Pinhole X-ray Fluorescence Imaing of Gadolinium Nanoparticles
:A Preliminary Monte Carlo Study

2014 추계 원자력학회
서울대학교
정성문

Contents

- Introduction
- Material and Methods
- Results
- Conclusions
- Future Work
- Q&A

Introduction

- Metal nanoparticles in medical applications

1. Metal Enhanced Radiation Therapy

   - Dose enhancement due to photoelectrons/Auger electrons of High Z material
   - 140kVp source
     a. 3% gold in tissue ➡ 560% dose enhancement
     b. 0.7% gold in tissue ➡ 211% dose enhancement
     (Cho S.H.,2005,PMB)

2. Molecular Imaging

Tumor targeting metal nanoparticles as a molecular probe

- Molecular size
- Functional imaging

Introduction

- X-ray fluorescence imaging
  1. *in vivo* imaging of metal nanoparticles distributed within tumor and other critical organ → Location
  2. *in vivo* quantification of the amount of metal nanoparticles → Concentration

Actual accumulated concentration of nanoparticles

- The expected concentration of gold accumulated in tumors is on the order of 0.001% *(J.Hainfeld et al., BJR,2011)*

- In case of Cisplatin chemotherapy, concentrations of 0.0005% ~ 0.004% have been measured *(R. Jonson et al., Acta Oncol, 1991)*

Introduction

- Purpose

  1. Imaging relatively low concentrations of gadolinium nanoparticles using (1)x-ray fluorescence, (2)pinhole imaging system and (3)monochromatic x ray source

  2. Comparing two energy (1)50.5keV, (2)55keV of photon source

- Gadolinium(Z=64)

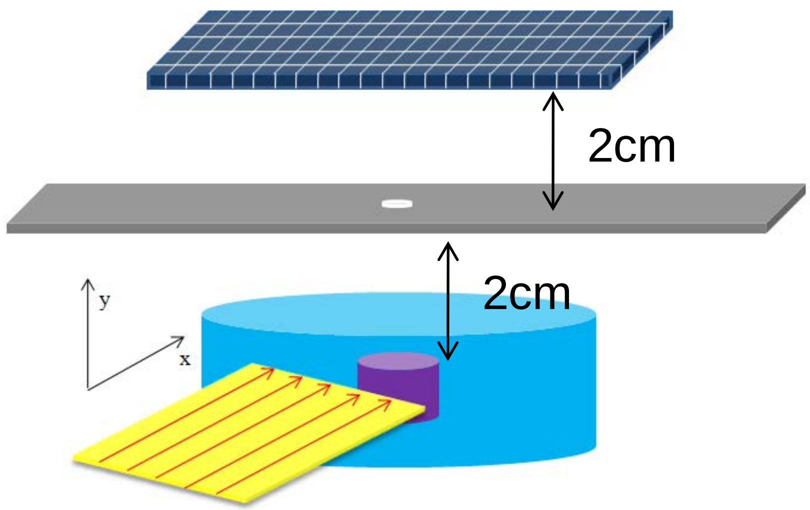
- Most widely used metal nanoparticles in medical applications
- MR contrast
- Dose enhancer in radiation therapy
- Kedge energy: 50.239keV
- Characteristic X-rays: $K_{\alpha1}$(42.996keV), $K_{\alpha2}$(42.309keV),..
- Kedge E < 60keV(포항광가속기에서 조사 가능한 최대 mono Energy)
- Toxicity → concentration of Gd injected should be low

Material and Methods

- Pinhole imaging system

1. Magnification, high spatial resolution
2. 2D radiography with 2D detector array
3. Benchmarking an image modality pinhole SPECT(Single Photon Emission Computed Tomography)

- Monte Carlo simulation geometry



Dexel: $0.25 \times 0.25 cm^2$
Detector array:$4.5 \times 4.5 cm^2$

Pinhole:0.4cm diameter

Source: 1mm height rectangular shaped x-ray beam

Water phantom:5cm diameter
Gd column:1cm diameter

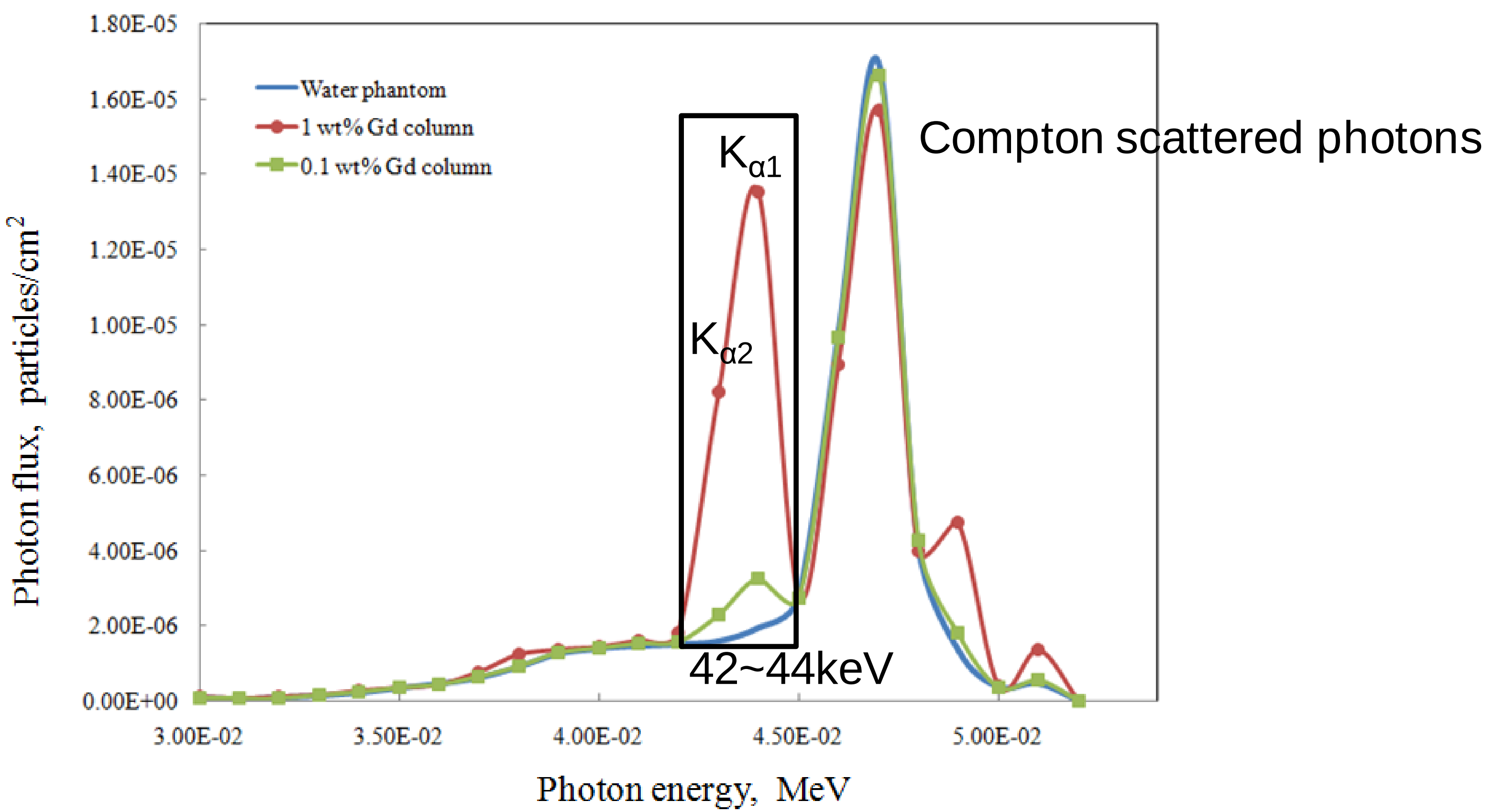
Material and Methods

- Monte Carlo simulation
- MCNP6
- Photon only, phys:default, E cutoff: 41.9keV, no variance reduction
- Flux and energy bin tally of each detector pixel
- Nps 2.0E10
- Uncertainty < 5%

- Simulation conducted for
- Water phantom
- Single column inserted water phantom: 0.001%~0.1% by weight of Gd
- Three columns inserted water phantom: 0.1-0.25-0.5,
  0.05-0.075-0.1 % by weight of Gd

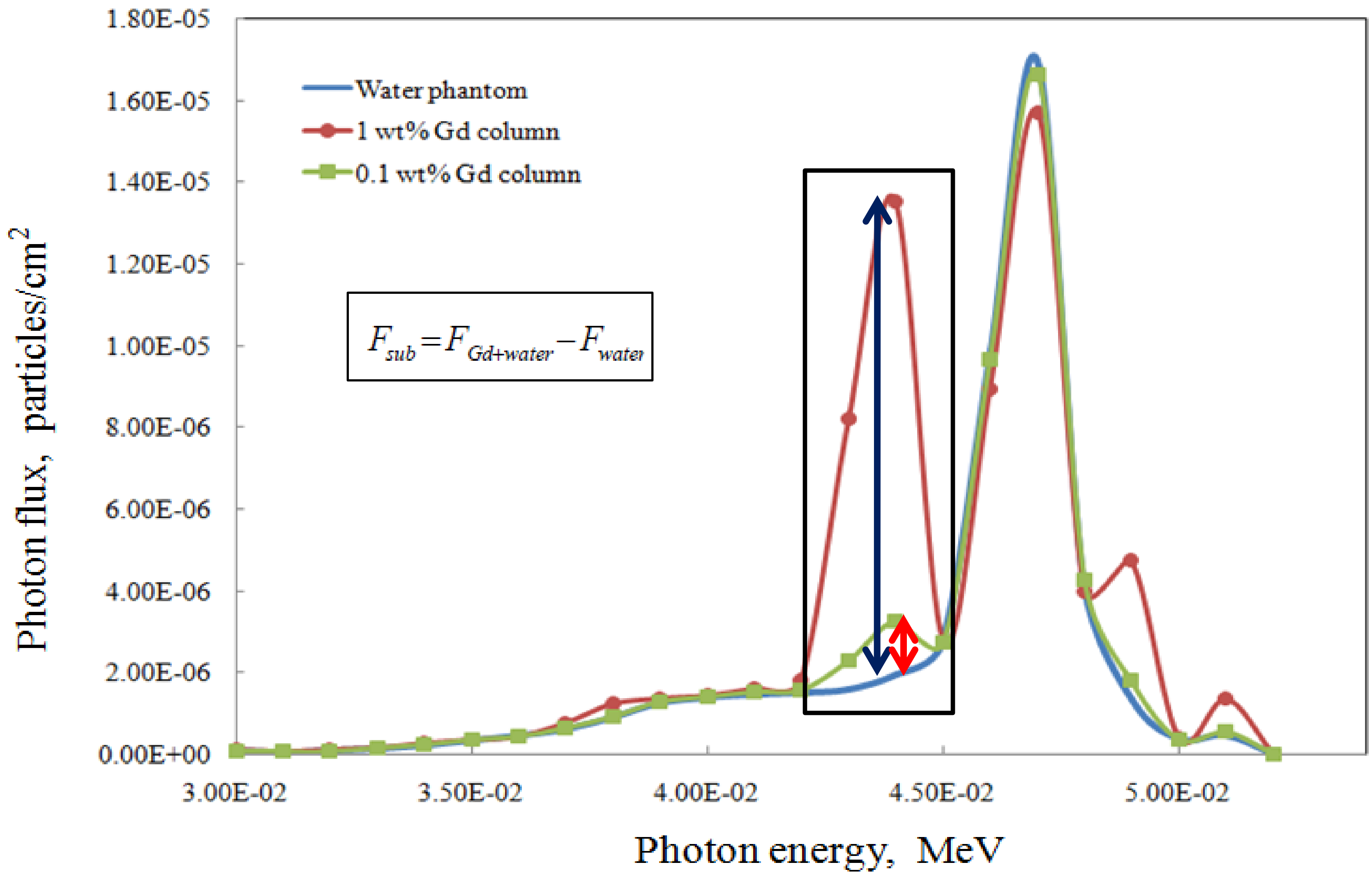
Material and Methods

- Data acquisition
  - 50.5keV source
  - energy spectrum of central pixel with and without Gd column



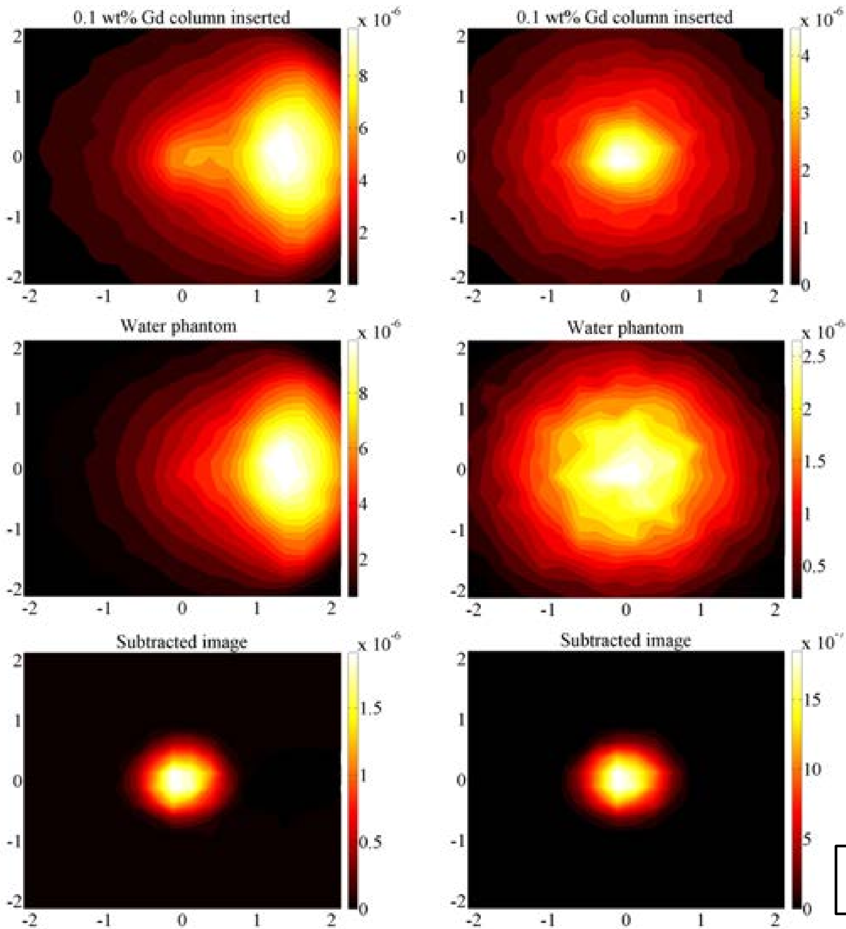
Material and Methods

- Data acquisition



Material and Methods

- Data acquisition



(a) 50.5keV (b) 55keV

(a) 50.5keV

The effect of Compton scattered photons is bigger than 55keV

$$E' = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0 c^2}(1 - \cos\theta)}$$

If E'=43keV, E_γ=50.5keV, then ϴ = 140°

If E'=43keV, E_γ=55keV, then ϴ does not exist

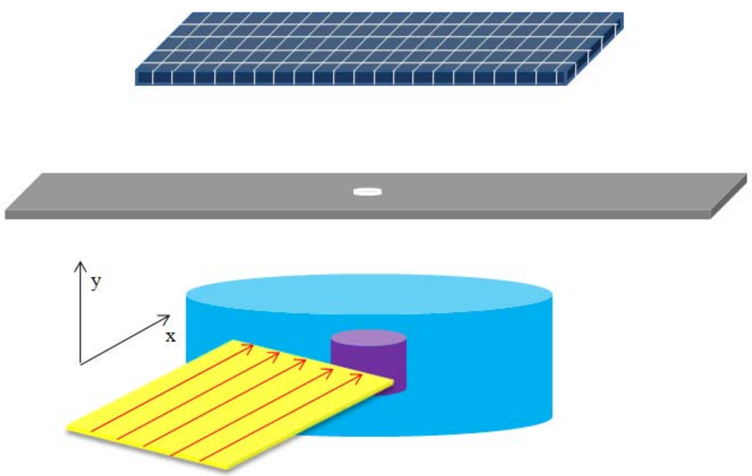
0.1 wt% Gd

Material and Methods

- **Image processing**

1. Attenuation correction, k_a

- x direction: the primary beam through the phantom
- y direction: Gd fluorescence *en route* to the detector



$$k_a = \frac{1}{e^{-\mu_{w,E} \cdot x} \cdot e^{-\mu_{w,K} \cdot y}}$$

$\mu_{w,E}$: Linear attenuation coefficient of water for photons of energy E

$\mu_{w,K}$: Linear attenuation coefficient of water for photons of K characteristic x-rays

x: the path length of photons before photoelectric interaction

y: the path length of fluorescence photons after the interactions

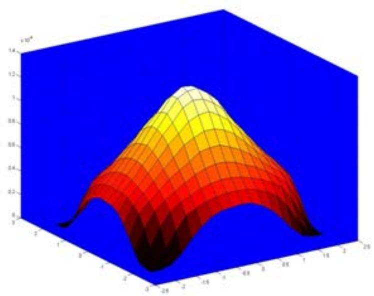
Material and Methods

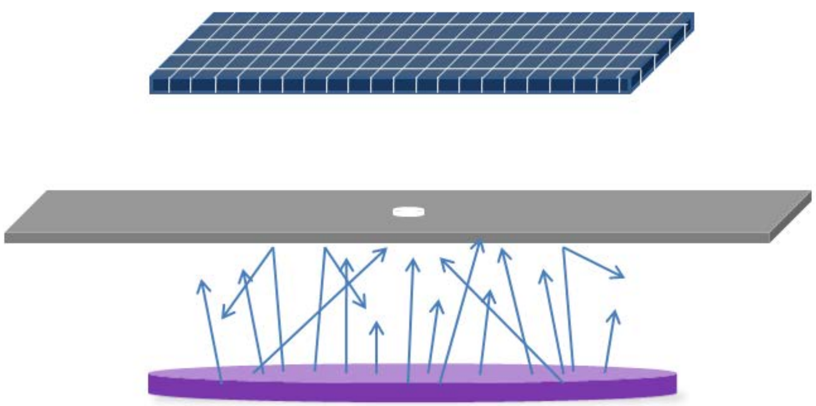
- **Image processing**

2. Inverse correction, k_r

- Inverse r square law
- Point spread function

→ could inversely get a correction factor from the left Monte Carlo simulation





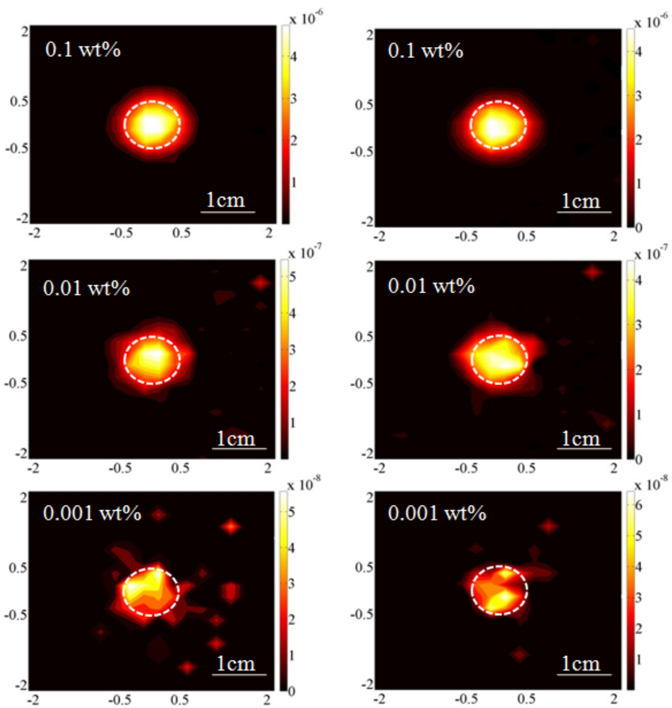
K characteristic like 43keV isotropic photon emitting disc source

$$F = F_{sub} \cdot k_a \cdot k_r$$

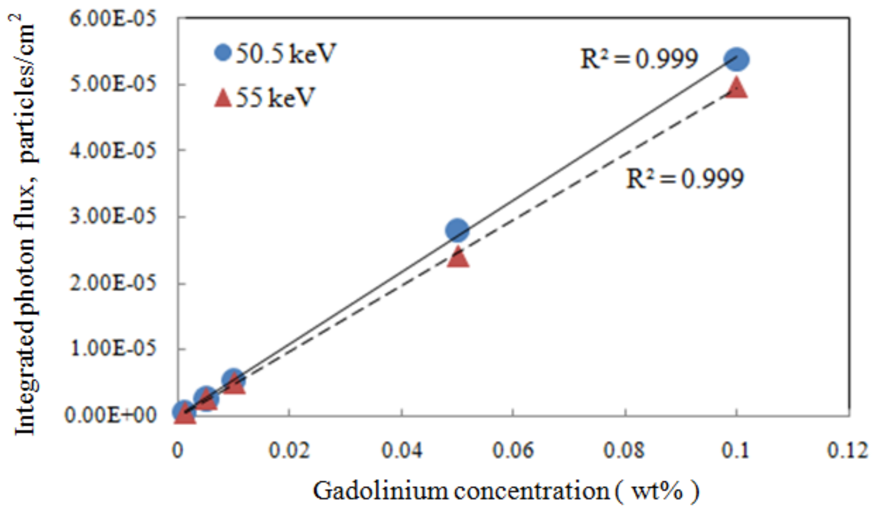
Pixel value of image

Results

- Relation between concentration and F value
  - Integrated photon flux
  - F values of the pixels expected to detect Gd nanoparticles could be integrated, since we know the locations of Gd columns
- Single column, 0.001~0.1 wt% Gd

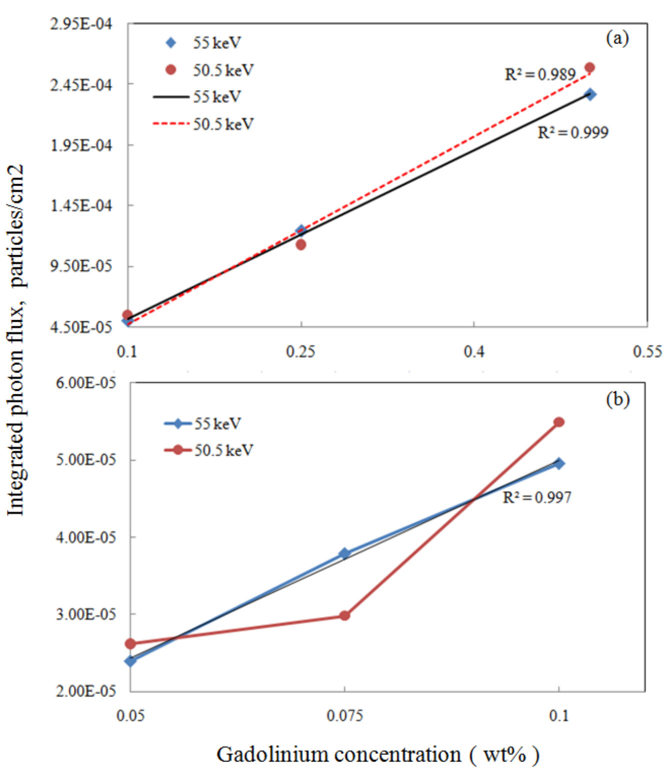


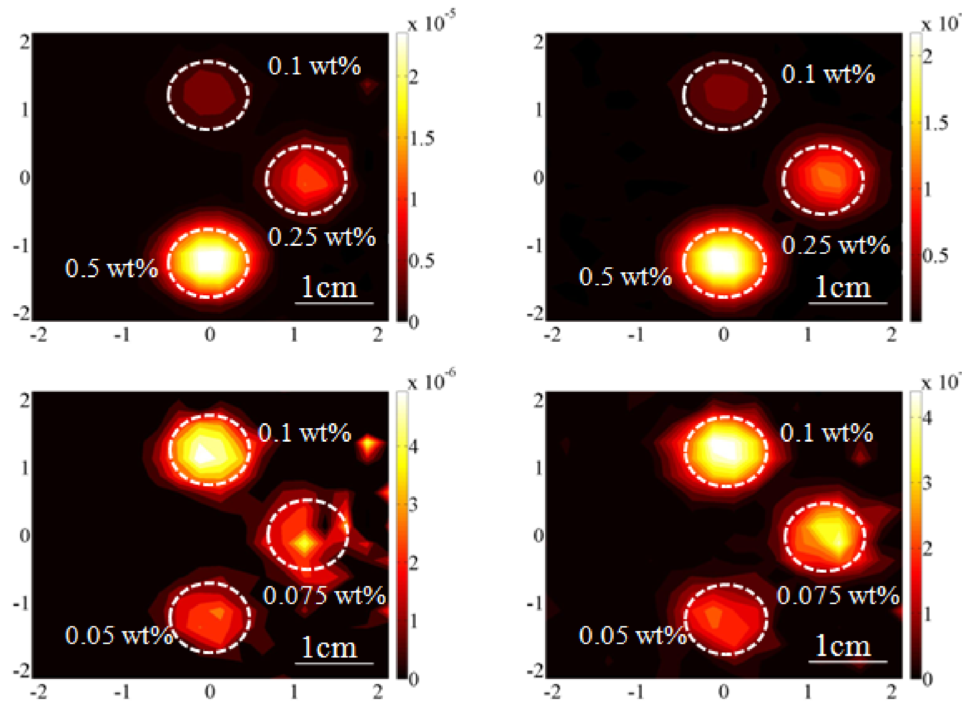
(a) 50.5keV (b) 55keV



Results

- Three columns





(a) 50.5keV (b) 55keV

Conclusion

- Using Monte Carlo simulations, the feasibility of imaging low concentrations of Gd nanoparticles with x-ray fluorescence using monochromatic synchrotron x-rays of two different energies was shown

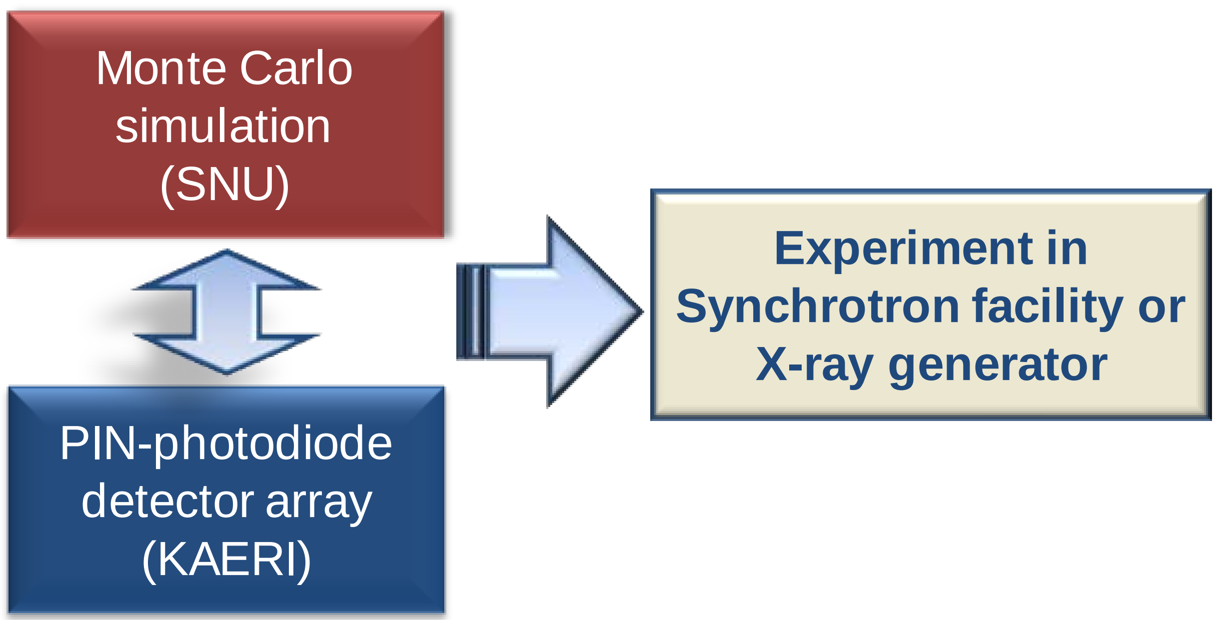
- The photon beam of 55keV showed better images and linear relationship between the three different concentrations and locations Gd columns

- Due to the region of Compton scattering noise, images of Gd columns irradiated by 50.5keV failed to make a linear relationship

Future Work

- More simulations are needed for Gd columns with lower concentrations
- 2D radiography(current study) ➡ 2D reconstruction image
- Imaging metal nanoparticles during Microbeam Radiation Therapy(MRT)
- Benchmarking multi-pinhole SPECT
- Simulations for magnified images
  - High spatial resolution

- Experiment



Q&A

Thank you