Development of 2D SiPM-based Photon Counting CT using newly designed high-performance ASIC aimed at preclinical applications

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Outline

- Introduction
  - Conventional CT
  - Photon Counting CT
- Previous Research and Research Objectives
- Basic Performance
- Multicolor 3D-CT Imaging
- Conclusion

Conventional CT ～Why Monochrome ?～

Energy Integrated Detector (EID)

GOS scintillator (τ ～3us) + Photodiode (I_D ～0.1nA/mm^2)

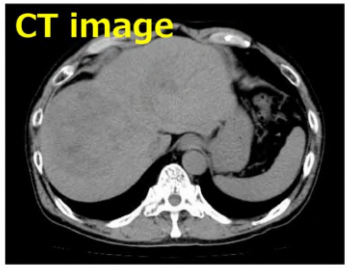
- Each individual pulse signal is extremely weak (cannot be separated)

  → **<u>Integrating the current signal and reading it out</u>**

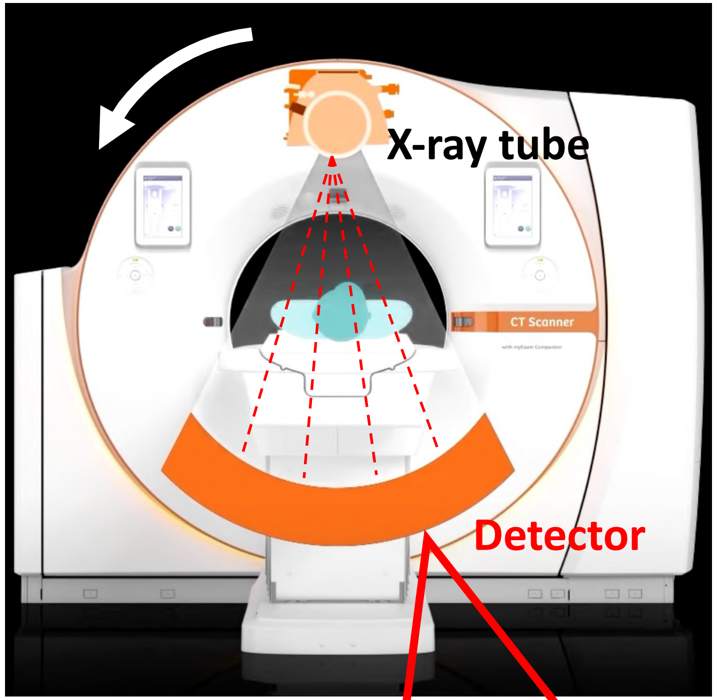
This leads to …

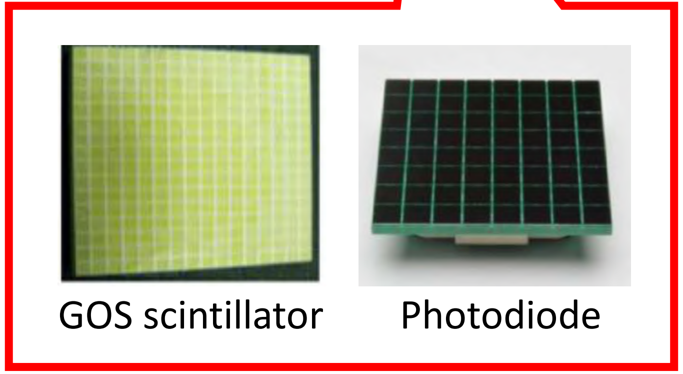
→ Require high dose (～100 Mcps/mm²)

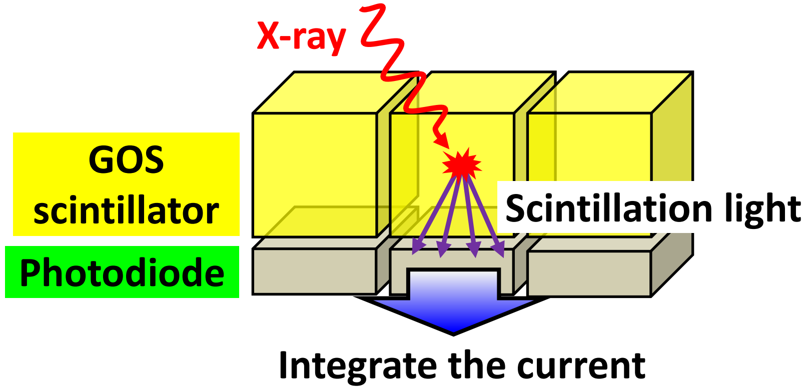
→ Monochrome = Lack of energy information

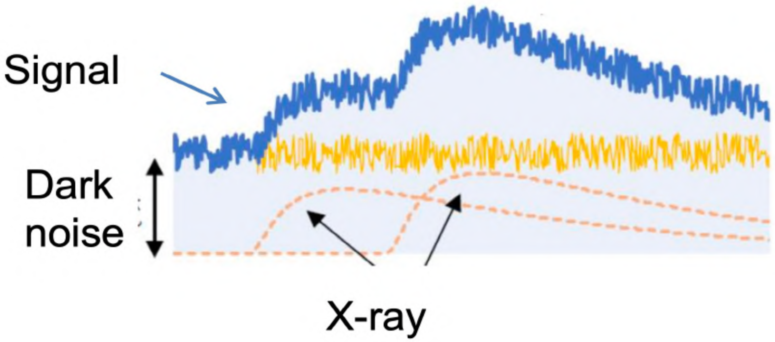


(© National Cancer Center Hospital East)









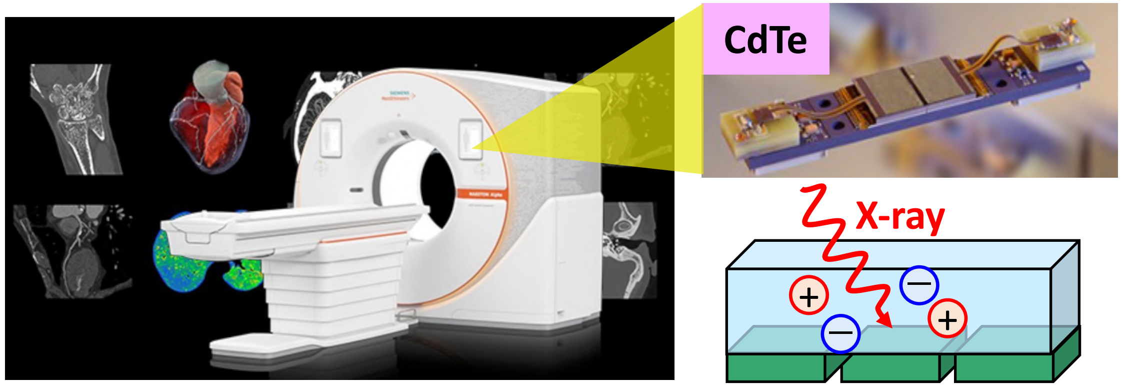
Photon Counting CT（PCCT）

Recent Progress（2000～）

■ Semiconductor Detector（Cdte, CZT）

- R&D by Siemens, Canon, Phillips, GE …
- Good ΔE but expensive
- Fine pixel but complicated electronics（no Internal gain）
- Charge sharing problem

World's First Clinical PCCT（2022）
Siemens Naeotom Alpha（～10M USD）

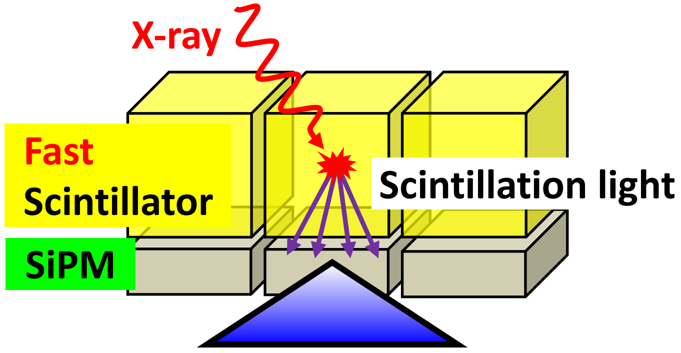


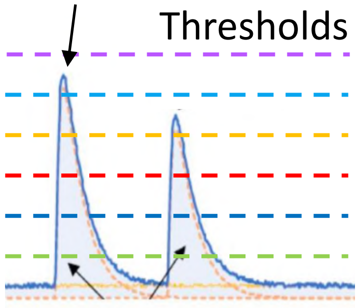
Our Approach（2015～）

■ Fast Scintillator + SiPM Detector

- Cost-effective（**～1/10 of CdTe**）, but low ΔE
- Simple electronics（Internal gain: **M～10^6**）
- Flexible optimization options: thickness, Material composition, multi-layer
- Also, charge sharing free

→ Poster #50
R. Minagawa et al.





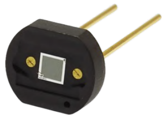
Our Previous Progress

2015～

Single Channel

YAP

SiPM



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NIM modules

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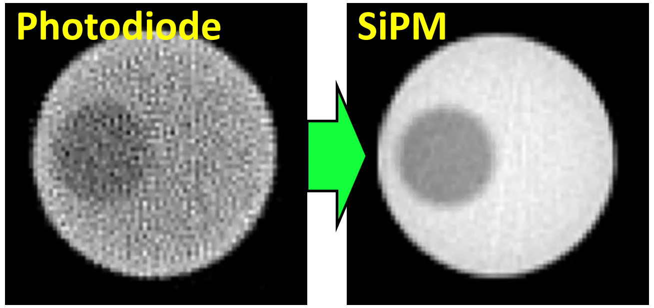
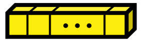


Morita et al. (2017)

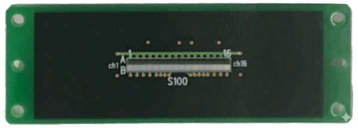
2017～

1 × 16 Channels

YGAG



SiPM



16ch Array（～16mm）

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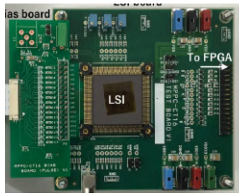
16ch ASIC



M.Arimoto et al. (2018)

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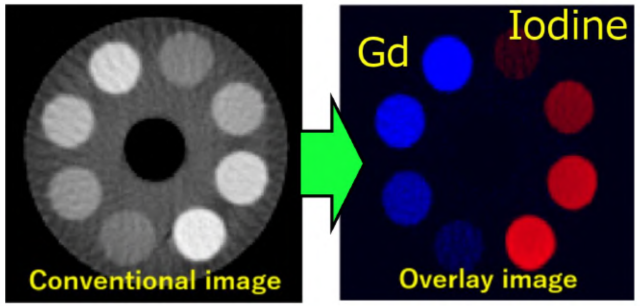
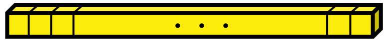


Maruhashi et al. (2019)

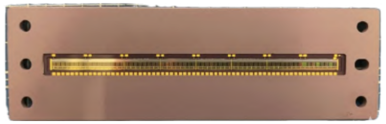
2019～

1 × 64 Channels

YGAG



SiPM



64ch Array（～64mm）

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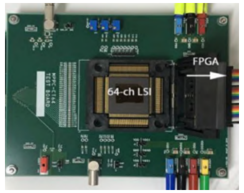
64ch ASIC



M.Arimoto et al. (2023)

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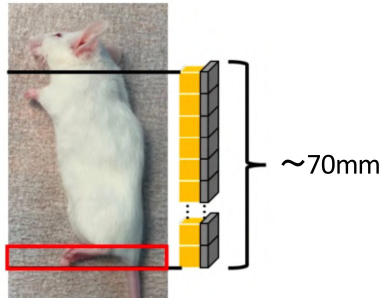
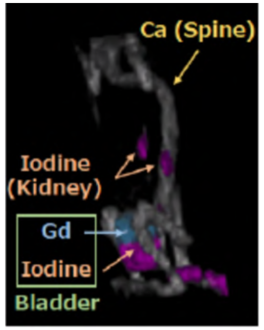




Sato et al.; Sagisaka et al. (2022) etc.

Our Previous Progress

2015～

2017～

2019～

■ Challenges of the Latest Systems

- Cannot acquire 3D images in a single scan（＝Poor **dose efficiency** and **time efficiency**）

  → Requires expansion to **2D** & **large area** detectors

- **Speed** and **convenience** of ASIC

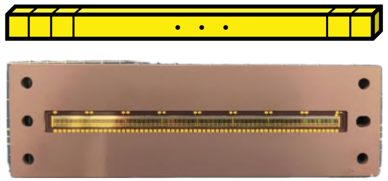
  → Next-generation ASIC renewal

It takes **several hours** to image a mouse!!

1×64 Channels

YGAG

SiPM



64ch Array（～64mm）

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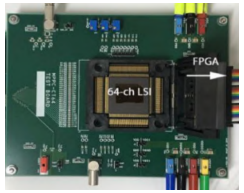
64ch ASIC



M.Arimoto et al. (2023)

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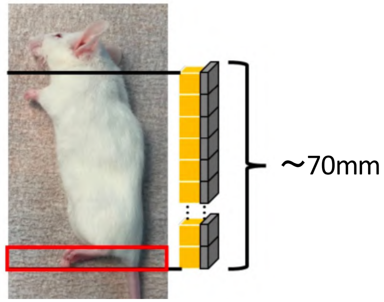
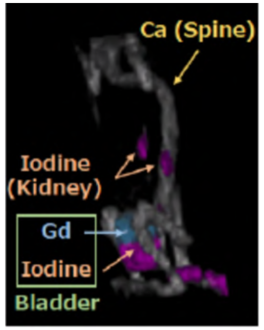




Sato et al.; Sagisaka et al. (2022) etc.

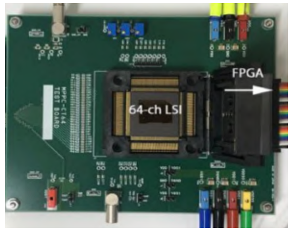
Objective

For the next step toward clinical application…

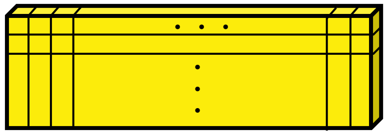
Development of a 2-dimensional photon-counting CT system using newly designed high-performance ASIC

1 × 64 Channel

64ch ASIC



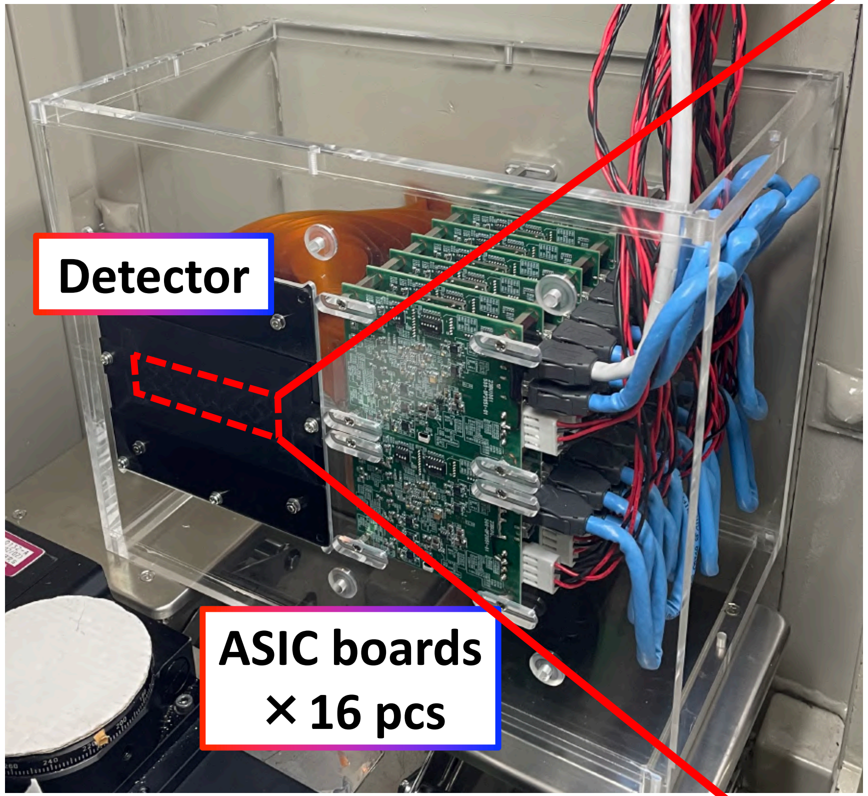
16 × 64 Channel



1024ch ASIC

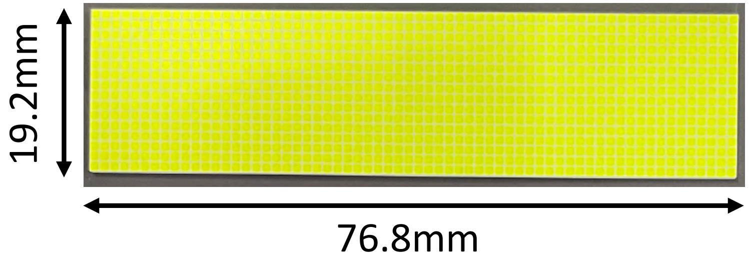
- Performance Evaluation
  - Spectroscopic performance
  - Pulse counting capability
  - CT imaging

Overview of 16 × 64ch PCCT system（1/2）



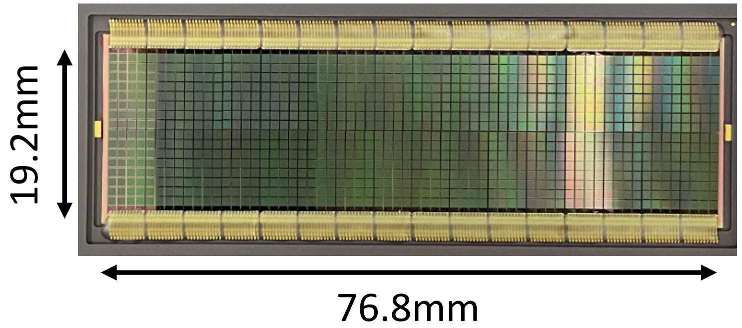
■ Detector

16 × 64ch YGAG:Ce scintilator array @Proterial Ltd.



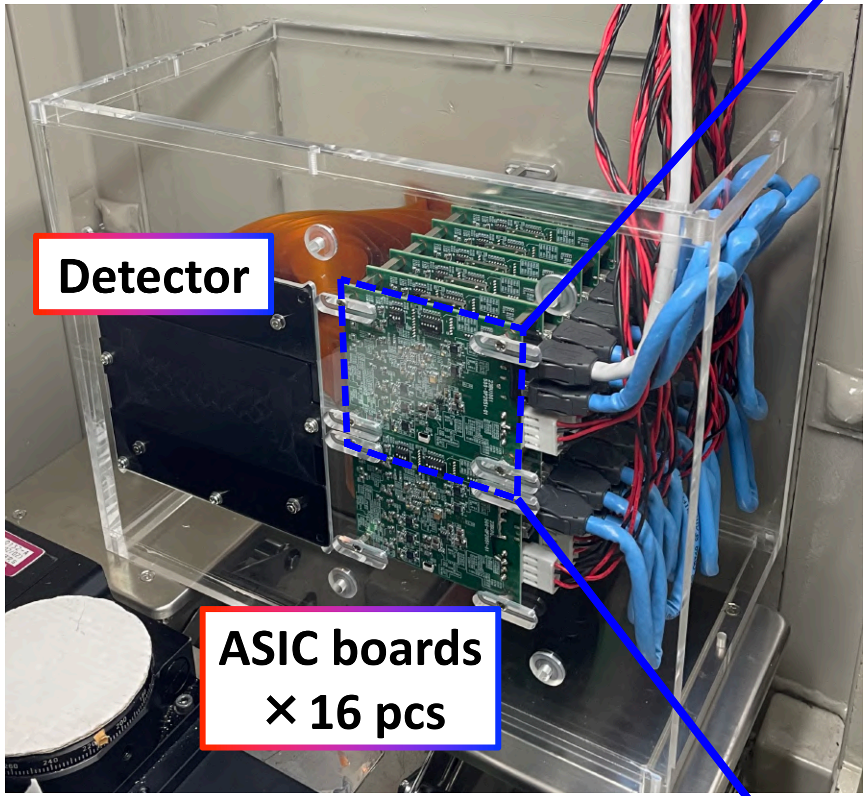
$\tau \sim 70$ns
$Y \sim 5\times10^4$ photon/MeV
Pixcel Size： $1\times1\times1\text{mm}^3$
Reflector Thickness： 0.2mm

16 × 64ch SiPM array @Hamamatsu Photonics

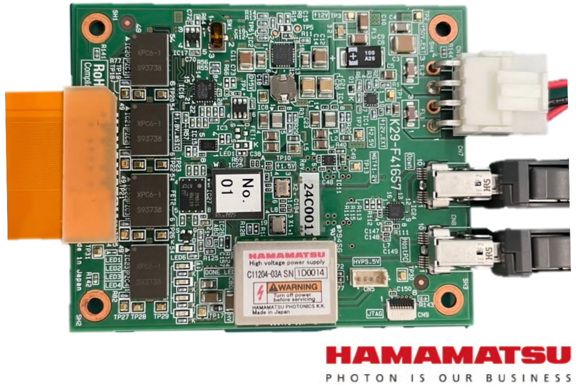


Base model： S14161 series
Active Area： $1\times1\text{mm}^2$
Cell Size： 15μm
$M \sim 10^6$

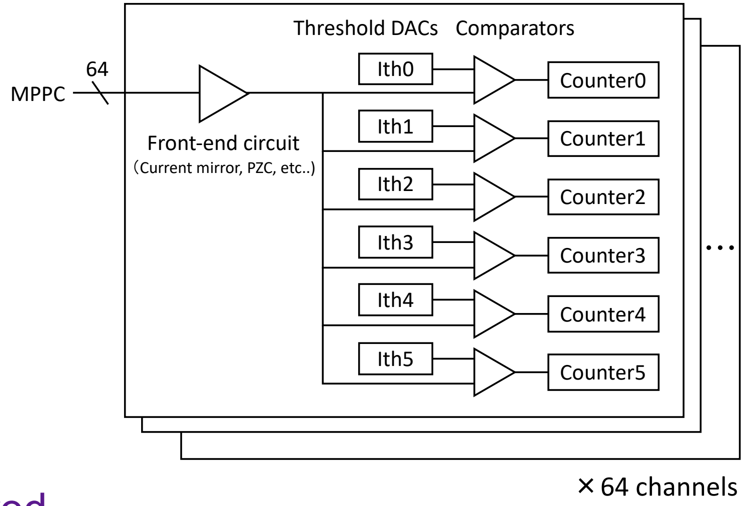
Overview of 16×64ch PCCT system（2/2）



ASIC



Newly designed and manufactured by Hamamatsu Photonics



- ✓ 64ch / board（up to 1024ch / 16 boards）
- ✓ 6-color images with 6 thresholds
- ✓ Calibration function within digital circuits
- ✓ Differential circuitry + PZC

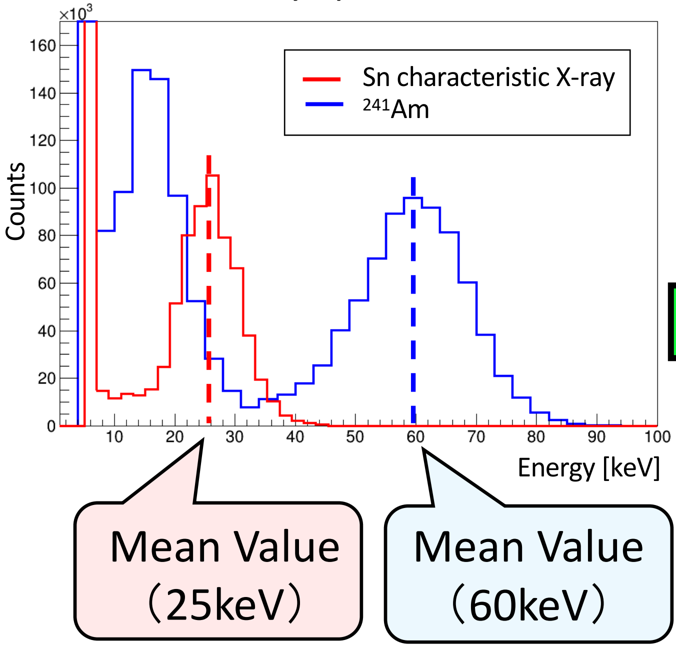
Basic Specifications

Item	Value
Maximum number of channels	1024
Number of thresholds	6
Counter bit depth	32bit
Comparator threshold DAC bit	10bit

Outline

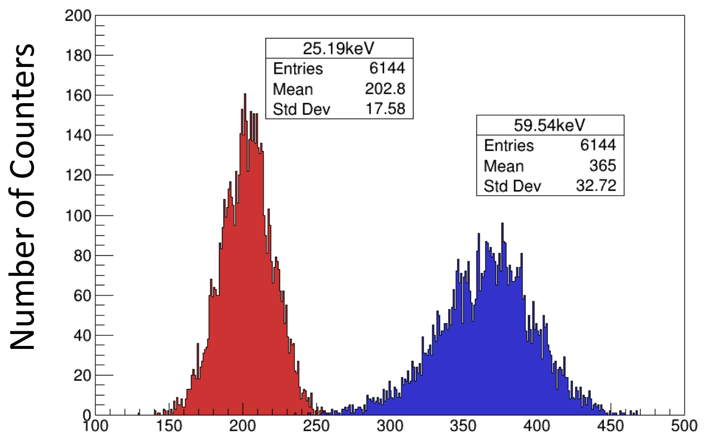
Spectroscopic Performance

X-ray spectrum



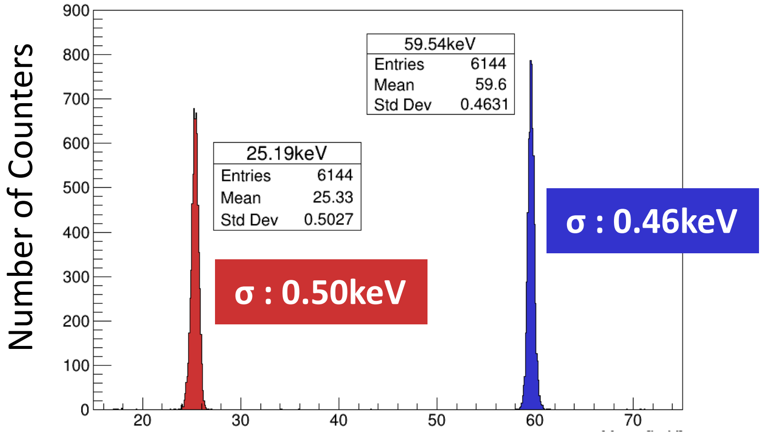
Before

Photopeak histogram@6144counters

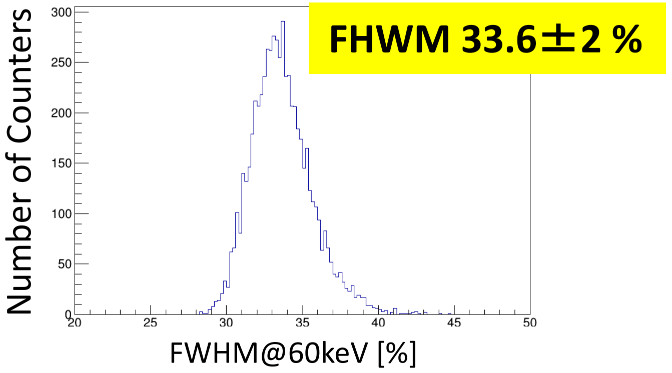


After

Photopeak histogram@6144counters



FWHM histogram@60keV

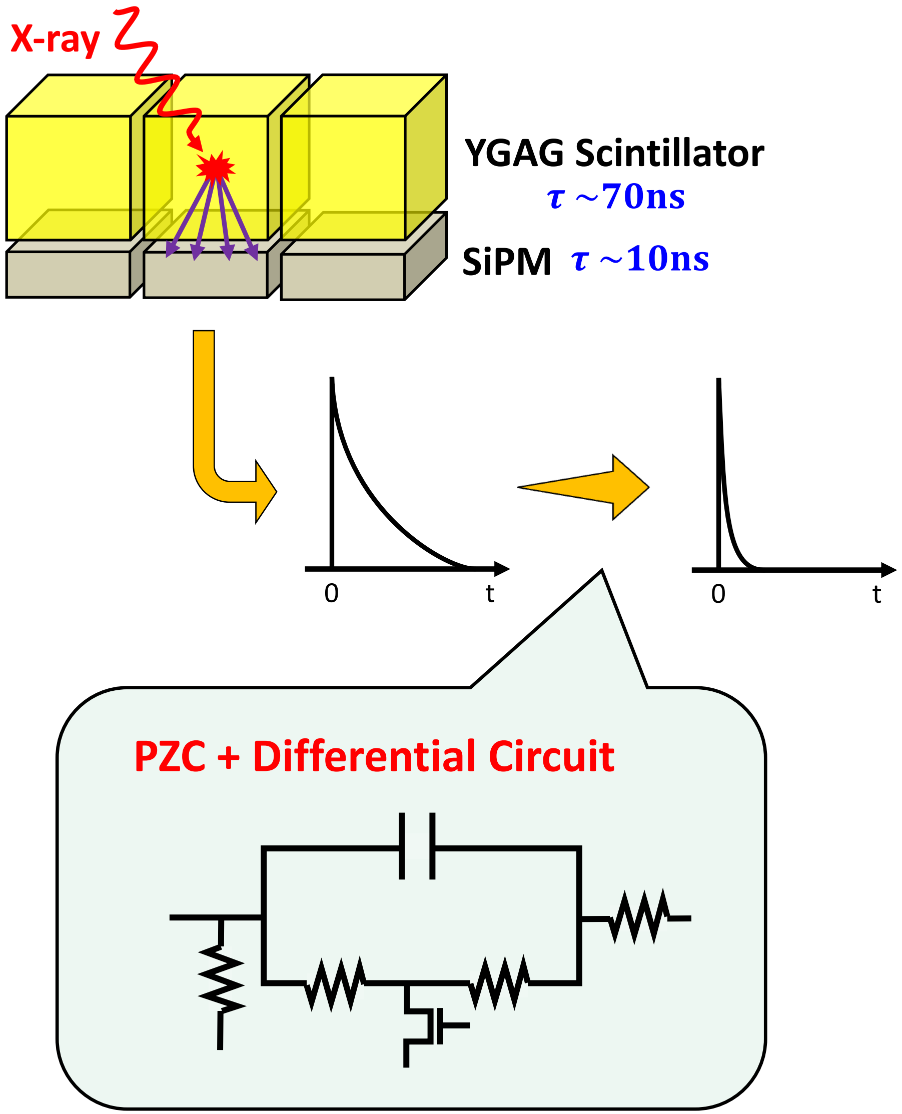


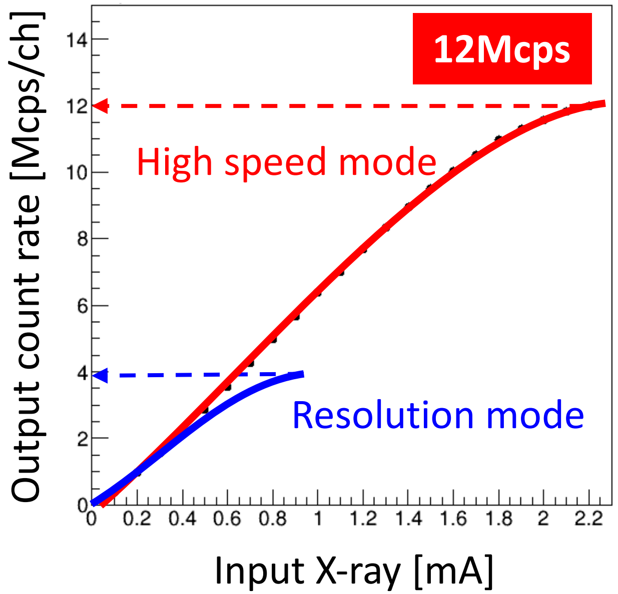
- ✓ Incorporating calibration functions within the digital circuit enables convenient and accurate (±0.5 keV) energy calibration
- ✓ Energy resolution: 33%
  → Improved compared to conventional 64ch-system (40%*)

Achieved the refinement of energy information

*M.Arimoto et al. (2023)

Counting Rate Capability





	Energy Resolution FWHM@60keV[%]	Max Count Rate [Mcps/ch]
Resolution Mode	33.6±2.0	4
High Speed Mode	39.8±2.5	12

Energy resolution and count rate are a trade-off.

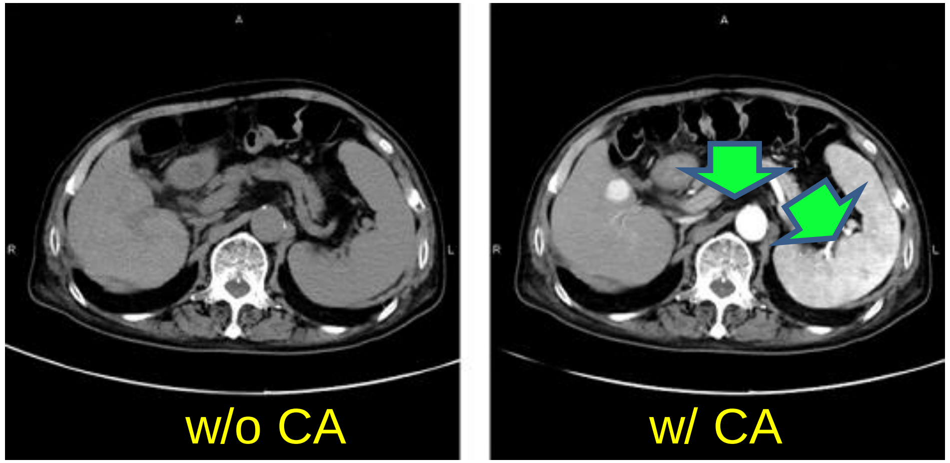
<u>New ASIC</u>

It can shorten the decay time of X-ray signals

→ Even with sensors having the same decay time constant, count rate tolerance improves

Outline

Imaging Methods : K-edge imaging

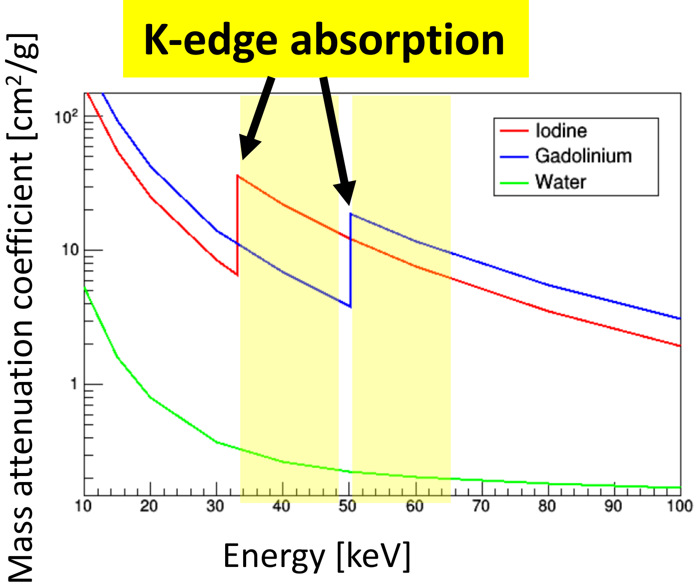


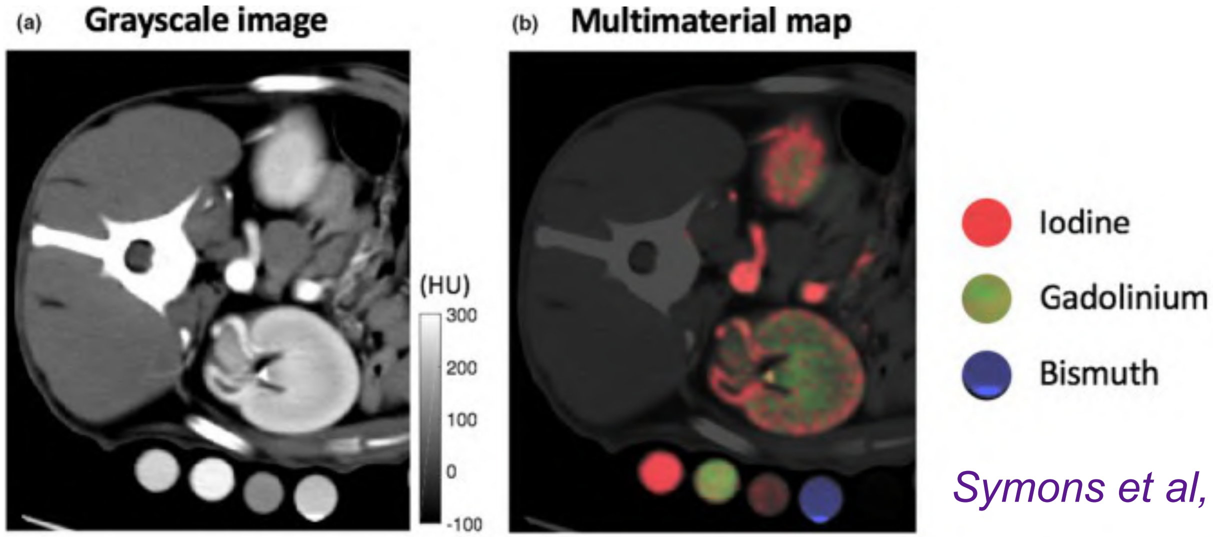
Contrast agents (CAs)

→ Often used to highlight blood vessel, specific organs

By creating difference images before and after the K-edge, absolute concentration estimation of multiple contrast agents is possible simultaneously.

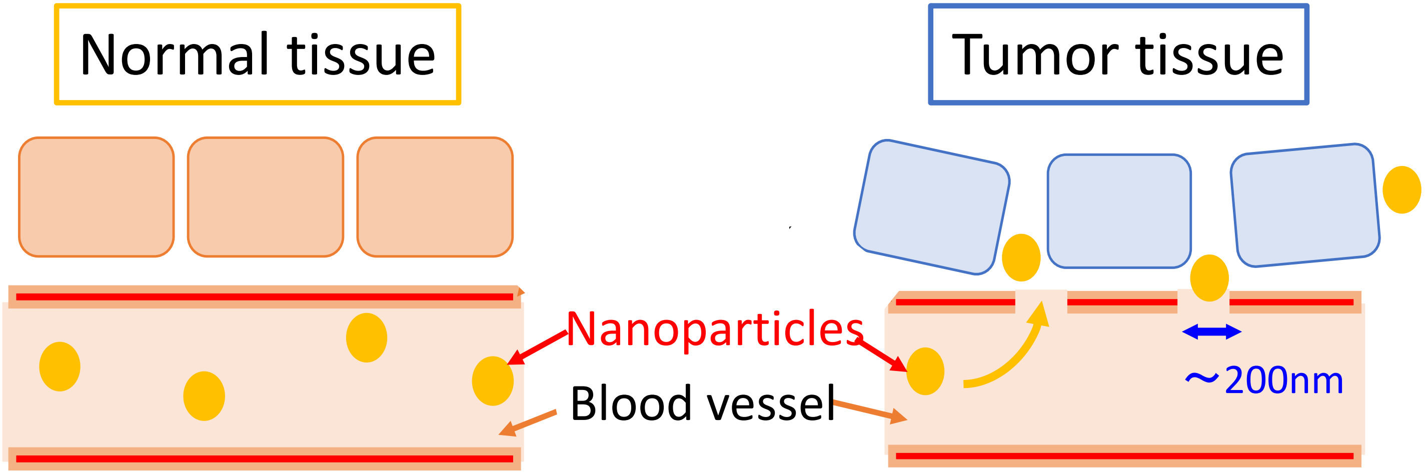
It is possible to identify the element-specific "color".



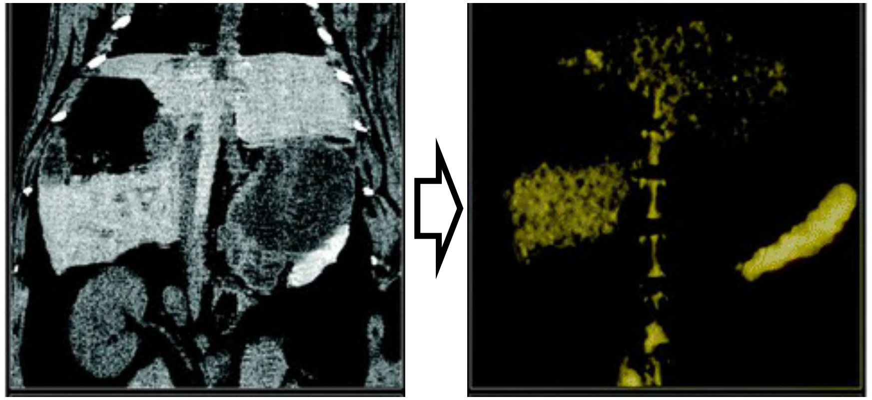


Symons et al, 2017, Med Phys

Background : Drug Delivery Monitor



Salim Si-Mohamed et al, 2017

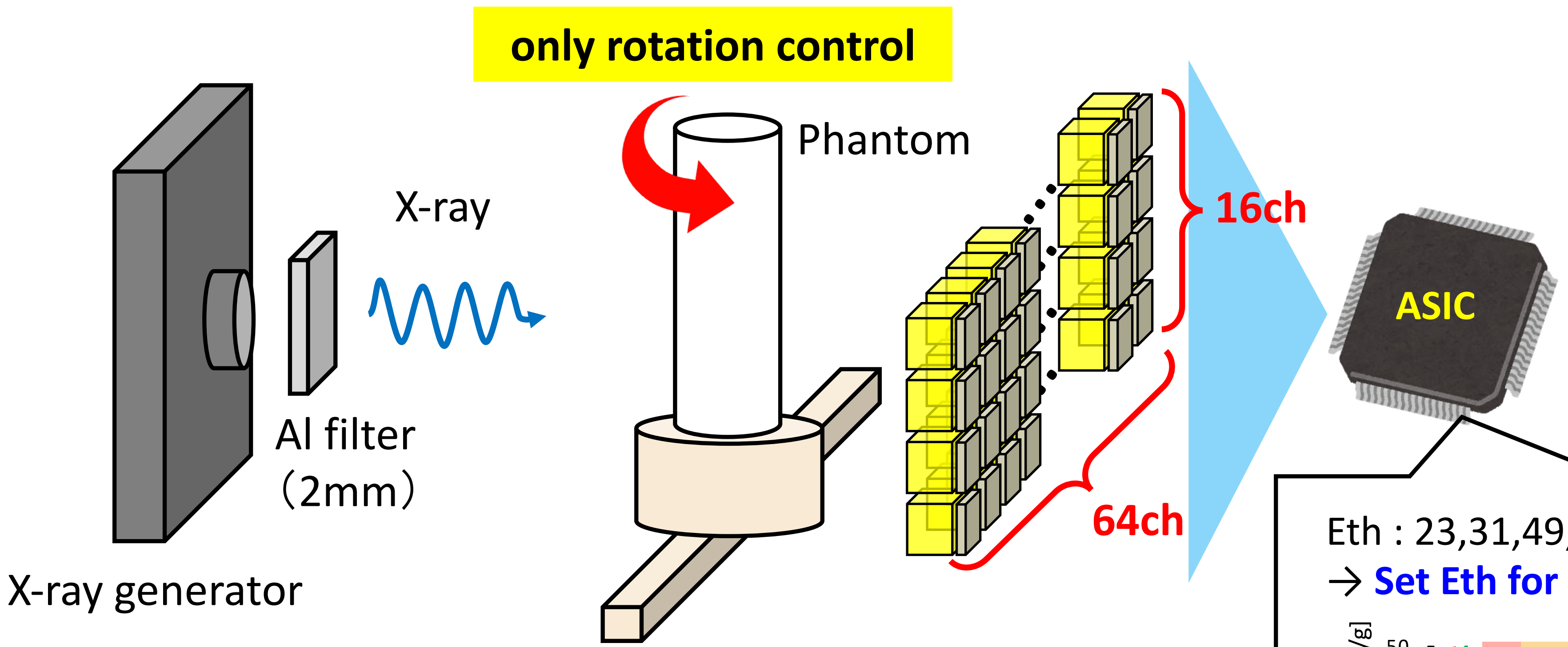


Conventional image　　AuNP map

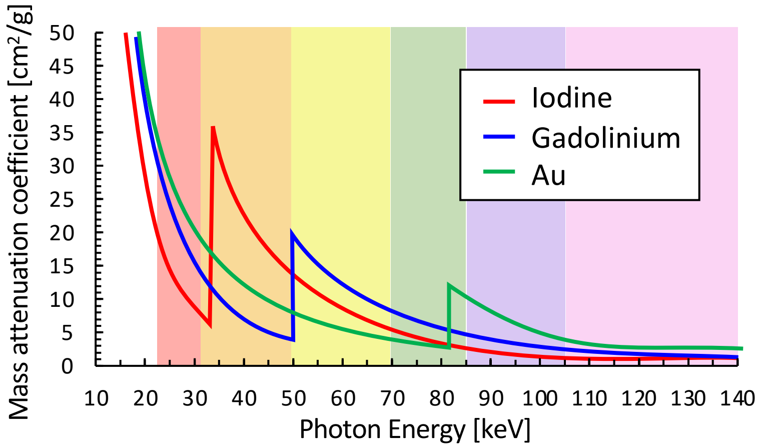
- ✓ Nanoparticles（~100 nm）accumulate in tumor tissue (cancer) – EPR effect –
  → Gaining attention as a "Drug Delivery Monitor" to deliver drugs to tumors
- ✓ K-edge of Au is 81 keV, which is higher than other CAs (c.f., I: 33keV, Gd: 50 keV)
  → **Gold nanoparticles (AuNPs)** have huge potentials in dynamic monitor w/ CT

Real-time monitoring of anticancer drugs made possible using K-edge imaging

Experimental Setup



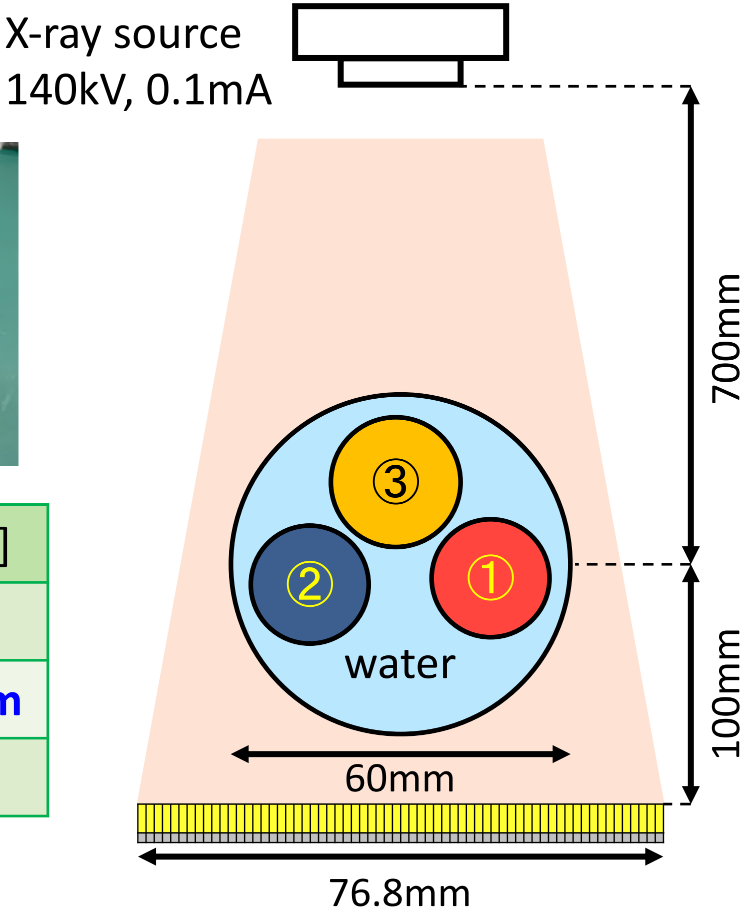
Eth : 23,31,49,70,85,105 [keV]
→ **Set Eth for Iodine, Gd, and Au K-edge**



- ✓ **Multi-Slice** × **Wide-View** imaging
  → <u>Clinical-like imaging methods</u>
- ✓ Reading Method : Resolution Mode
- ✓ Reconstruction method : Filtered back projection

Material

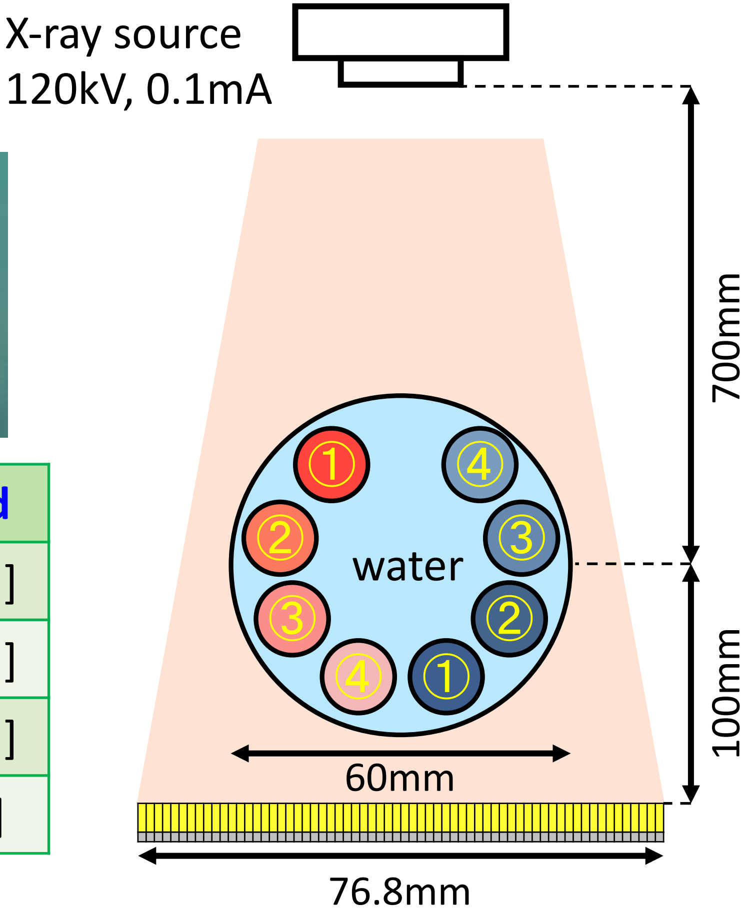
Phantom A



	20[mg/ml]
①	Iodine
②	**Gadolinium**
③	**AuNP**

Aiming for simultaneous K-edge imaging of three CAs.

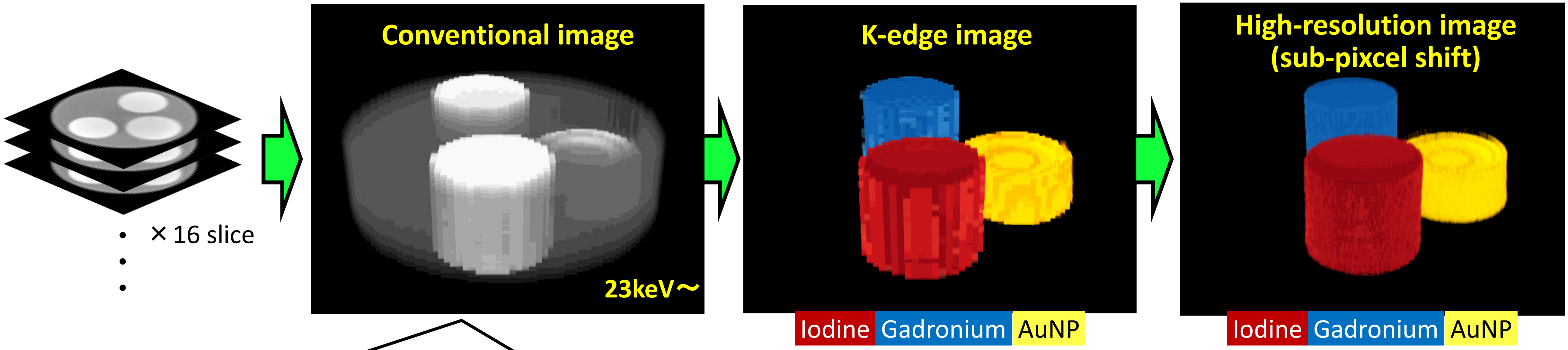
Phantom B



	Iodine, Gd
①	20 [mg/ml]
②	15 [mg/ml]
③	10 [mg/ml]
④	5 [mg/ml]

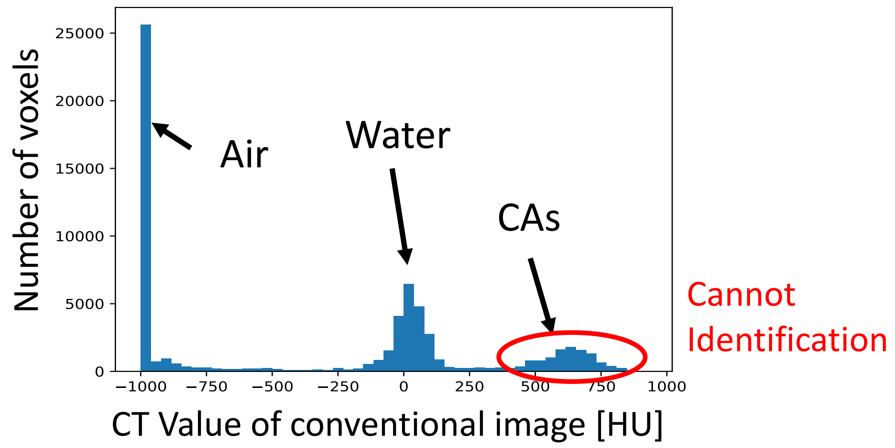
Aiming to estimate the concentrations of multiple CAs.

Results： Phantom A



$$CT[HU] = \left(\frac{\mu_s - \mu_w}{\mu_w}\right) \times 1000$$

μ_s = sample linear attenuation
μ_w = water linear attenuation

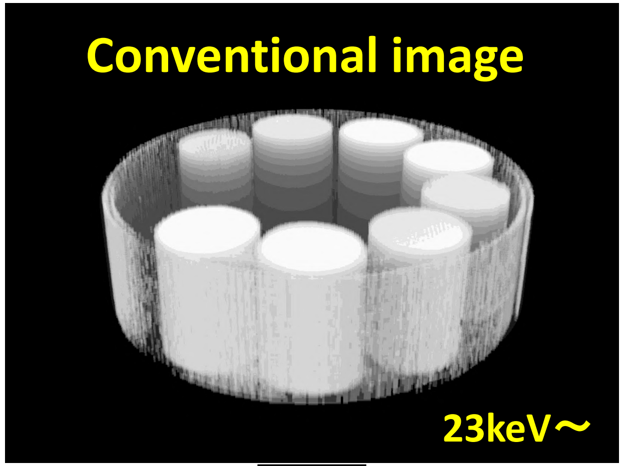


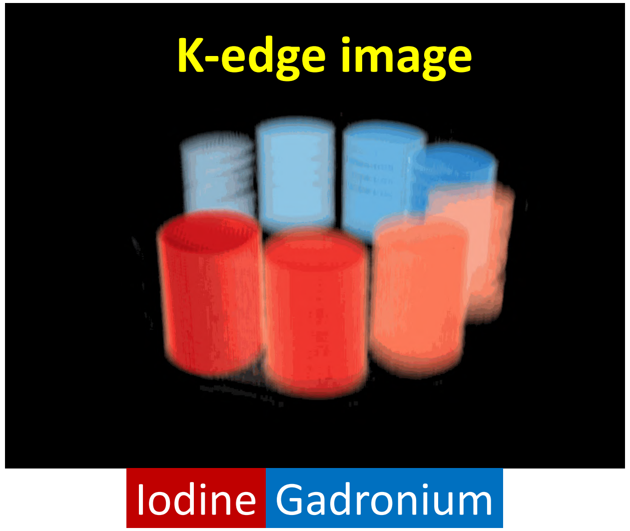
3D Multi-material K-edge Imaging

- ✓ **Successfully achieved 3D K-edge imaging of three materials**
  → Imaging performed **only with rotation control**
- ✓ **Demonstrated energy-resolved imaging** using **new system**
- ✓ **Simultaneous K-edge imaging of three materials** enabled by **six energy thresholds**
- ✓ **High-resolution imaging** achieved through **sub-pixel shifting**

Results： Phantom B

Sub-pixcel Shift image

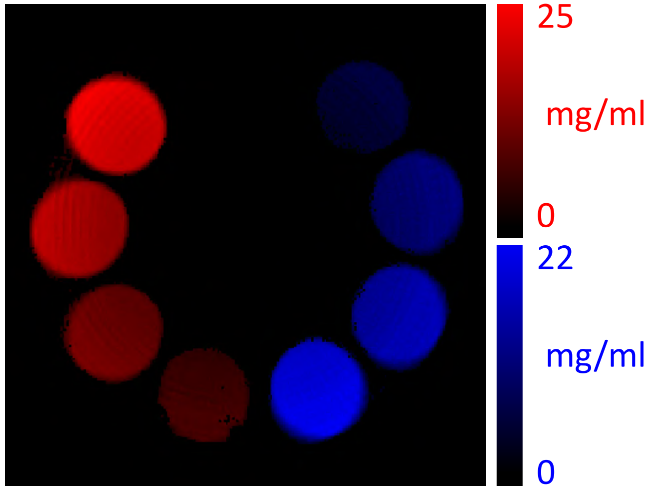


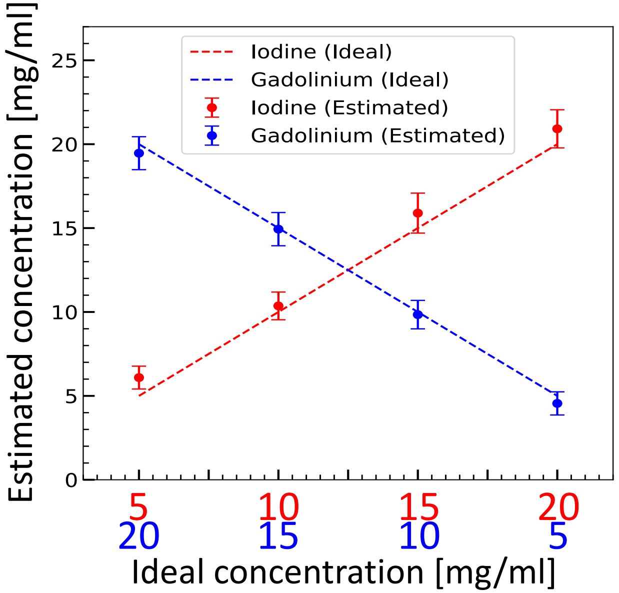


Least Square Method

$$J = \sum_{E} \left(\mu_{measured_E} - \rho\, \mu_{m_E}\right)^2$$

ρ : Concentration of CAs [mg/ml]





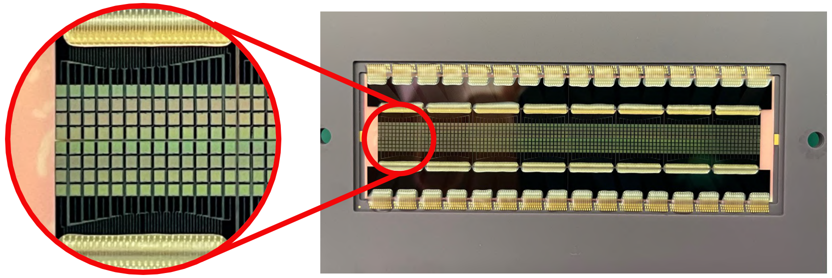
3D Concentration Estimation

✓ Successfully acquired concentration maps for two CAs

✓ Acquired with accuracy: **RMSE 0.85 mg/ml (Iodine), 0.36 mg/ml (Gd)**

Conclusion

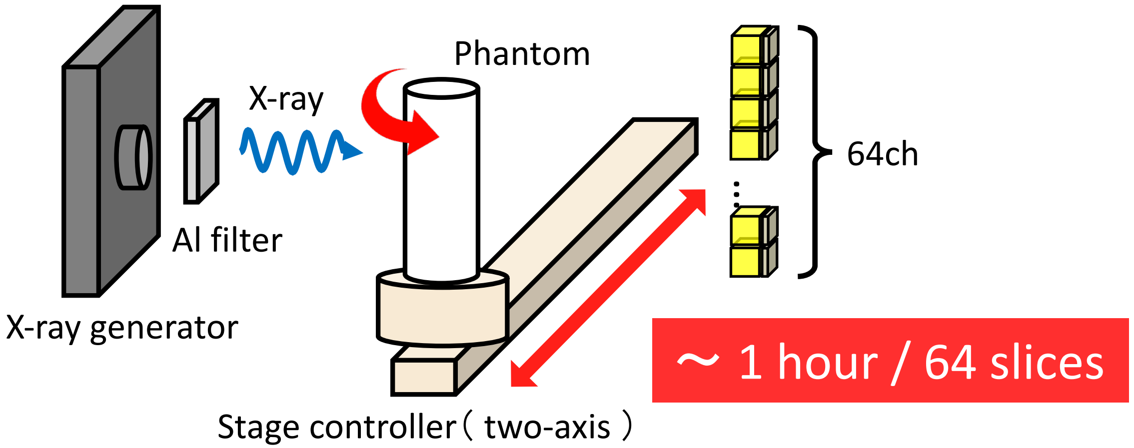
- **Toward clinical application:**
  - Developed a **large-area 2D PCCT system** with **1024-channel array**
  - Introduced a **new high-speed ASIC module** to handle **high count-rate X-ray CT**
- **Performance:**
  - Achieved **m**ax count rate: **12 Mcps/ch** and energy resolution: **40% @ 60 keV**
  - In **Resolution mode:** achieved **33% @ 60 keV**
  - Enabled **3D imaging** with **rotation control only** using the large-area detector
  - Achieved **3-material K-edge imaging** using **6 energy thresholds**
  - Obtained **dual contrast-agent concentration maps** with **RMSE = 0.3–0.8 mg/mL**
- **Future work:**
  - In vivo imaging of mice → **Poster #82（M. Oshima et al.）**
  - Faster scintillator development
  - Smaller pixel pitch (1 × 1 mm² → 0.5 × 0.5 mm²)



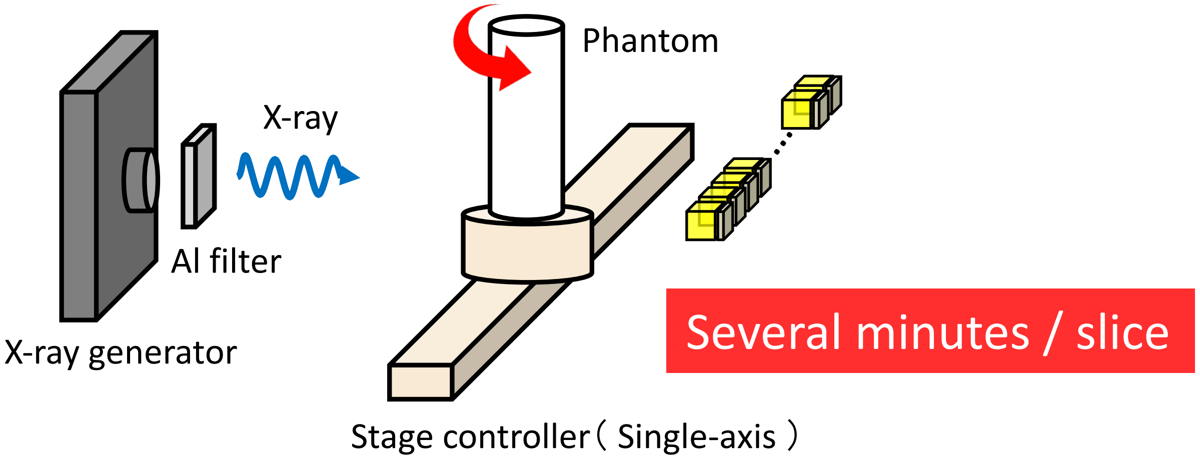
appendix

64ch CT scan

- First-generation setup



- Third-Generation Setup



△ Long shooting time

▶ Limitations in drug imaging in animal experiments

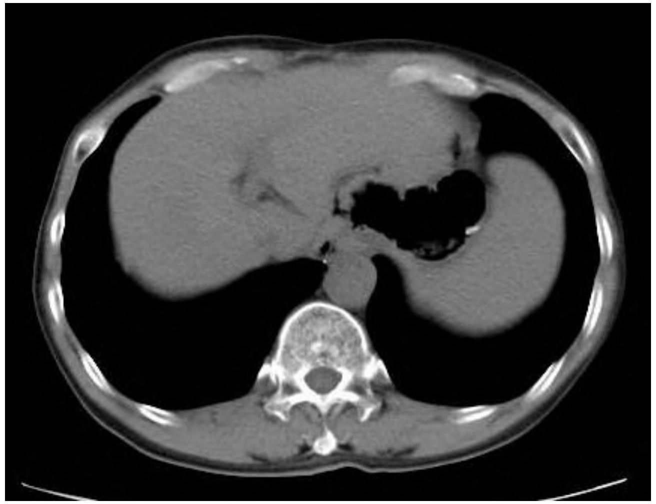
△ Only one slice can be captured.

In all cases, it is impossible to acquire 3D images in a short time.

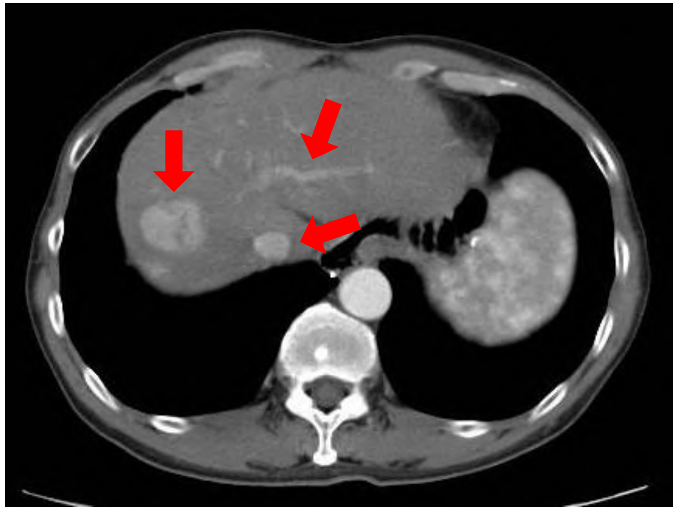
Dynamic CT

Inject the contrast agent

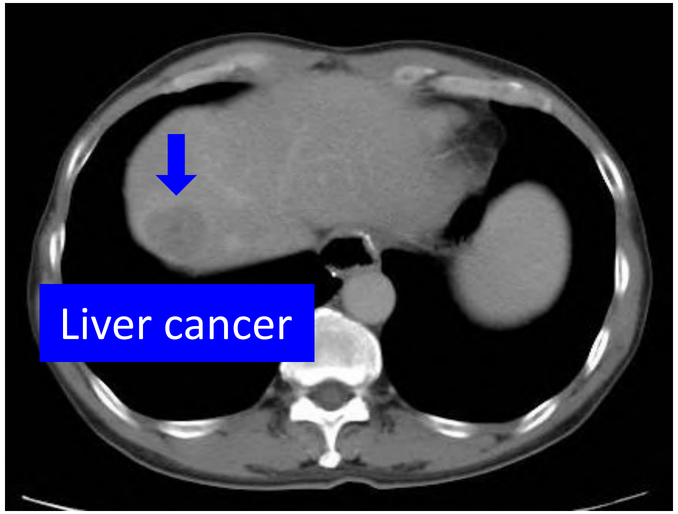
Before injection



3 minutes after injection



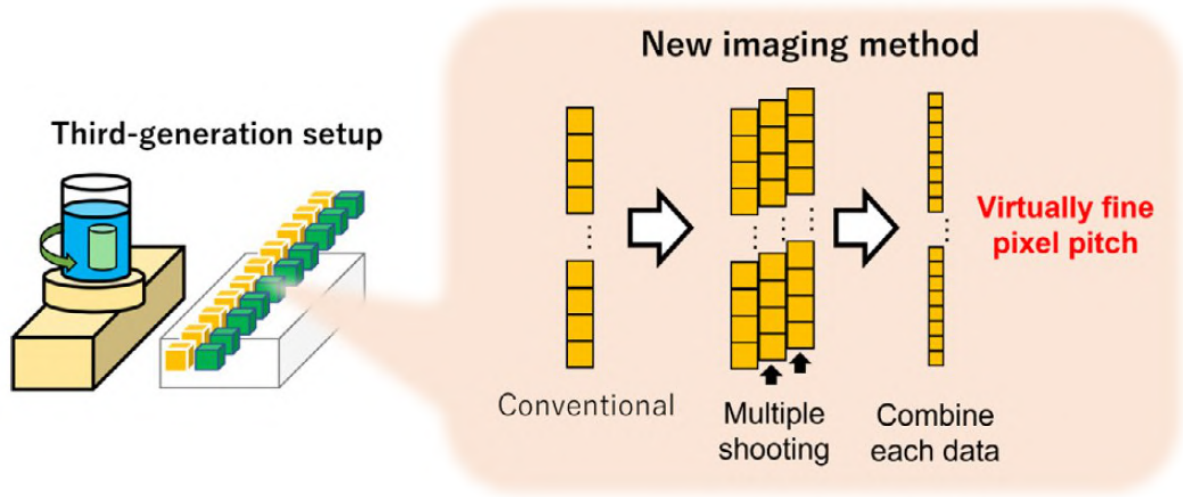
15 minutes after injection



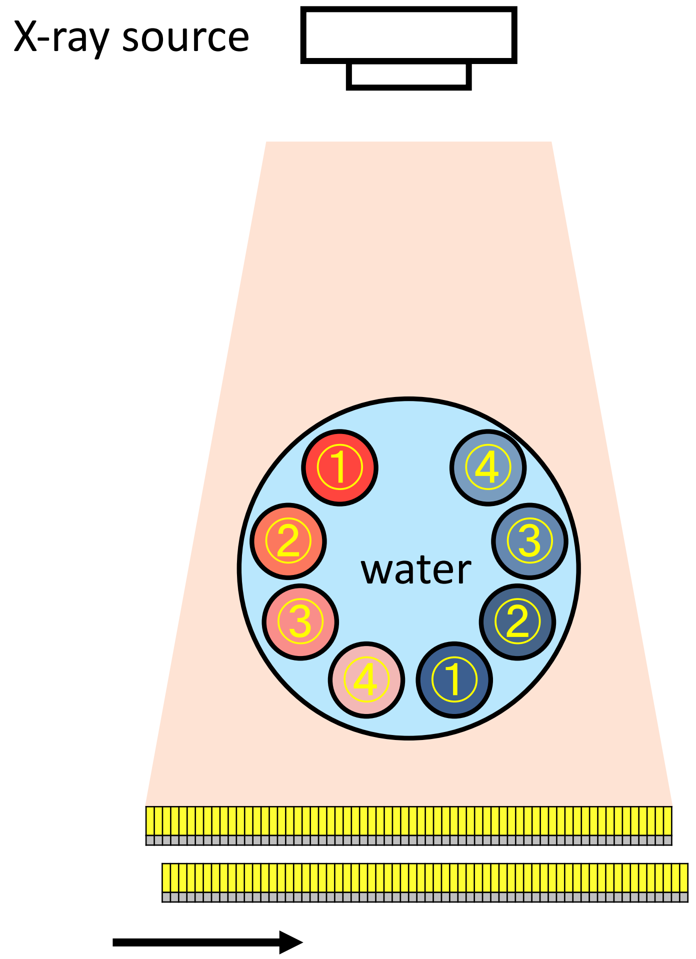
By tracking changes in concentration over time, the presence of tumors can be determined.
→ Time resolution of several minutes is required.

Sub-Pixcel Shift

Toyoda et al. 2022, NIM-A
Sagisaka et al. 2023, NIM-A



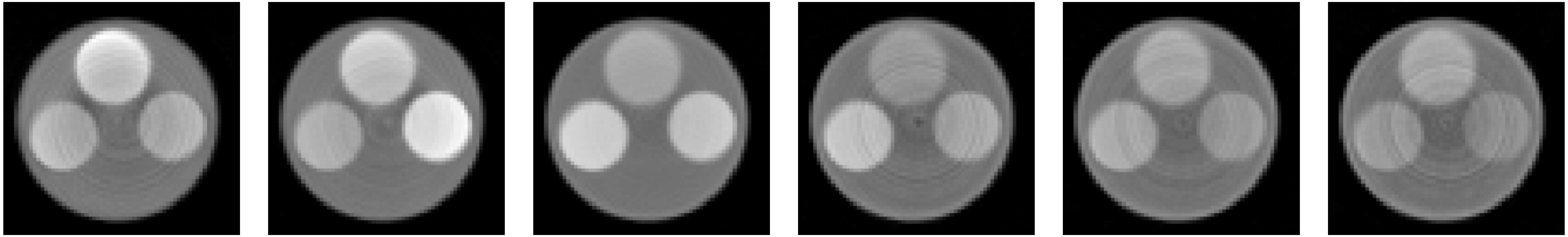
Measurement time increased by x2-3



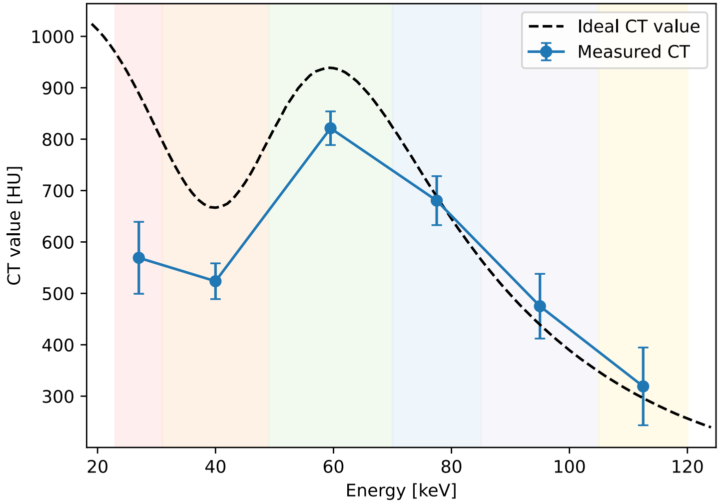
Shift the detector by 1/2 ch.

CT Value

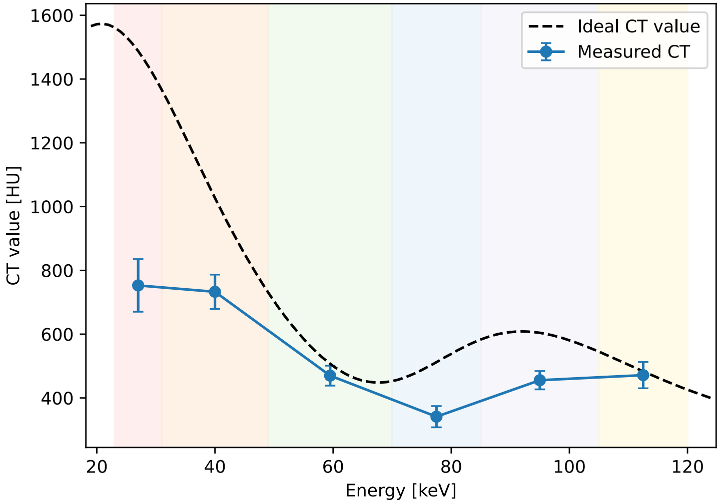
23-31keV | 31-49keV | 49-70keV | 70-85keV | 85-105keV | 105-keV



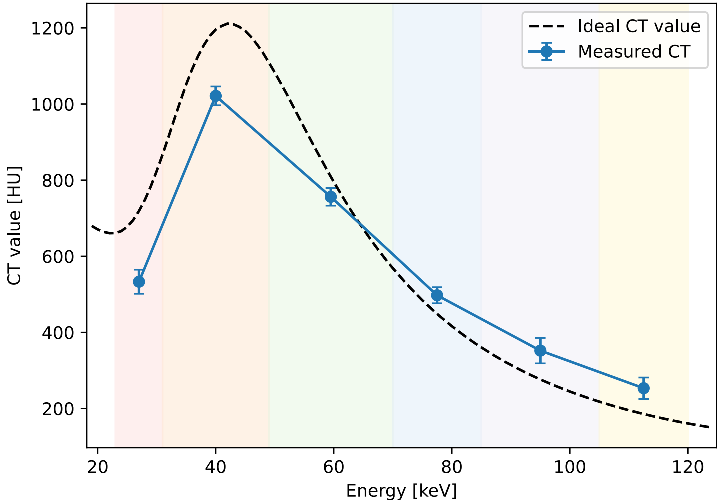
Gadolinium



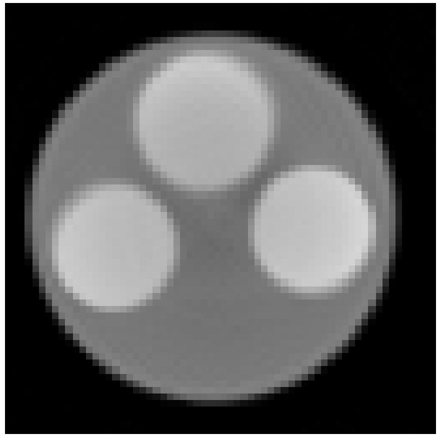
Au

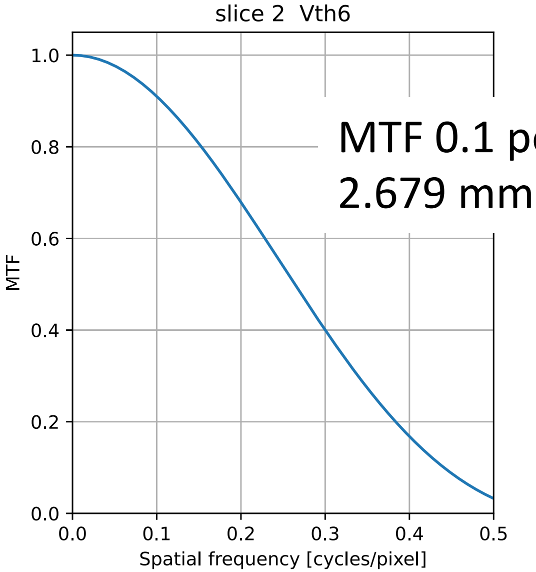


Iodine



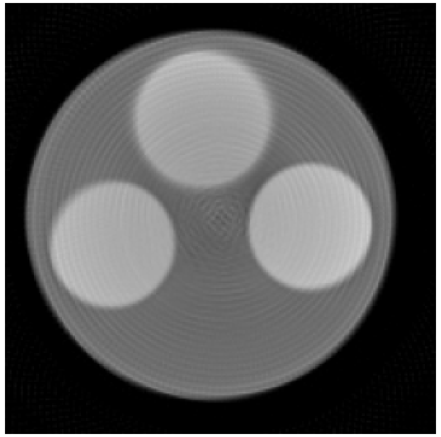
Resolution

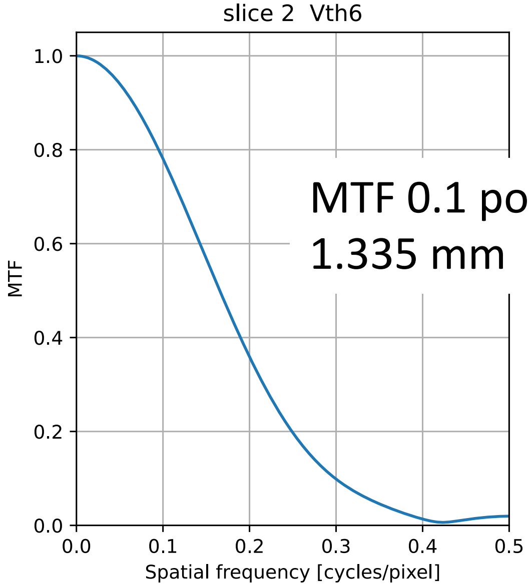




MTF 0.1 point resolution:
2.679 mm

Sub-Pixcel Shift





MTF 0.1 point resolution:
1.335 mm

Research Objectives

1. Enhancing Energy Resolution

→ Improvements to scintillator and SiPM

2. Enhancing spatial resolution

→ Development of fine pixel detectors

→ Machine learning utilizing energy information

3. Reducing imaging time

→ Development of High-Speed Scintillators

→ Expansion of Detector Area