Imaging of Scattered Radiation for Real-Time Tracking of Tumor Motion During Lung SBRT

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RUSH UNIVERSITY

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Lung Cancer

- Lung cancer is the most lethal cancer:
  - Over 224,000 new diagnoses in the U.S. predicted for 2015
  - 159,000 expected deaths in the U.S. predicted for 2015
  - More lung cancer related deaths than breast cancer related deaths in women

- Various treatment options:
  - Chemotherapy
  - Targeted therapy (e.g., monoclonal antibodies)
  - Surgery (e.g., wedge resection, lobectomy, pneumonectomy, cryosurgery)
  - Radiation therapy (e.g., 3D, IMRT, **SBRT**)

"Cancer facts and figures 2015"

Lung SBRT

- Promising alternative to surgery
  - Large radiation dose in few fractions (e.g., 18Gy×3 or 12Gy×5)
  - Increased TCP
  - Increased NTCP
- Requires accurate target localization
  - Radiation delivery accuracy ~1mm
  - Lung tumor motion ~2-3cm
  - Internal target not directly visible

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Lung SBRT Image Guidance

Current tumor localization methods:

- EPID
- CBCT
- FBCT
  (kV: CT–on–rails or MV: Tomotherapy)
- Stereoscopic kV imaging
  (snapshots or fluoroscopic)
- Ultrasound
- Optical Imaging (surface tracking)
- MRI
- Electromagnetic transponder tracking
- Chest expansion/contraction
- Hybrid modalities (e.g., ExacTrac)

Current limitations:

- Only 2D or limited 3D information
- Additional radiation dose
- Not available during treatment
- Not real-time
- Logistically complex (limited positioning options, collision danger)
- Invasive fiducial implants required
- Poor image contrast
- Not directly imaging the target

J. De Los Santos ,et al. "Image guided radiation therapy (IGRT) technologies for radiation therapy localization and delivery" (2013)

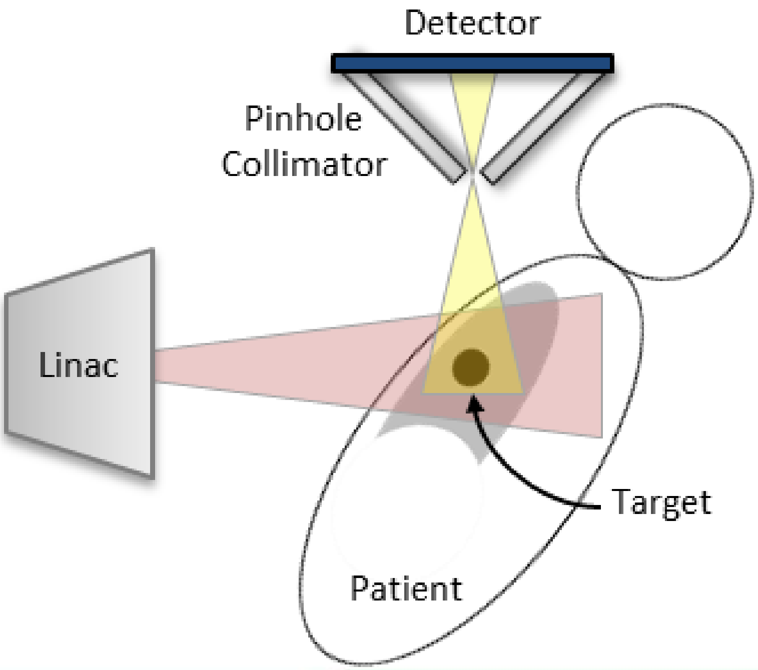
Scatter Imaging

General Concept:

- Incident radiation interacts within patient
- Energy not deposited carried away
- Scatter from internal structures dependent on material composition
- Image of spatial distribution of scatter gives 2D anatomical information

Benefits:

- No additional radiation dose
- No required fiducial implants
- Flexible detector placement
- Multiple detectors ➔ 3D
- Rapid image formation ➔ real-time imaging



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Scatter Imaging

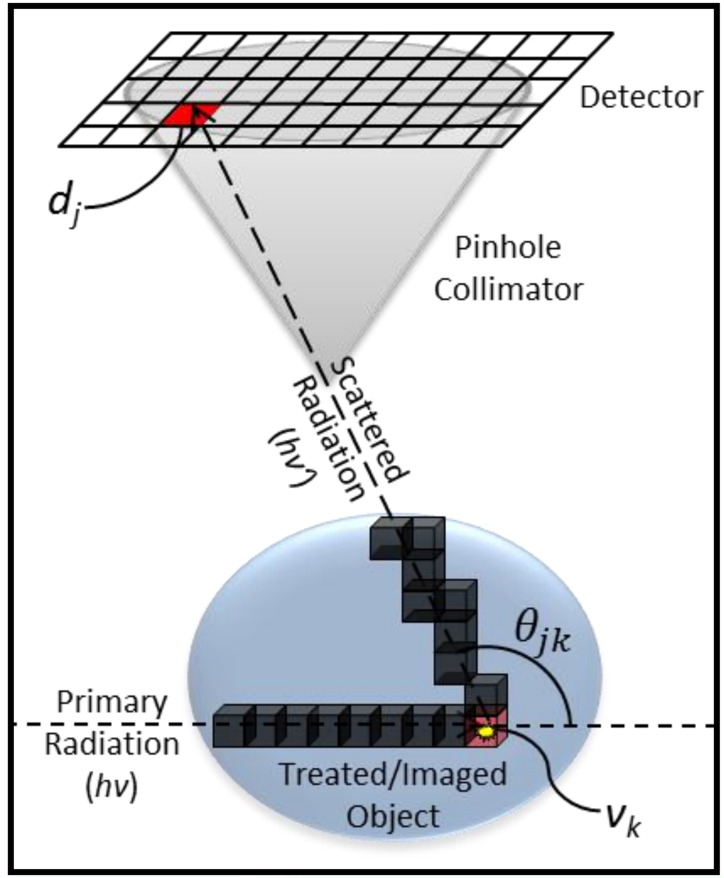
Analytic System Model:

$$\left(g_{j\times 1} = \mathcal{H}_{j\times k}\, f_{k\times 1}\right)$$

$$\boxed{\mathcal{H}_{jk} = \left[\exp\left(-\sum_n \bar{\mu}_n l_n\right)\right] \times [\bar{C}_k] \times [\bar{T}_k] \times \left[\exp\left(-\sum_m \bar{\mu}'_m l'_m\right)\right]}$$

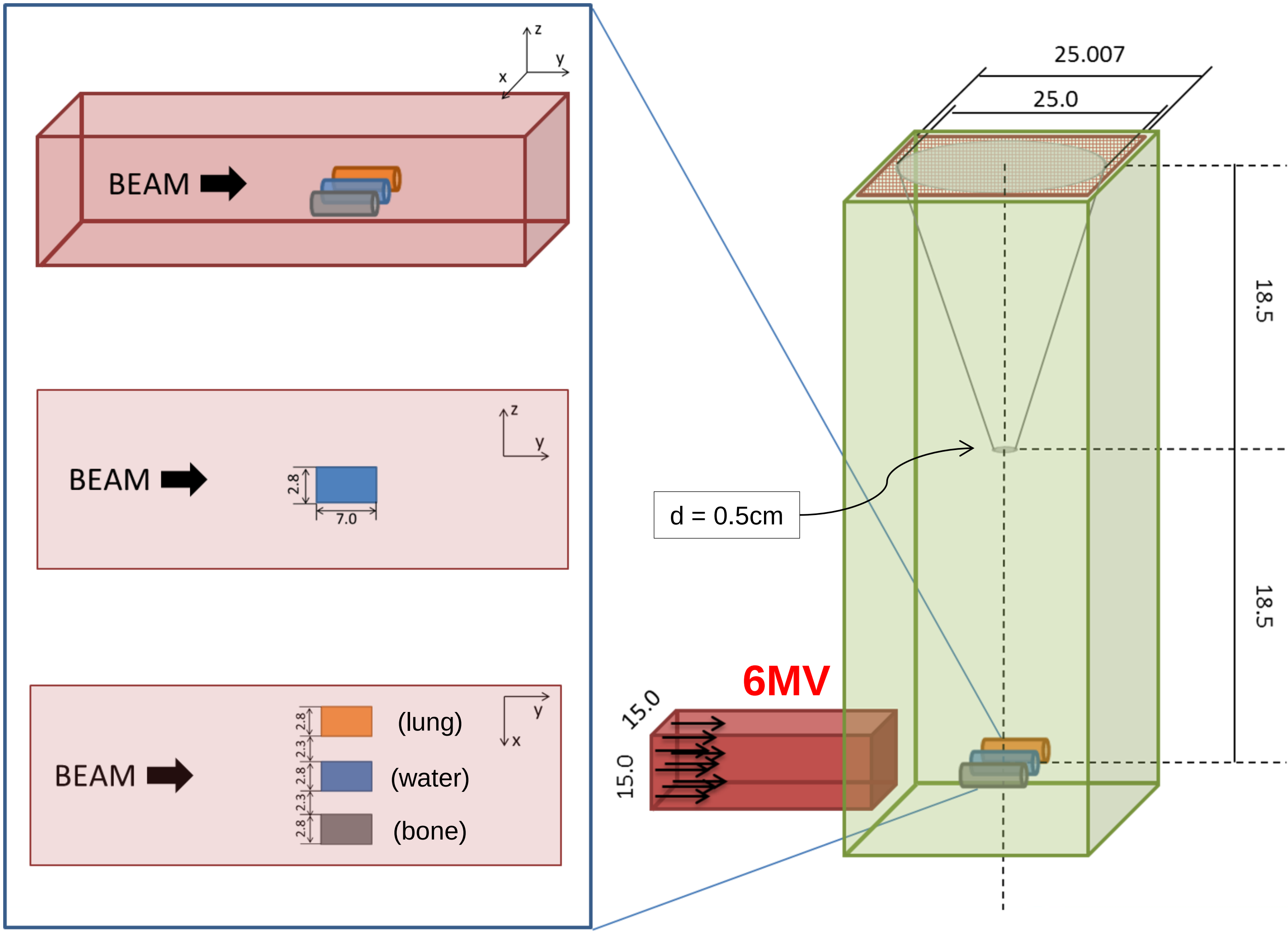
$\mathcal{H}_{jk}$ – signal contribution from scattering element v_k to detector element d_j

- Incident beam attenuation
- Probability of scatter event
- Probability of scattering angle θ_{jk}
  - Geometric considerations (pinhole size, object-pinhole distance, pinhole-detector distance)
  - Klein-Nishina differential cross section
- Scattered radiation attenuation



Scatter Imaging – Monte Carlo Simulation

Contrast Between Materials



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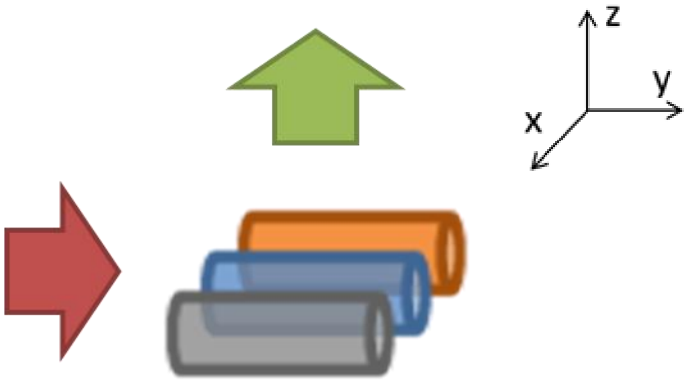
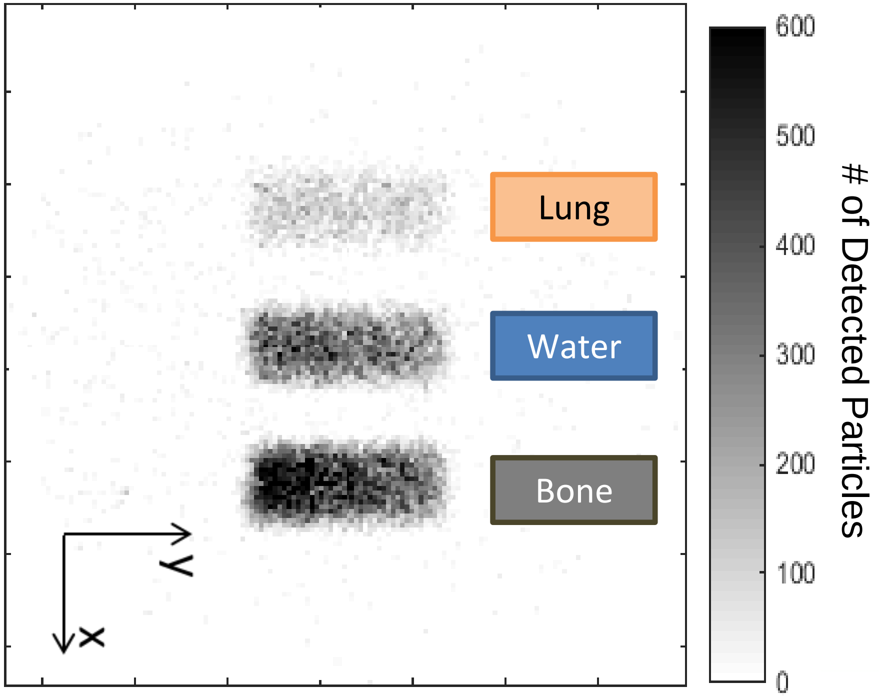


- Dose to water cylinder = 0.065 cGy
  - SNR_L = 1.9, SNR_W = 3.3, SNR_B = 3.5
- Assuming $N \propto {}^{1}/_{\sqrt{Dose}}$, for 1.0 cGy
  - SNR_L = 7.6, SNR_W = 12.7, SNR_B = 13.7

Material	Monte Carlo	Analytic Calculation
Water	1.00 ± 0.28	1.00
Lung	0.31 ± 0.12	0.35
Bone	1.39 ± 0.40	1.35

(148x148 pixels, each 0.169x0.169 cm²)



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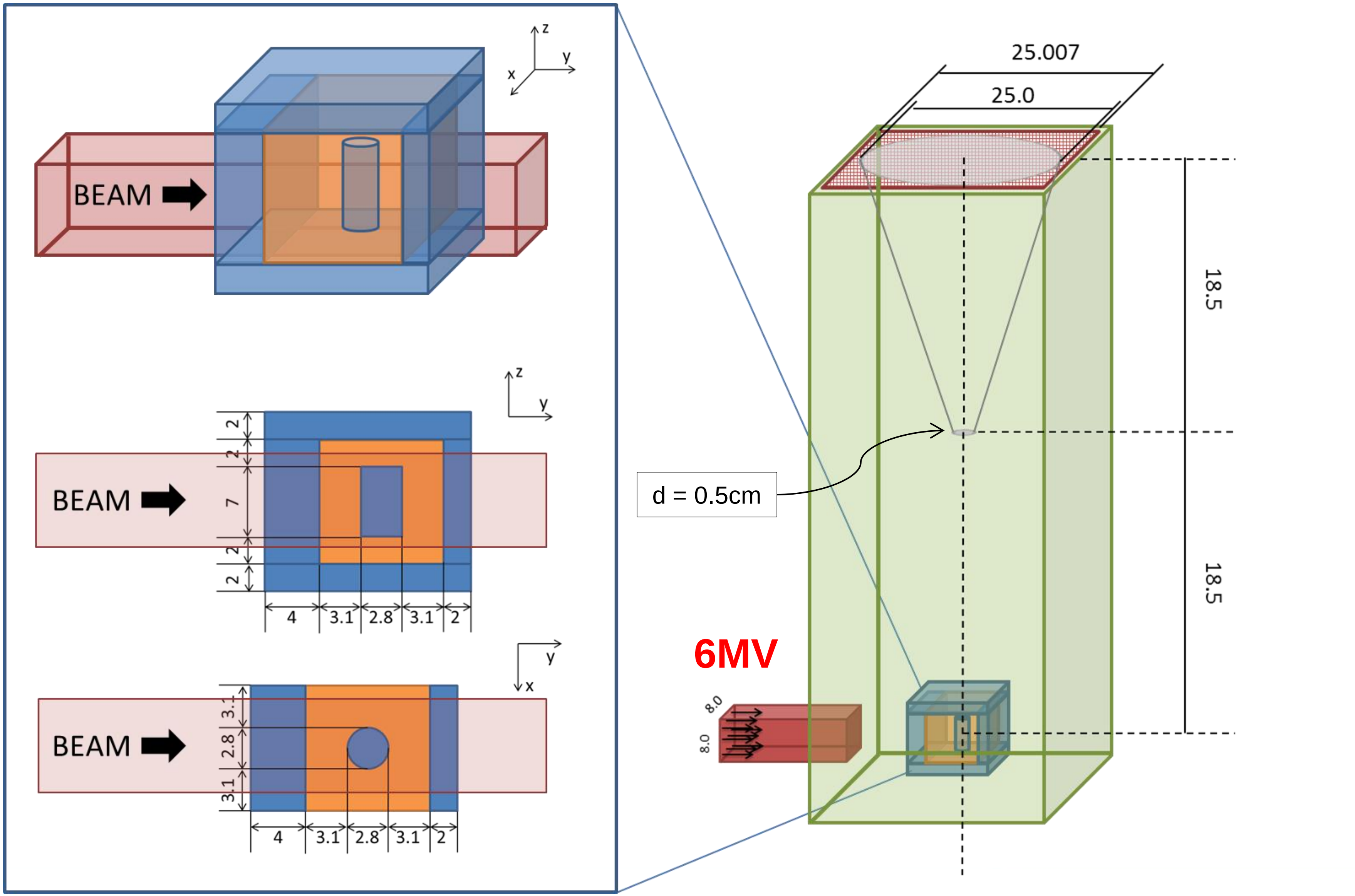
Scatter Imaging – Monte Carlo Simulation

Lung Tumor Phantom



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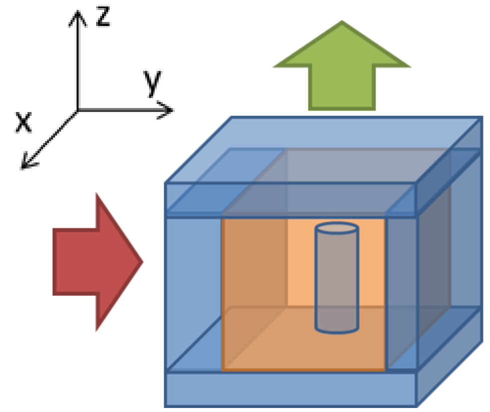
Scatter Imaging – Monte Carlo Simulation

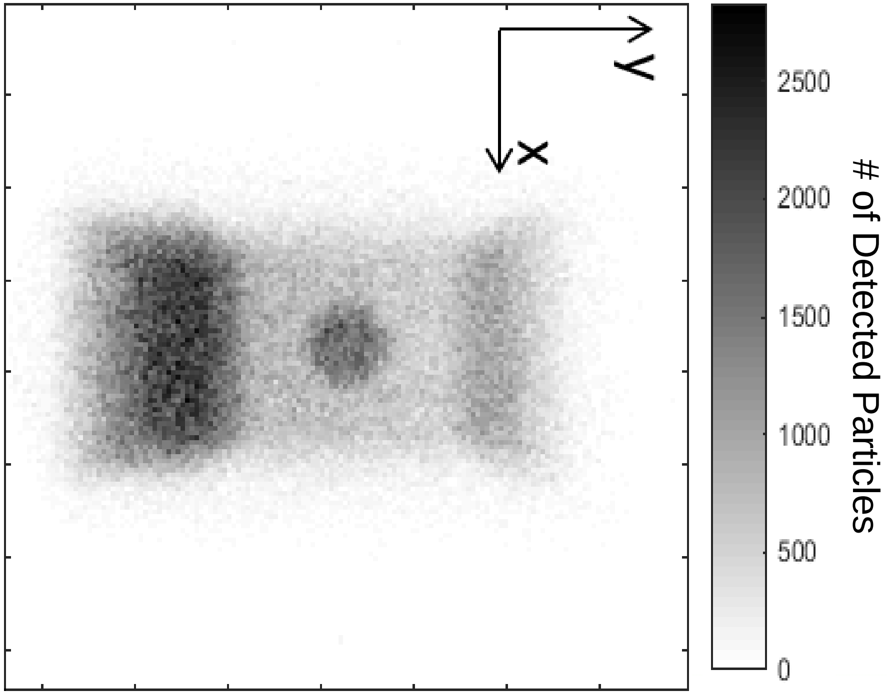
Lung Tumor Phantom

$$CNR = \frac{|S_T - \bar{S}_L|}{\sigma_T}$$



- Dose to isocenter = 0.153 cGy
  - SNR = 8.3
  - CNR = 4.8
  - 1200 cGy/min ➔ 0.153 cGy < 0.01 sec
- Assuming $N \propto {}^{1}/_{\sqrt{Dose}}$, for 1.0 cGy
  - SNR = 21.2
  - CNR = 12.3
  - 1200 cGy/min ➔ 1.0 cGy = 0.05 sec

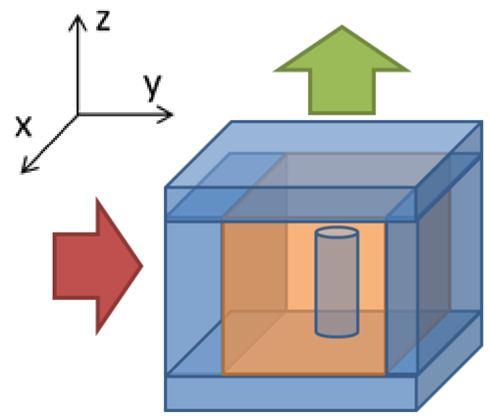
(148x148 pixels, each 0.169x0.169 cm²)



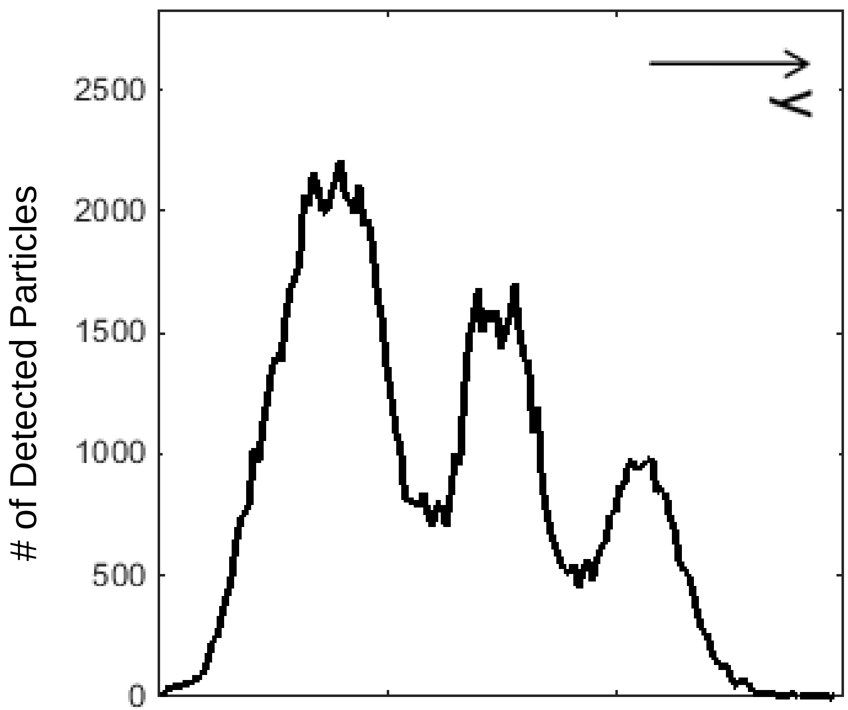
Scatter Imaging – Monte Carlo Simulation

Lung Tumor Phantom

- Clear contrast between water and lung
- Beam intensity attenuates through object



(average over 8 central pixels)



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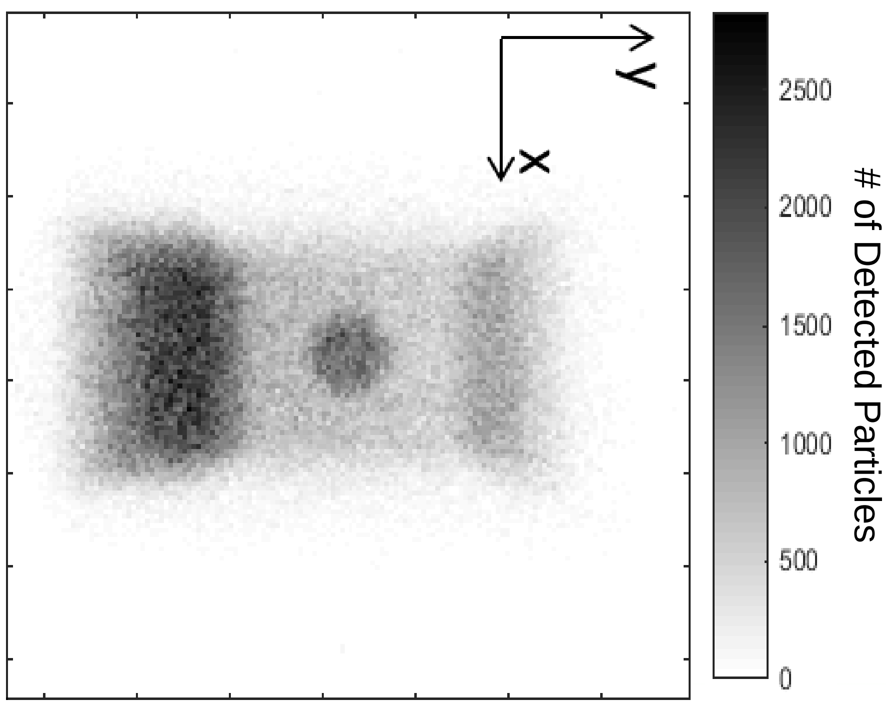
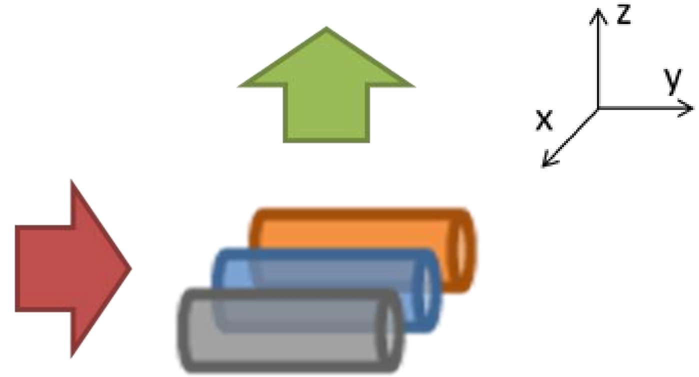
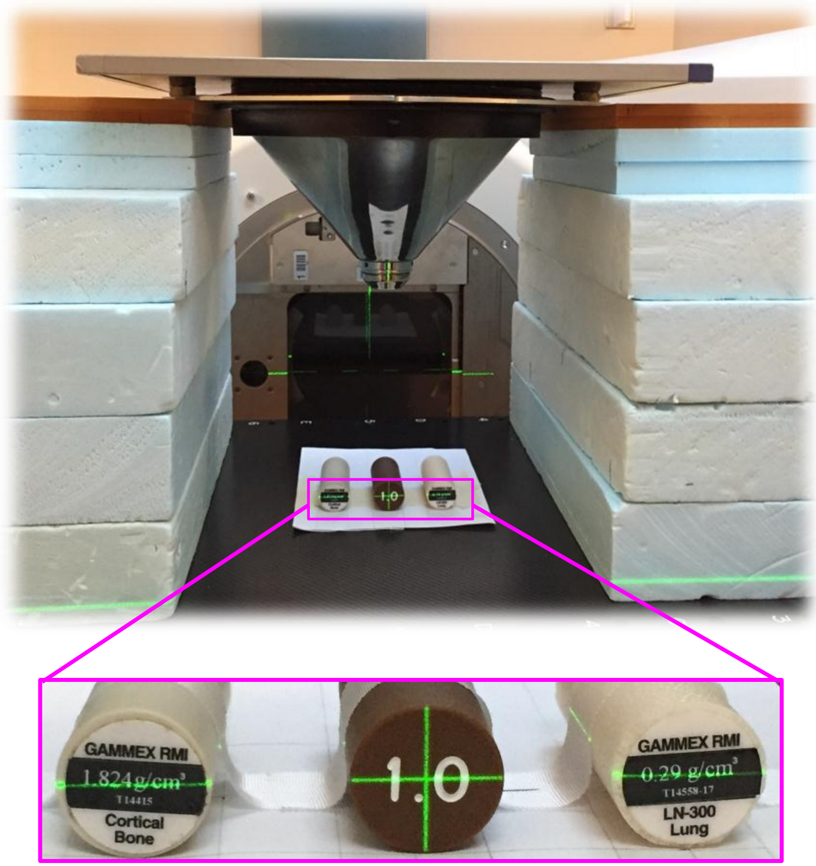


Scatter Imaging – Experimental Data

Contrast Between Materials

- Lung SBRT treatment parameters used:
  - Varian TrueBeam Linac
  - 6MV FFF
  - Dose rate = 1200 MU/min
- 5000 MU delivered
- Diagnostic flat panel detector
- Nuclear medicine pinhole camera
- Background image acquired/subtracted





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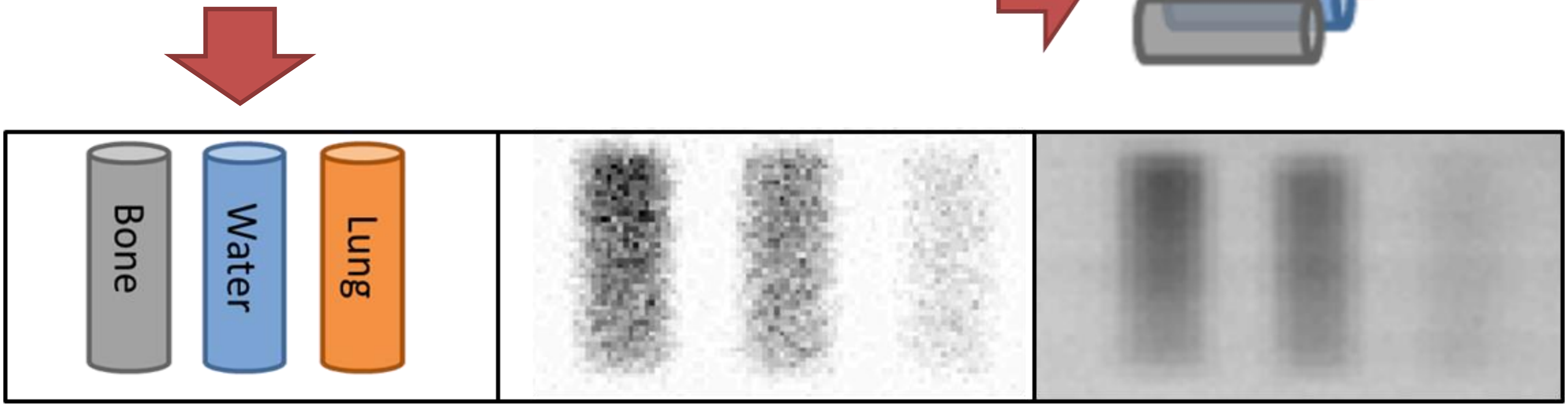
Contrast Between Materials

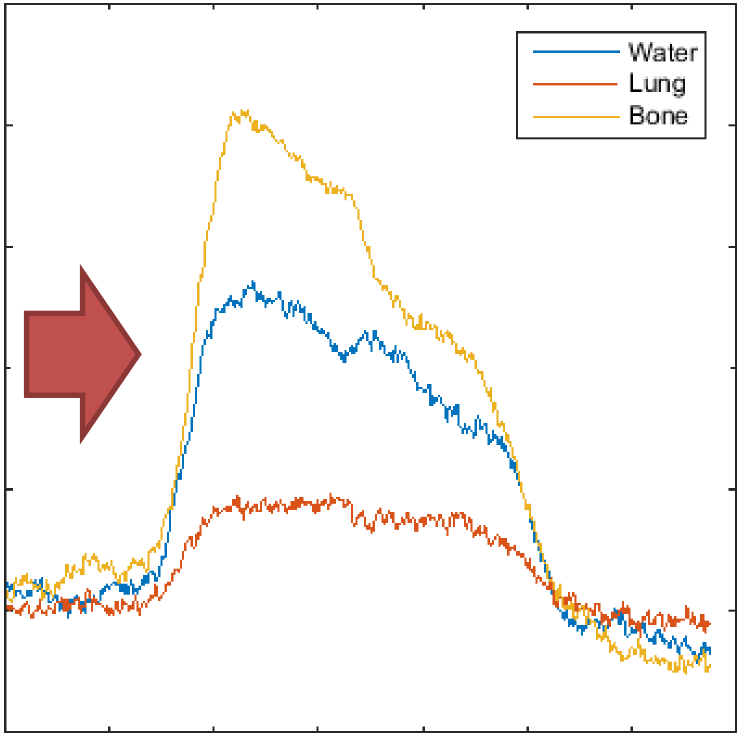


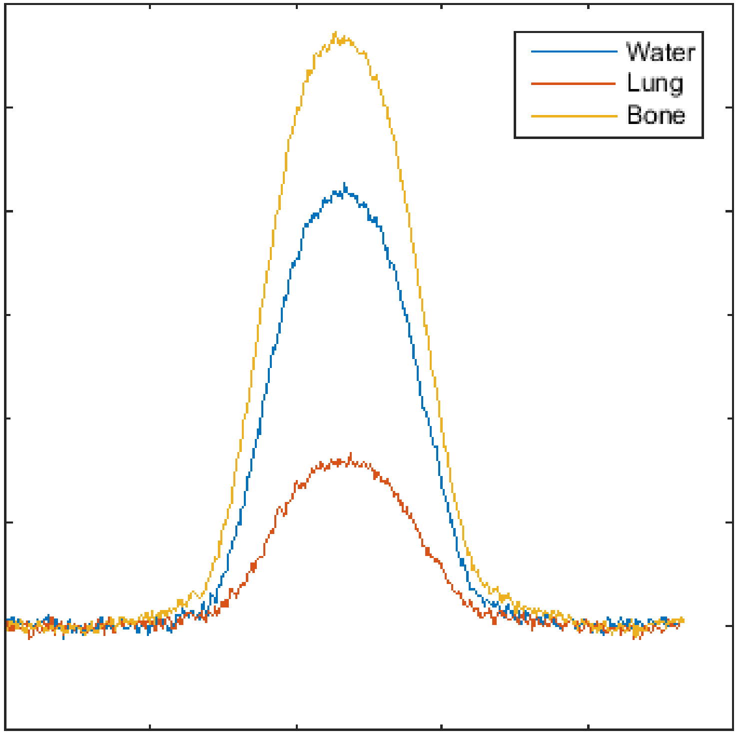
(Simulation) (Experiment)

Material	Monte Carlo	Analytic Calculation	Experiment
Water	1.00 ± 0.28	1.00	1.00 ± 0.08
Lung	0.31 ± 0.12	0.35	0.37 ± 0.08
Bone	1.39 ± 0.40	1.35	1.36 ± 0.08

Scatter Imaging – Experimental Data

Contrast Between Materials





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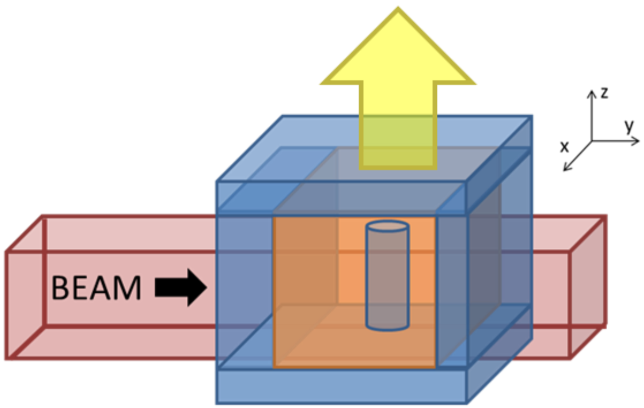
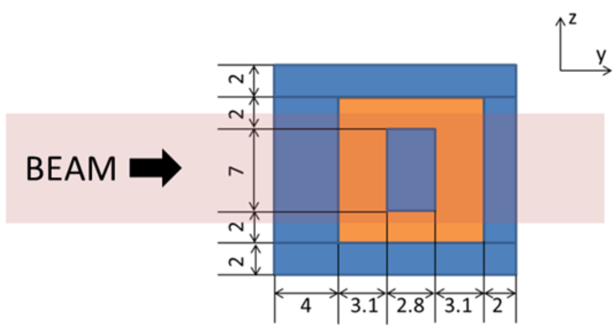
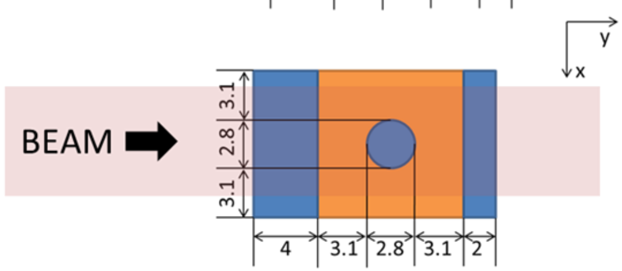
Scatter Imaging – Experimental Data

Lung Tumor Phantom







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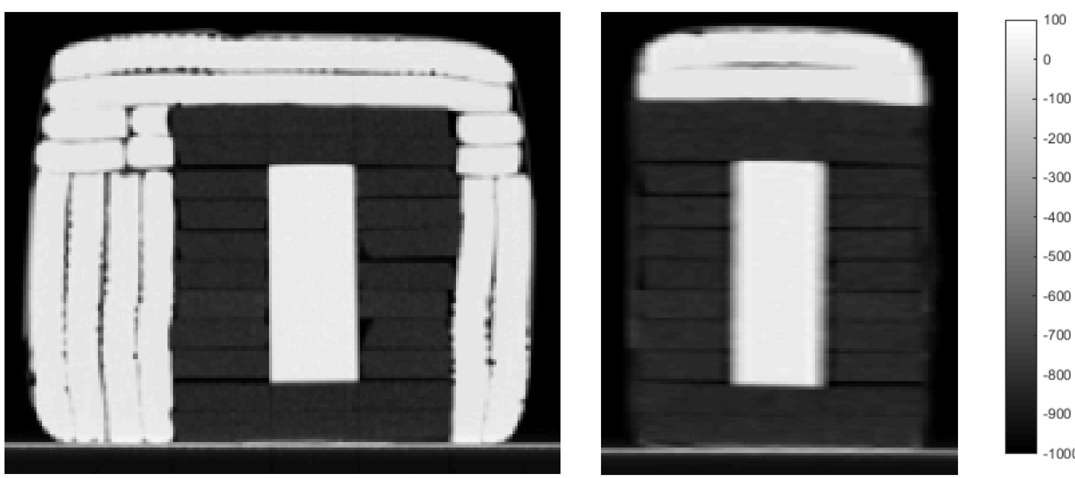
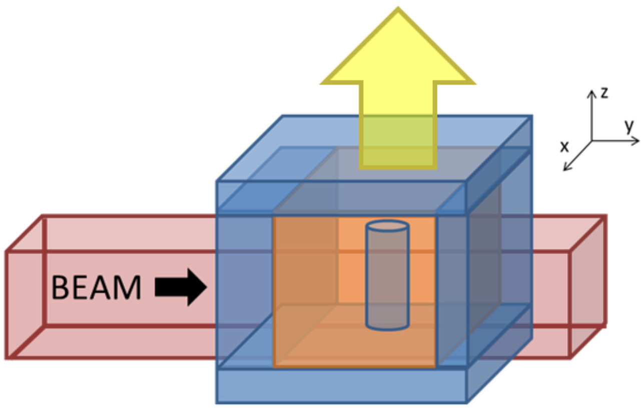
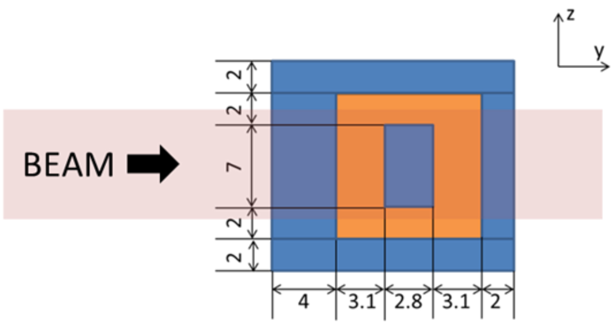
Solid Water = 9.1 ± 3.4 Bolus = -7.1 ± 3.7 Cork = -828.5 ± 13.2

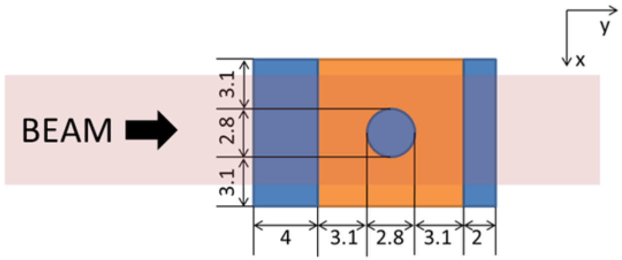


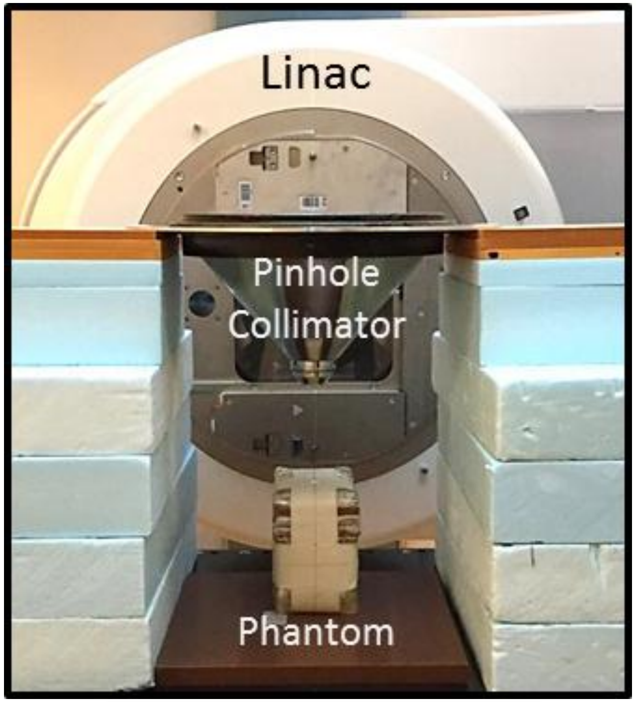
Scatter Imaging – Experimental Data

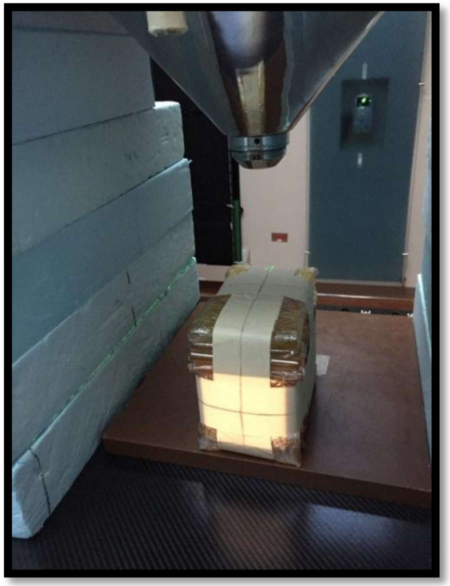
Lung Tumor Phantom











Scatter Imaging – Experimental Data

Lung Tumor Phantom

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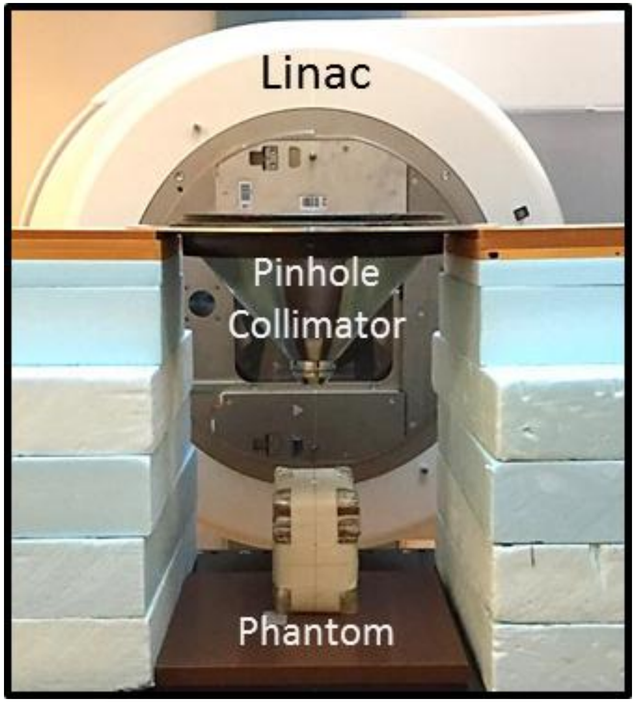

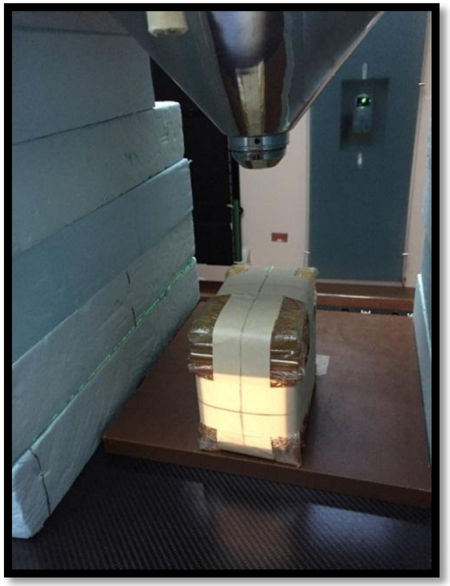

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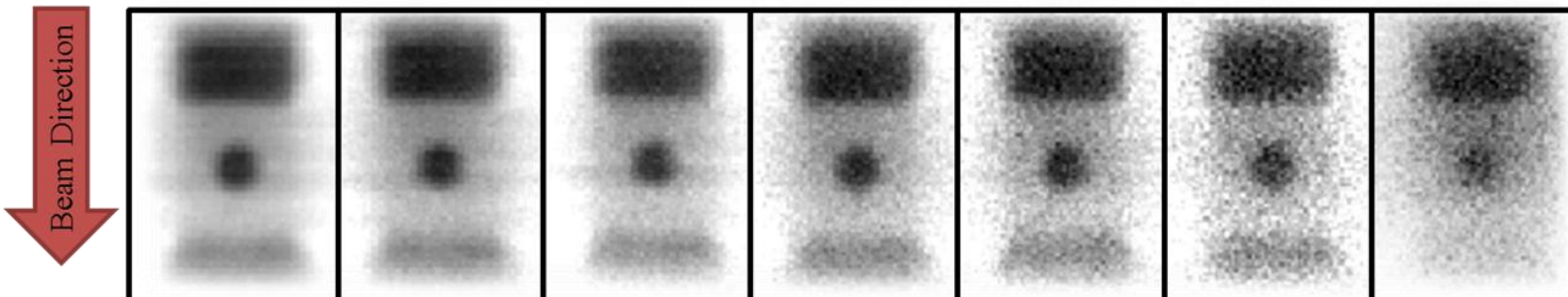
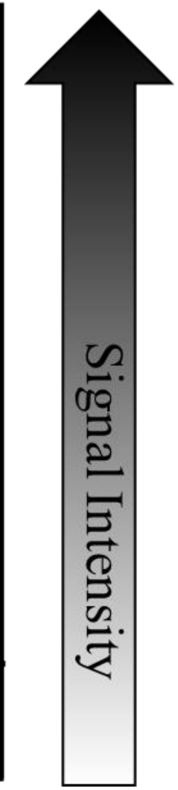
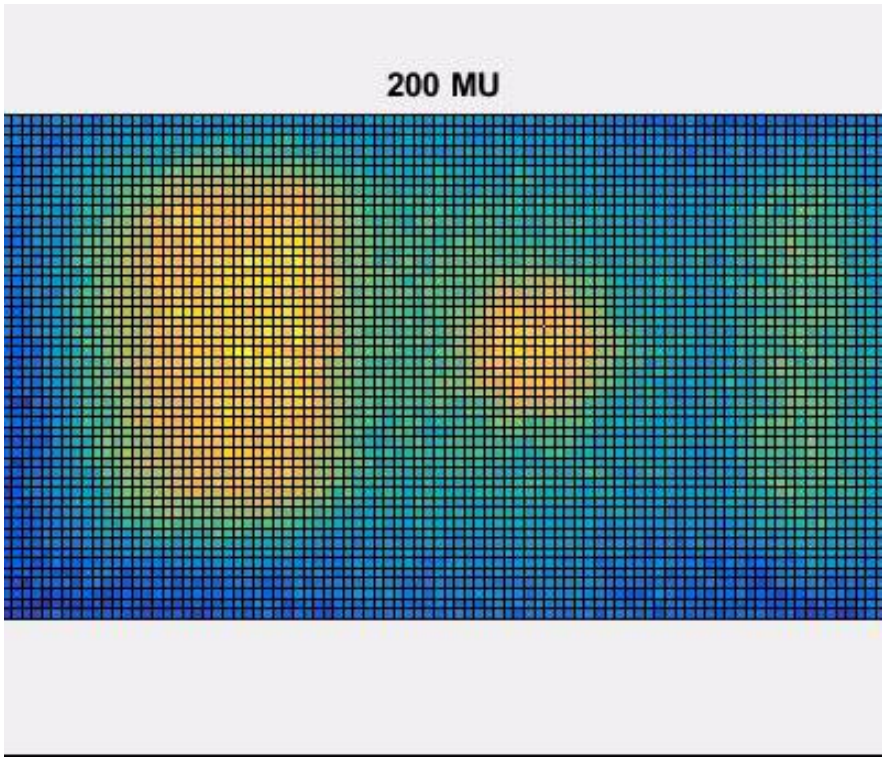


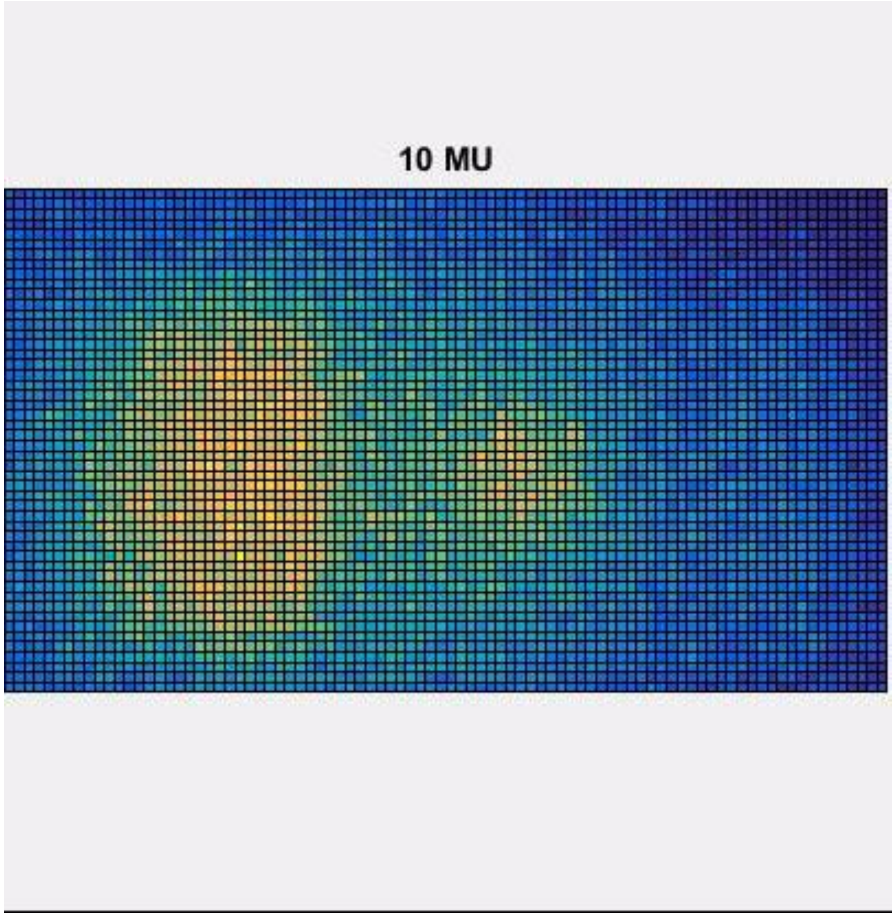
Dose (MU)	5000	1000	500	200	100	50	10
Time (sec)	250	50	25	10	5	2.5	0.5
SNR	149.9	99.3	78.8	49.8	32.3	30.0	8.9
CNR	29.1	19.0	15.5	9.7	6.7	5.5	4.1



Scatter Imaging – Experimental Data

Lung Tumor Phantom





Summary and Conclusions

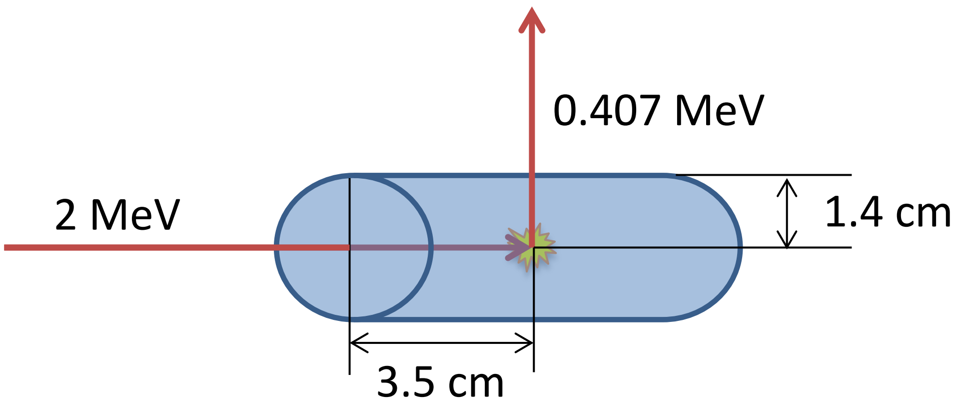
- Scatter imaging may be useful for image based tumor tracking
  - No additional radiation dose
  - No required fiducial implants
  - Flexible detector placement
  - Multiple detectors ➔ 3D
  - Rapid image formation ➔ real-time imaging
- Analytic model developed to describe scatter imaging
- Preliminary Monte Carlo simulations
  - Scatter imaging differentiates objects of different composition
  - Using a simplified lung tumor model the target can be clearly identified
- Preliminary experimental measurements agree qualitatively with simulation results
  - Images as fast as 0.5sec (10MU) begin to resolve target ➔ Real-time imaging

Thank You

Questions?

Analytic System Model

$$\mathcal{H}_{jk} = \left[\exp\left(-\sum_n \bar{\mu}_n l_n\right)\right] \times [\bar{C}_k] \times [\bar{T}_k] \times \left[\exp\left(-\sum_m \bar{\mu}'_m l'_m\right)\right]$$



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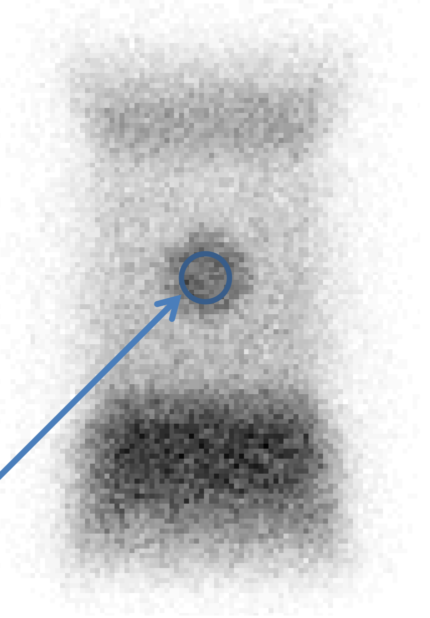
Water	1.00 ± 0.28	1.00 ± 0.08
Lung	0.31 ± 0.12	0.37 ± 0.08
Bone	1.39 ± 0.40	1.36 ± 0.08

(Assume scatter at 90º, so ignore $\bar{T}_k$)

Material	$\bar{C}_k \left(\frac{Z}{A}\right)$	$\rho \left[\frac{g}{cm^3}\right]$	$\frac{\mu}{\rho}\left[\frac{cm^2}{g}\right]$ (2 MeV)	$\mu\,[cm^{-1}]$ (2 MeV)	$\exp\left(-\sum_n \bar{\mu}_n l_n\right)$ (2 MeV)	$\frac{\mu}{\rho}\left[\frac{cm^2}{g}\right]$ (0.407 MeV)	$\mu\,[cm^{-1}]$ (0.407 MeV)	$\exp\left(-\sum_m \bar{\mu}'_m l'_m\right)$ (0.407 MeV)	$\mathcal{H}_{jk}$
Water	1.00	1.00	0.0493	0.0493	0.8415	0.1061	0.1061	0.8620	0.725 (1.00)
Lung	0.28	0.29	0.0461	0.0142	0.9515	0.1053	0.0305	0.9582	0.255 (0.35)
Bone	1.69	1.824	0.0490	0.0840	0.7453	0.0991	0.1808	0.7764	0.978 (1.35)

Defining SNR



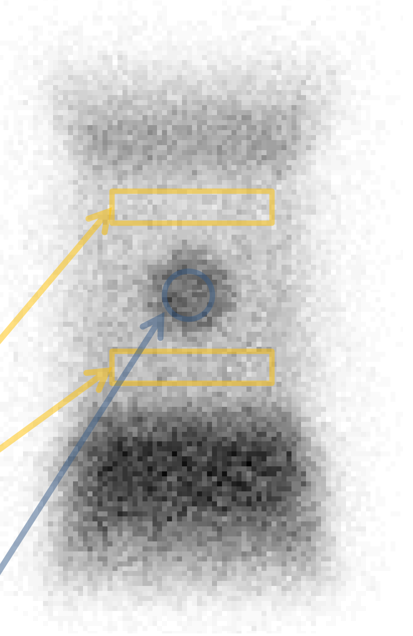
- Specifically looking at “tumor” in image

$$SNR = \frac{S_T}{\sigma_T}$$

  - S_T is the image intensity, averaged over a central region within the tumor
  - σ_T is the standard deviation of the image intensity over the same central region within the tumor

Note: SNR and CNR should be approximately proportional to $\sqrt{dose}$ and to linear pixel dimension

Defining CNR



- Specifically looking at "tumor" in image
- Tumor is embedded in lung
- CNR is a metric to quantify how well tumor can be differentiated from the surrounding lung relative to the random noise present in the image

$$CNR = \frac{|S_T - \bar{S}_L|}{\sigma_T}$$

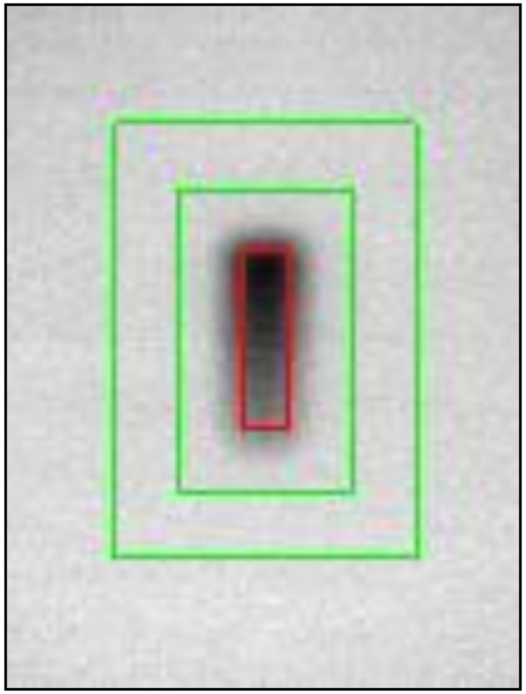
- S_T is the image intensity, averaged over a central region within the tumor
- $\bar{S}_L = \frac{S_{L_1} + S_{L_2}}{2}$, where S_{L_1} and S_{L_2} are image intensity, averaged over regions within the lung surrounding the tumor
- σ_T is the standard deviation of the image intensity over the same central region within the tumor used to calculate S_T

Note: SNR and CNR should be approximately proportional to $\sqrt{dose}$ and to linear pixel dimension

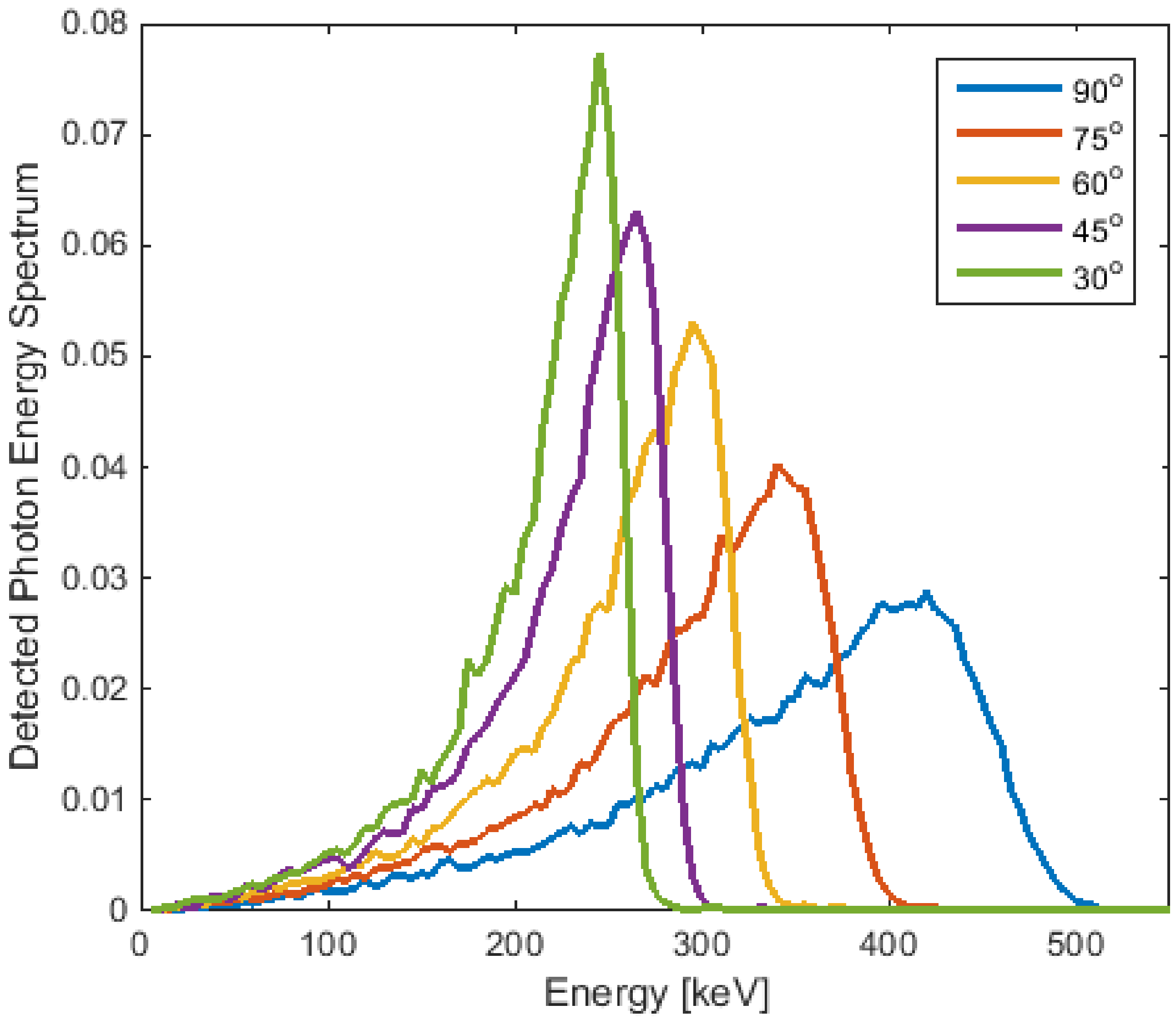
Scatter Imaging – Experimental Data

Contrast Between Materials

- Signal ➔ Average over 18,216 pixel cylinder ROI
- Noise ➔ Standard deviation in cylinder ROI
- Background ➔ Average over surrounding 189,880 pixel ROI
- $SNR_L = 6.1$, $SNR_W = 6.7$, $SNR_B = 5.3$
- $CNR_L = 4.4$, $SNR_W = 5.3$, $SNR_B = 4.1$



Scatter Imaging – Monte Carlo Simulation



Lung SBRT Image Guidance

Current limitations:

- Only 2D or limited 3D information
- Additional radiation dose
- Not available during treatment / Not real-time
- Logistically complex (limited positioning options, collision danger)
- Invasive fiducial implants required
- Poor image contrast
- Not directly imaging the target

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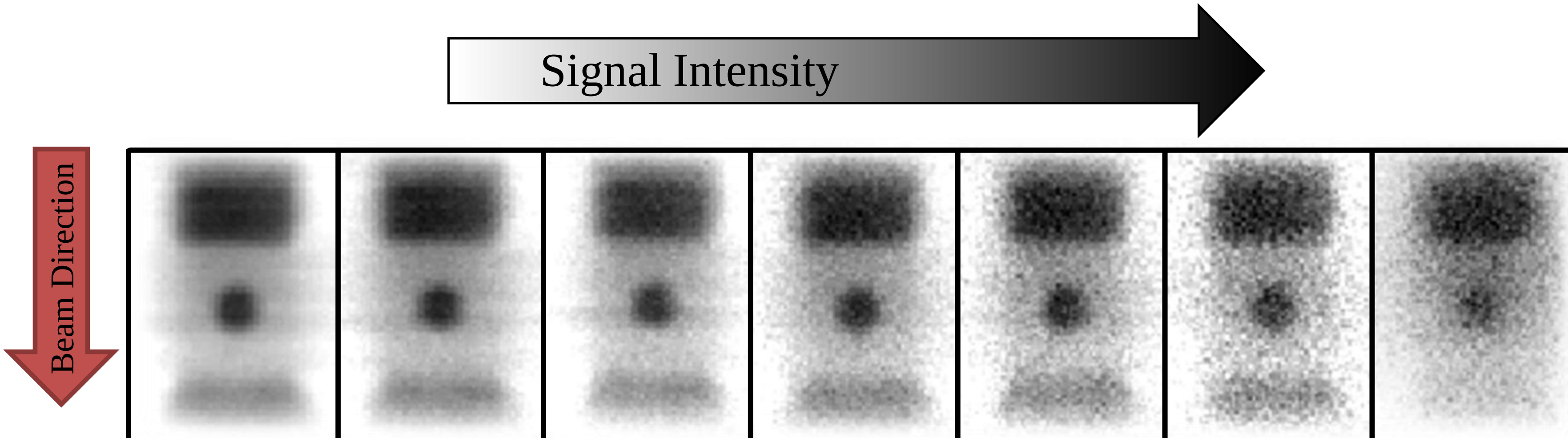
Scatter Imaging – Experimental Data

Lung Tumor Phantom



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