation (10 realizations with high/low-counts)

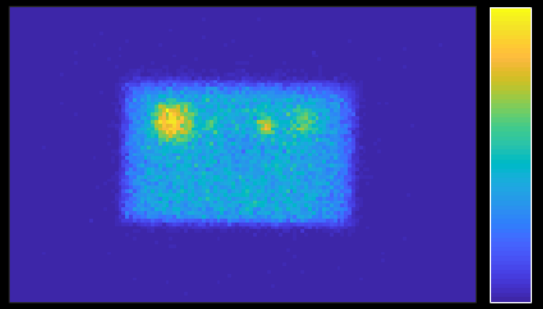
IV. Patient scan

Physical phantom measurement 1

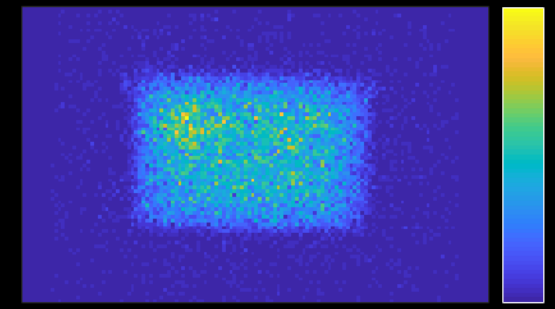
- Sphere phantom measurement (4 scans to assess noise)
  - Sphere-to-background ratio was 6:1 , 30 minutes acquisition
  - Main window width: 20%, scatter window width: 10 %



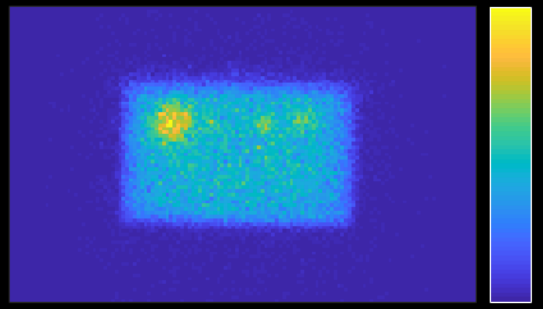
208-keV main window



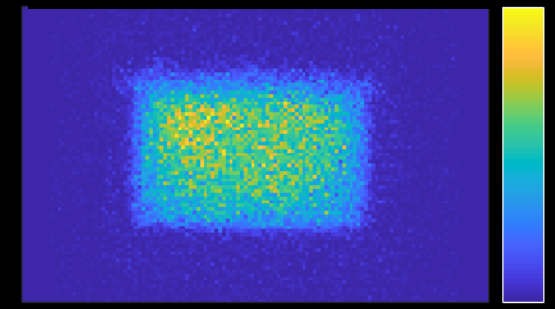
208-keV scatter window



113-keV main window

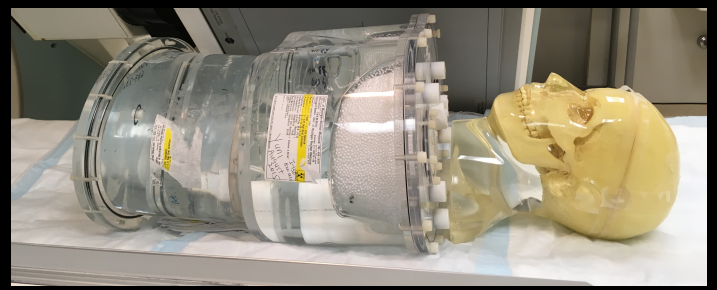


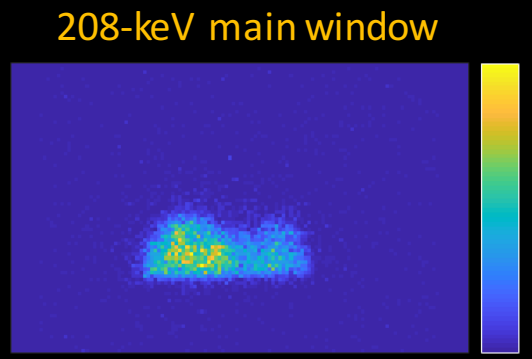
113-keV scatter window



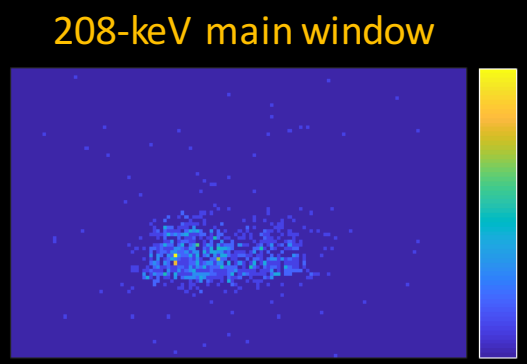
Physical phantom measurement 2

- Liver-torso phantom measurement
  - 4 scans to assess noise:
    - 4 scan of 35 min (mimicking Day3 post ^{177}Lu-DOTATATE)
    - 4 scans of 3 min (mimicking Day3 pre-therapy diagnostic imaging)
  - Lesion-to-liver ratio was 4:1





35 minutes scan

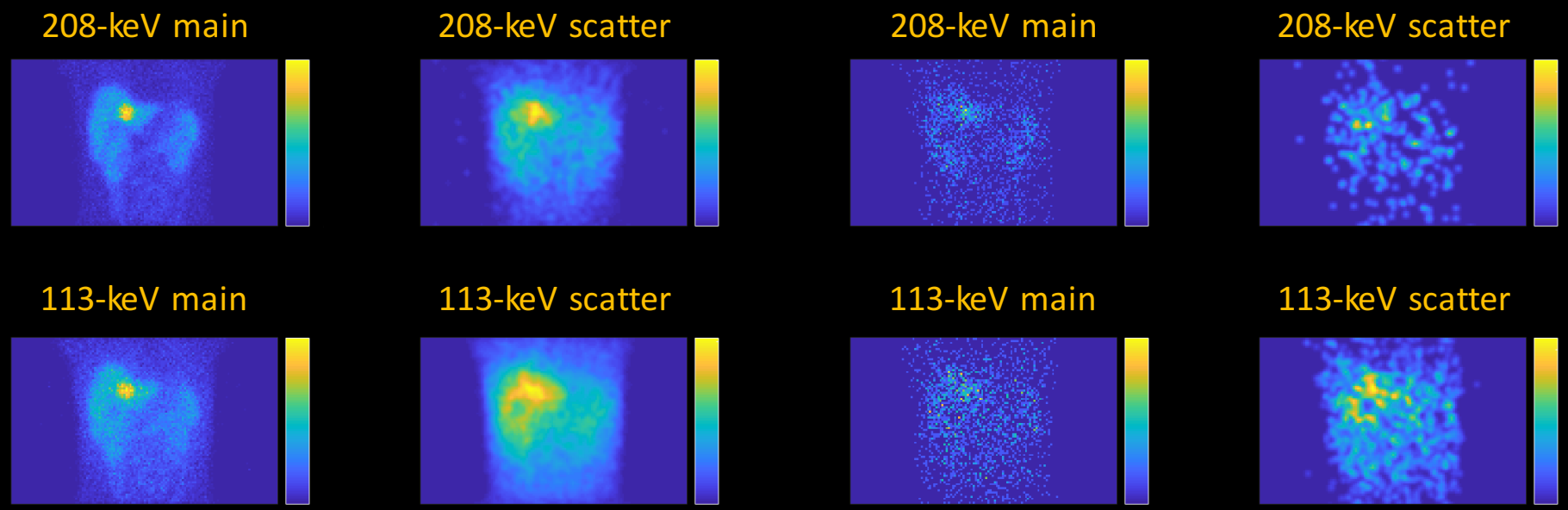


3 minutes scan

XCAT simulation

- XCAT coupled with SIMIND[2] simulation (10 realizations to assess noise)
  - Realistic activity distribution for ^{177}Lu-DOTATATE

Organ	Relative activity concentration
Lesion in liver	1.00
Spleen	0.59
Kidney	0.48
Liver	0.16
Gall bladder	0.02
Renal pelvis	0.02



Post-therapy Day1 count-level

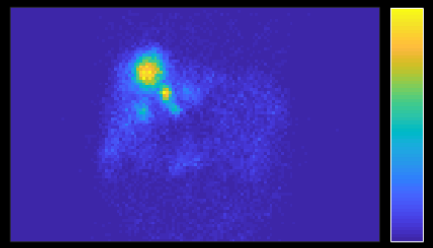
Pre-therapy Day1 count-level

2. Ljungberg M. Monte Carlo Calculation in Nuclear Medicine: Application in Diagnostic Imaging, 2nd edn, 2012.

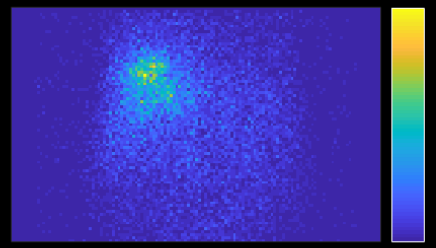
^{177}Lu-DOTATATE Patient scan

- Day5 acquisition
  - 1 clinical scan with 208-keV (Scanned for 25 minutes)
  - 3 research scans with both photopeaks (Scanned for 2 minutes to mimic pre-therapy)

208-keV main window

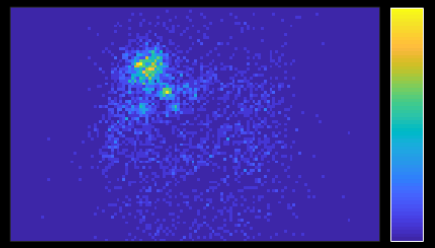


208-keV scatter window

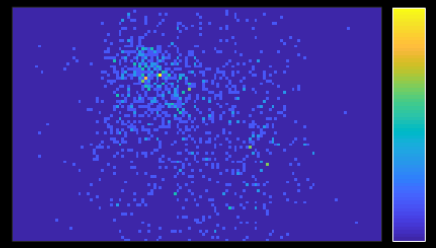


25 minutes scan at Day 5

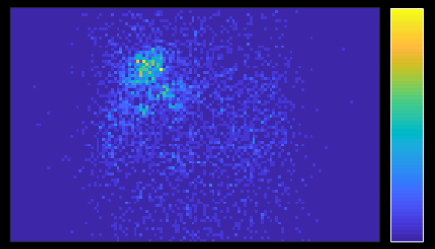
208-keV main window



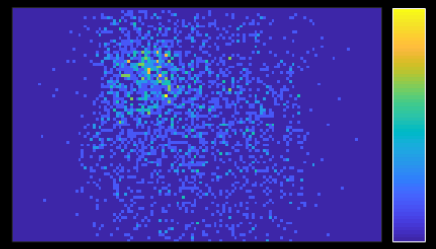
208-keV scatter window



113-keV main window



113-keV scatter window



2 minutes scan at Day 5

Reconstruction and Evaluation methods

- Reconstruction details (for both single and joint)
  - Applied Gaussian smoothing to TEW scatter estimate
  - EM algorithm + 50 iteration (1 subset)
- Evaluation metrics

I. Activity-recovery

$$\text{Activity recovery (\%)} = \frac{\text{Estimated mean activity in VOI}}{\text{True mean activity in VOI}} \times 100\ \%$$

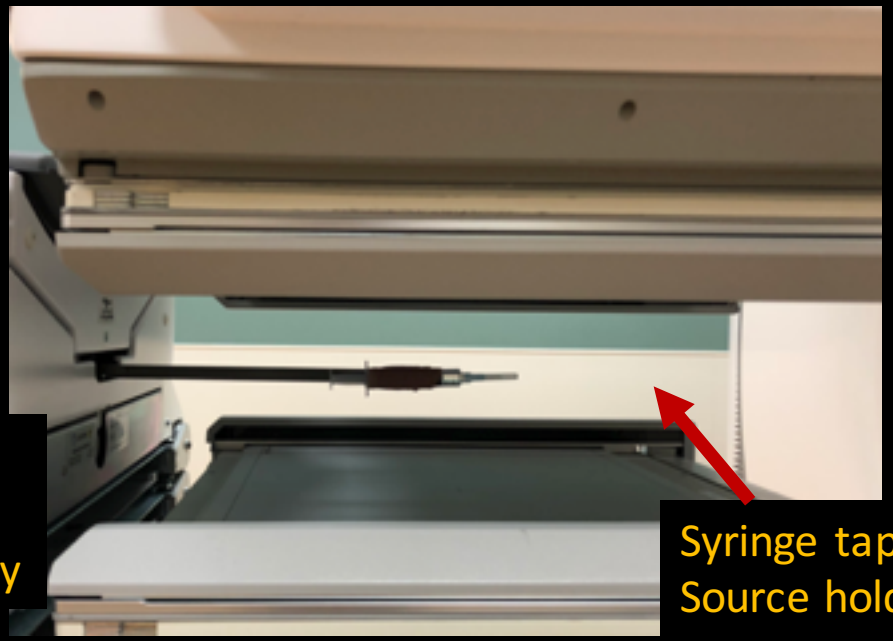
II. Contrast-recovery

$$\text{Contrast recovery (\%)} = \frac{\frac{\text{Estimated mean counts in VOI}}{\text{Estimated mean counts in BKG}} - 1}{\text{True activity concentration ratio between VOI and BKG} - 1} \times 100\ \%$$

III. Image-ensemble-noise (variability across multiple acquisitions)

$$\text{Image ensemble noise (\%)} = \frac{\sqrt{\frac{1}{J_{\text{BKG}}} \sum_{j \in \text{BKG}} \left(\frac{1}{M-1} \sum_{m=1}^{M} (\hat{\boldsymbol{x}}_m[j] - \frac{1}{M} \sum_{m'=1}^{M} \hat{\boldsymbol{x}}_{m'}[j])^2 \right)}}{\frac{1}{J_{\text{BKG}}} \sum_{j \in \text{BKG}} \frac{1}{M} \sum_{m=1}^{M} \hat{\boldsymbol{x}}_m[j]} \times 100\ \%$$

Calibration factor for absolute quantification

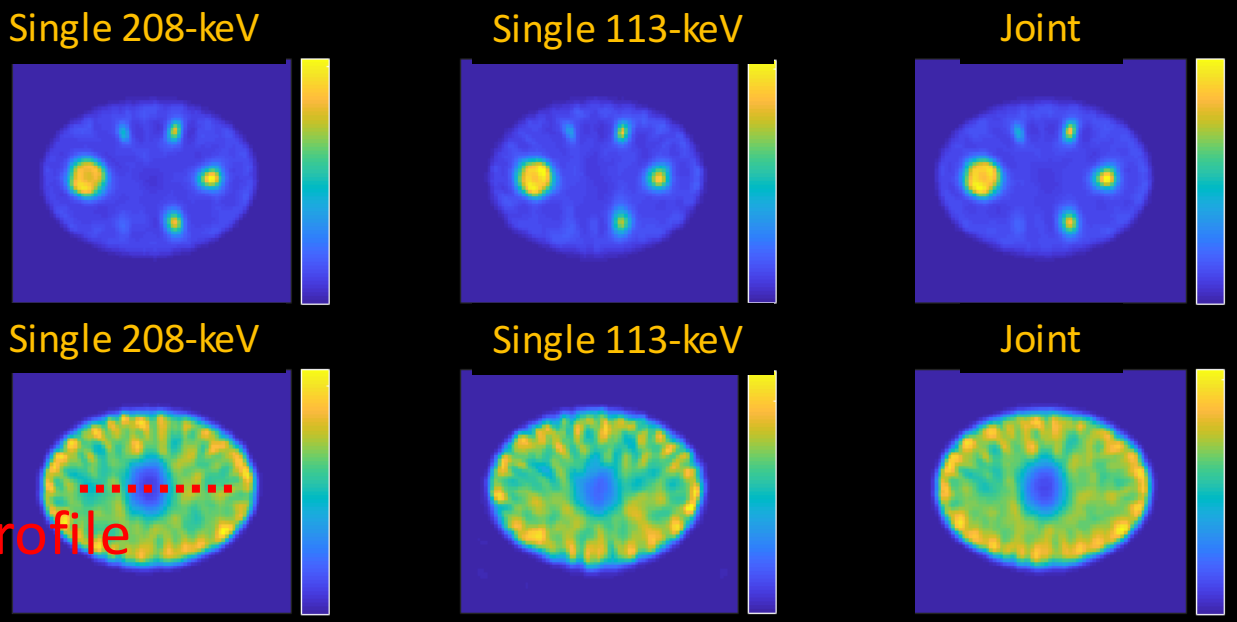


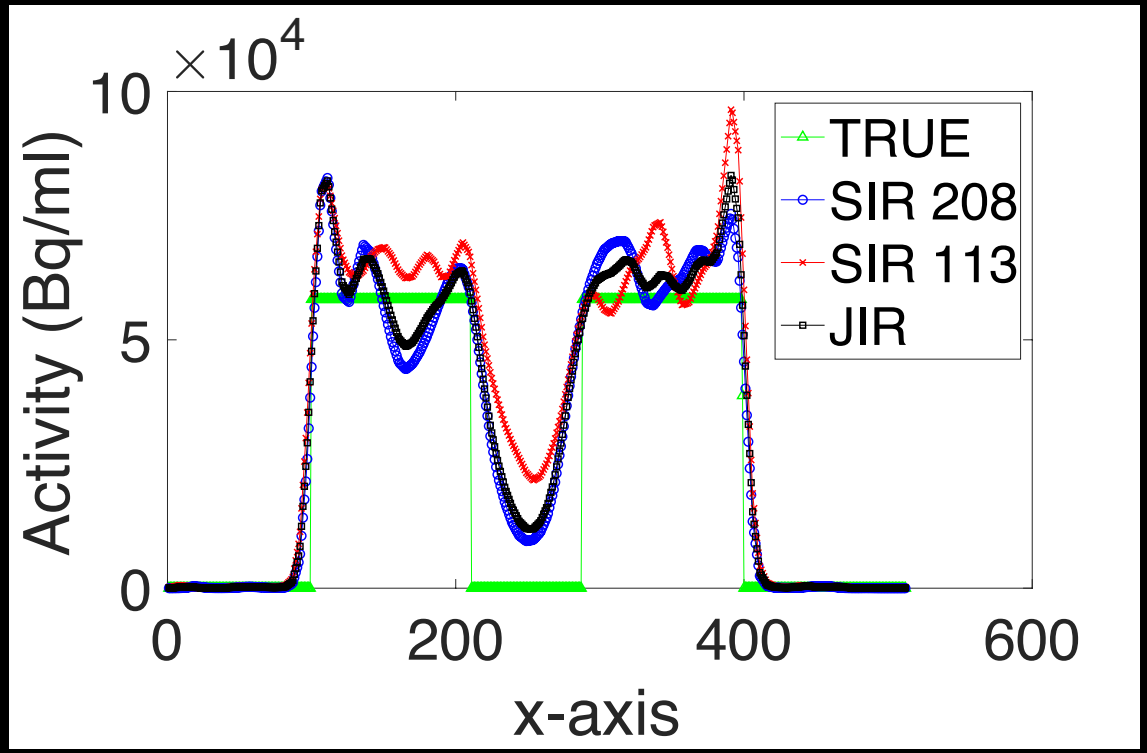
1. NIST recommendation[3] (0.9 % uncertainty)
   - 3 mL ^{177}Lu in a 10 mL Schott vial: CRC-15R dial setting 449x10
2. Transferring Calibration to a new geometry (10 mL syringe)
   - Activity in syringe = activity in vial - residual
3. With the syringe in the dose calibrator adjust setting
   - Setting to get correct reading for 3 mL in syringe: 480 x 10

- ❑ Imaging for calibration factor
  - planar with 20% main window & 10% TEW SC
- ❑ 208 keV (head1): 12.9 cps/MBq
  (head2): 13.4 cps/MBq
  → (within 1 % of manuf. specified value for 5/8" xtal)
- ❑ 113 keV (head1): 9.2 cps/Mbq (70% of above)
  (head2): 9.3 cps/MBq

3. Bergeron DE, Cessna JT. Nucl Med Commun. 2018 Jun;39(6):500-504

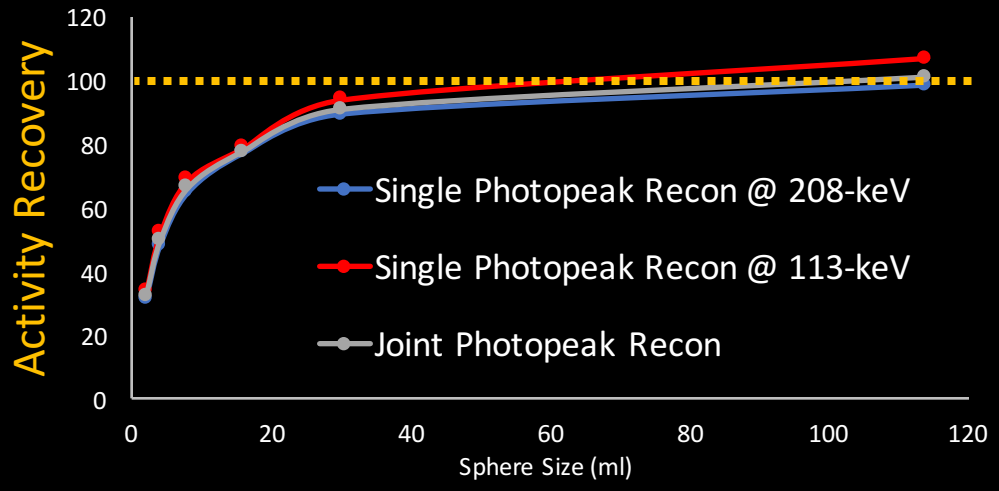
Result: Sphere phantom measurement

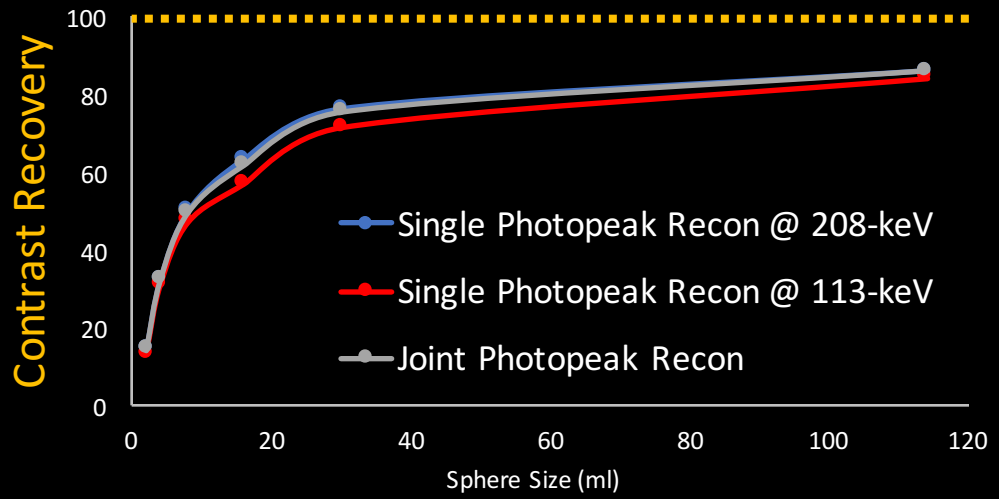


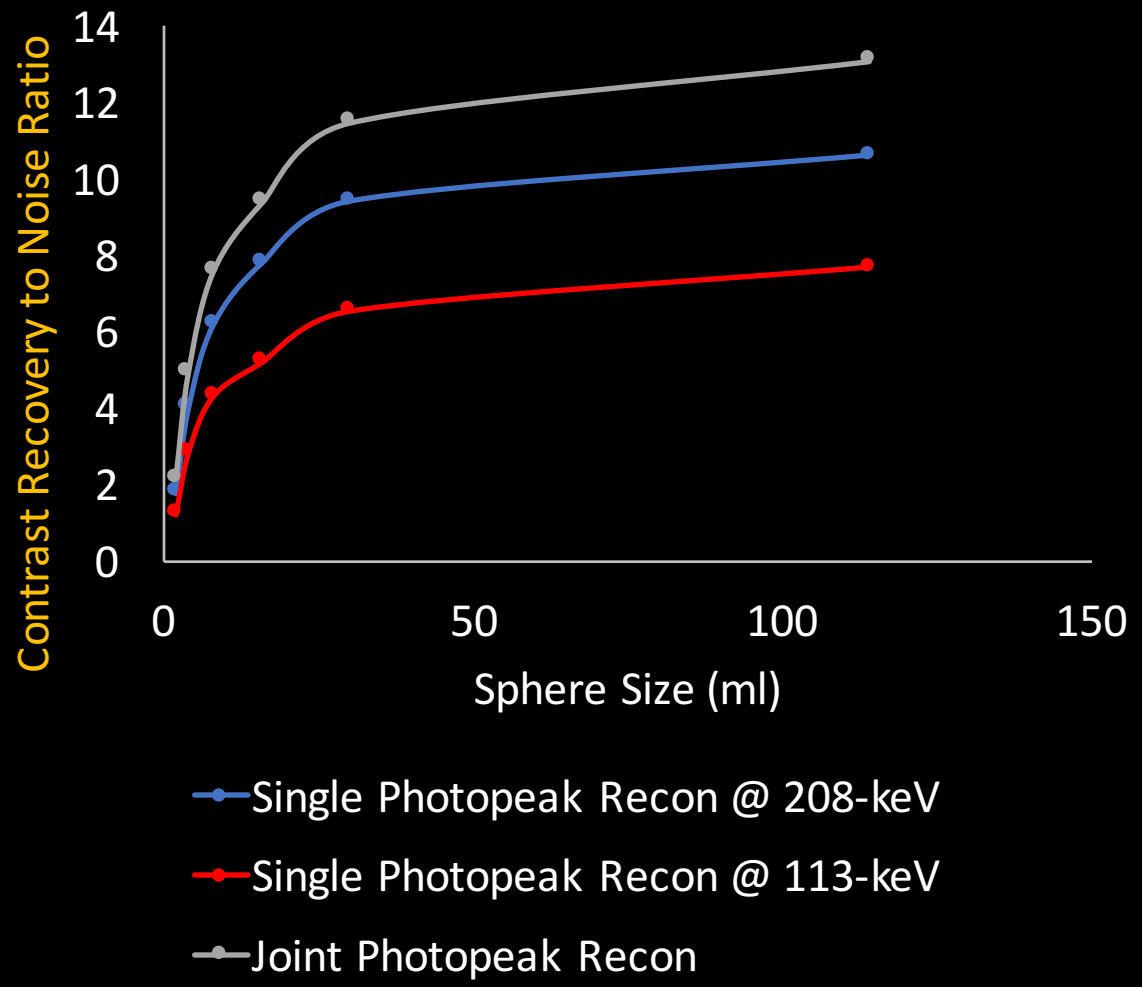


Profile across cold spot

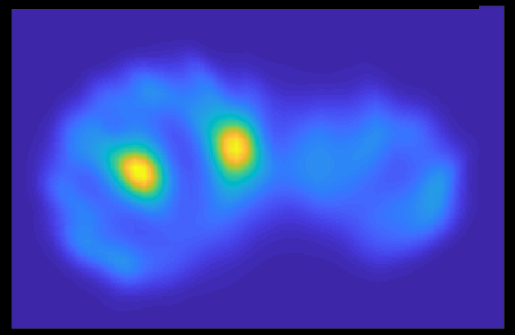
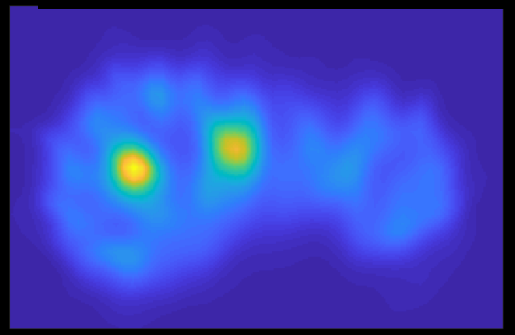
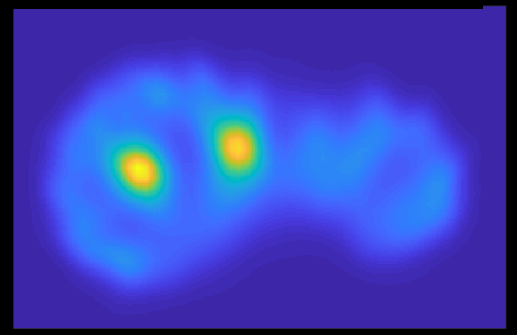
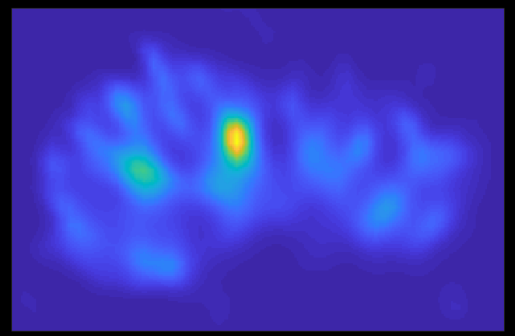
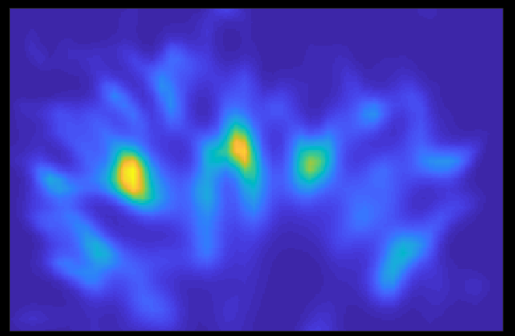
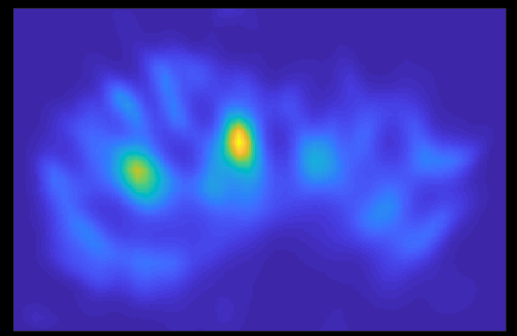
Result: Sphere phantom measurement







Result: Liver-torso phantom measurement (axial view)

	Single 208-keV	Single 113-keV	Joint
High Counts →			
Low Counts →			

Result: Liver-torso phantom measurement

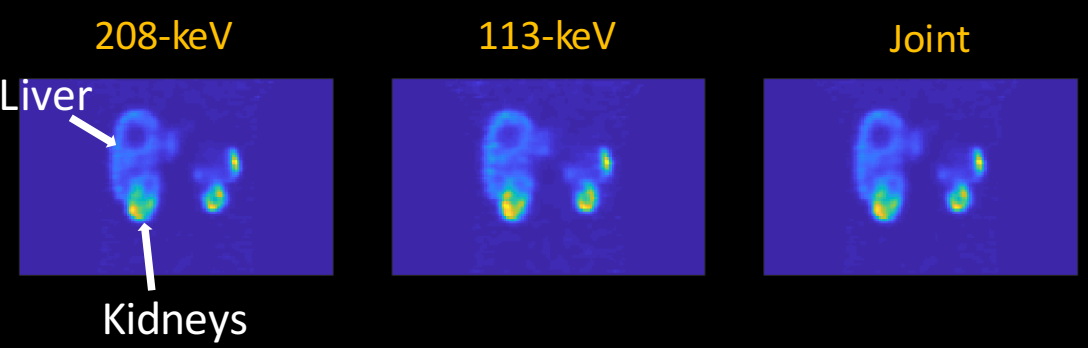
35 minutes scan

	Noise	Contrast Recovery		CRNR	
		29ml ovoid	16ml sphere	29ml ovoid	16ml sphere
208-keV	11.4	**75.3**	**70.4**	6.6	6.2
113-keV	16.4	72.4	66.6	4.4	4.1
Joint	**9.5**	74.4	69.1	**7.8**	**7.2**

3 minutes scan

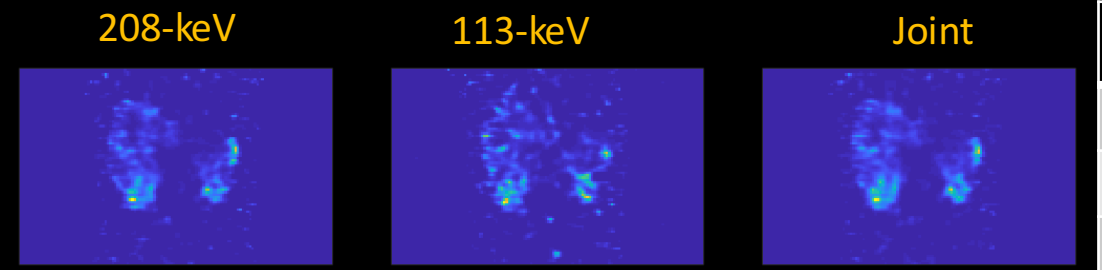
	Noise	Contrast Recovery		CRNR	
		29ml ovoid	16ml sphere	29ml ovoid	16ml sphere
208-keV	36.4	**65.2**	**63.7**	1.8	1.8
113-keV	48.5	58.7	51.8	1.2	1.1
Joint	**29.3**	62.1	58.1	**2.1**	**2.0**

Result: XCAT phantom simulation



Post-therapy Day1 count-level

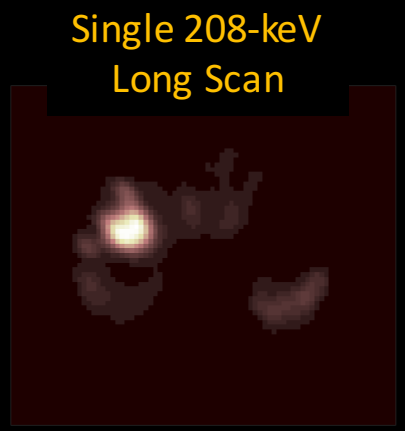
	Noise	Contrast Recovery		CRNR	
		29ml ovoid	16ml sphere	29ml ovoid	16ml sphere
208 keV	10.1	**76.3**	**92.9**	7.5	9.2
113 keV	12.9	73.3	90.4	5.7	7.0
Joint	**8.0**	75.0	91.8	**9.4**	**11.5**

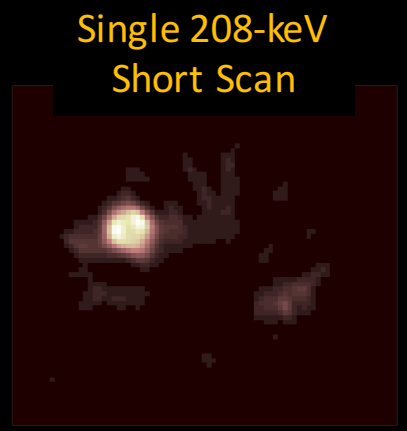


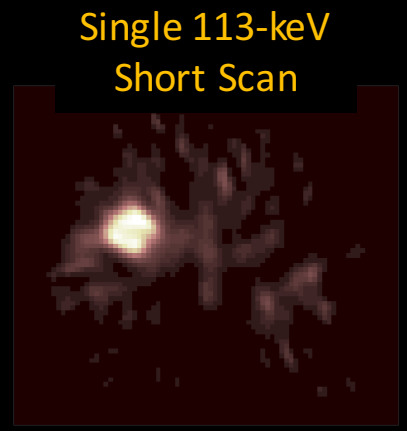
Pre-therapy count-level

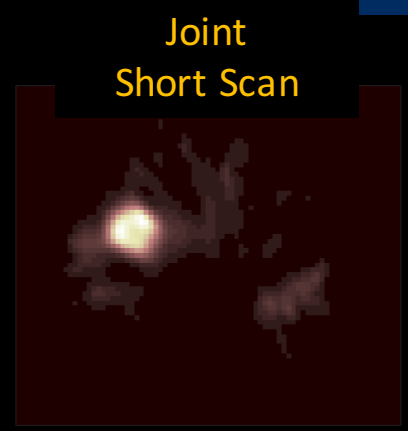
	Noise	Contrast Recovery		CRNR	
		29ml ovoid	16ml sphere	29ml ovoid	16ml sphere
208 keV	65.2	**75.8**	**91.7**	1.2	1.4
113 keV	85.5	68.7	91.5	0.8	1.1
Joint	**52.2**	72.8	91.6	**1.4**	**1.8**

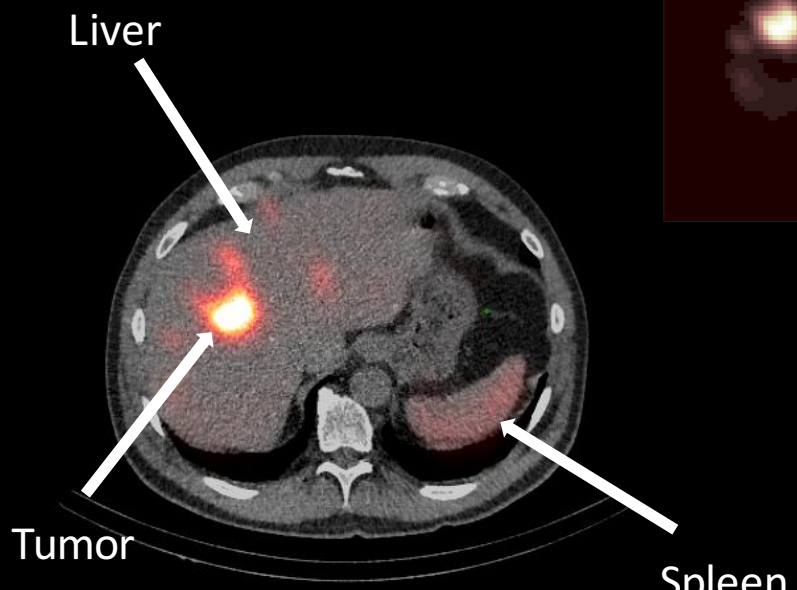
Result: Patient scan











25 minutes scan,
208-keV SPECT/CT

Recon (unit: Bq/ml)	RMSD*	Noise*
208-keV	1.47e4	332.9
113-keV	1.90e4	278.6
Joint	**1.45e4**	**260.4**

* RMSD relative to long scan
* Image ensemble noise between 3 repeat short scans

Summary

- ❑ Joint reconstruction w/ E-dependent system model & TEW SC is easy to implement
- ❑ Compared to single photopeak (208-keV) reconstruction, joint reconstruction
  - Gave comparable activity/contrast recovery
  - Improved noise significantly even for high-counts data

  → Important for voxel-level dosimetry
  - Improved contrast recovery to noise ratio: 16.7-27.3%
- ❑ Joint reconstruction can be beneficial for reducing scan time

Improvement (%) of Contrast Recovery to Noise Ratio over single 208-keV

	Experiments				
	Sphere phantom	Liver phantom		XCAT	
Count-level		High	Low	High	Low
Improvement(%)	20.9-23.2	16.7-17.5	17.3-21.5	25.4-25.8	24.7-27.3

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