Collimator Design for Gamma-Ray Cascade Angular Correlations in Medical Imaging

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Introduction

Medical imaging can be divided into two main branches, structural and functional. Structural imaging allows for examination of skeletal features and soft tissues. The main modalities of structural imaging are X-ray computed tomography and magnetic resonance imaging (MRI). Functional imaging allows for specific pathways, processes, or bodily functions to be observed. Functional imaging can be achieved using a contrast agent, functional MRI, or a nuclear tracer. The two main types of nuclear imaging are single photon emission tomography (SPECT) and positron emission tomography (PET). In either case, a radioactive nuclide is attached to a carrier molecule which participates in the process to be imaged. A SPECT tracer generally employs high-intensity gamma-rays of energies less than about 300 keV. Photon directional data are inferred from the collimator-detector assembly of the SPECT machine. A PET tracer emits a positron which yields a pair two back-to-back 511 keV photons due to annihilation with an electron. These two modalities make use of sinograms and back-projection techniques for image reconstruction, necessitating multiple decays to locate the decay vertices. We are working with a candidate isotope ^{43}K on a new imaging modality where non-collinear gamma cascade angular correlations will enable us to locate individual decay vertices. ^{43}K emits two high-intensity nearly isotropically distributed gamma-rays which can be used for imaging. This imaging modality will be tested using the MI-PET assembly at RIKEN-Kobe. Collimators for the MI-PET are being designed with the aid of GATE simulations.

Medical Isotopes for Imaging

In general, medical isotopes should have short half-lives (a few hours to a few days). The radioisotope must be chemically compatible with the process to be imaged. It is preferred, but not required, that the nuclide be non-toxic.

SPECT tracers - need one low-energy gamma-ray of sufficient intensity. A collimator is required to extract directional data from each detected gamma-ray.

PET tracers - in PET, the positron emitted in radioactive decay finds an electron and they annihilate each other, emitting two collinear photons. These annihilation photons are detected in coincidence. The vertex of an electron-positron annihilation is assumed to be on the line of detection. Data from multiple events are employed to estimate the source position(s).

Non-collinear tracers - non-collinearity makes use of the unique vertex determination of individual events. Low-energy gamma-rays (a few hundred keV) are preferred to avoid bulky collimators. The isotope ^{43}K emits two pairs of gamma-ray cascades: 617.5 & 372.8 keV, and 396.9 & 593.4 keV, both of which can be employed for imaging.

Photon Attenuation

For collimator choice, photon attenuation is the main criterion. Photon attenuation in a material medium follows an exponential law. The transmitted photon flux is given by:

$$I(x, Z, E_\gamma) = I_0 e^{-\mu(Z,E_\gamma)\rho x}$$

where

I	transmitted photon intensity
I_0	incident photon intensity
μ	mass attenuation coefficient of medium $[cm^2/g]$
Z	atomic number of medium
E_γ	energy of incident photons
ρ	density of medium $[g/cm^3]$
x	linear thickness of medium $[cm]$

This simple equation can be used to estimate the required collimator thickness.

Collimator Materials

The major concern when designing a collimator is scattering and leakage of photons through collimator walls, resulting in the mischaracterization of the photon trajectory and thus corrupted images. A good collimator design will maximize photon transmission while minimizing artifacts of absorption and scattering. The biggest factor in photon scattering and absorption is the collimator material. The two characteristics of a material that improve radiation absorption are high-Z number and high-density. Keeping in mind the practical aspects of design, the material must also be solid at room temperature, machinable, and ductile enough to fulfill the wall thickness constraints. Three promising materials are:
lead (Z = 82, ρ = 11.3 $[g/cm^3]$), tungsten (Z = 74, ρ = 19.3 $[g/cm^3]$), tantalum (Z = 73, ρ = 16.7 $[g/cm^3]$).

Table 1: Photon attenuation by 1 cm of material

Photon Energy, E_γ [keV]	Lead		Tungsten		Tantalum	
	$\mu\,[cm^2/g]$	$e^{-\mu\rho x}$	$\mu\,[cm^2/g]$	$e^{-\mu\rho x}$	$\mu\,[cm^2/g]$	$e^{-\mu\rho x}$
117	3.737	3.80e-19	2.973	1.20e-25	2.879	1.52e-21
243	0.6242	8.38e-4	0.4943	7.19e-5	0.4795	3.41e-4
373	0.2634	5.03e-2	0.2164	1.54e-2	0.2112	2.97e-2
617	0.1203	2.55e-1	0.1058	1.30e-1	0.1042	1.76e-1

MI-PET Machine

The MI-PET machine at RIKEN-Kobe will be used for the proof-of-concept experiments. Collimators for the MI-PET system are being designed. The detector system consists of 16 modules. Each module has a 15x11x2 array of GSO crystals. In the figure below, the inside diameter of the MI-PET machine is 10 cm.

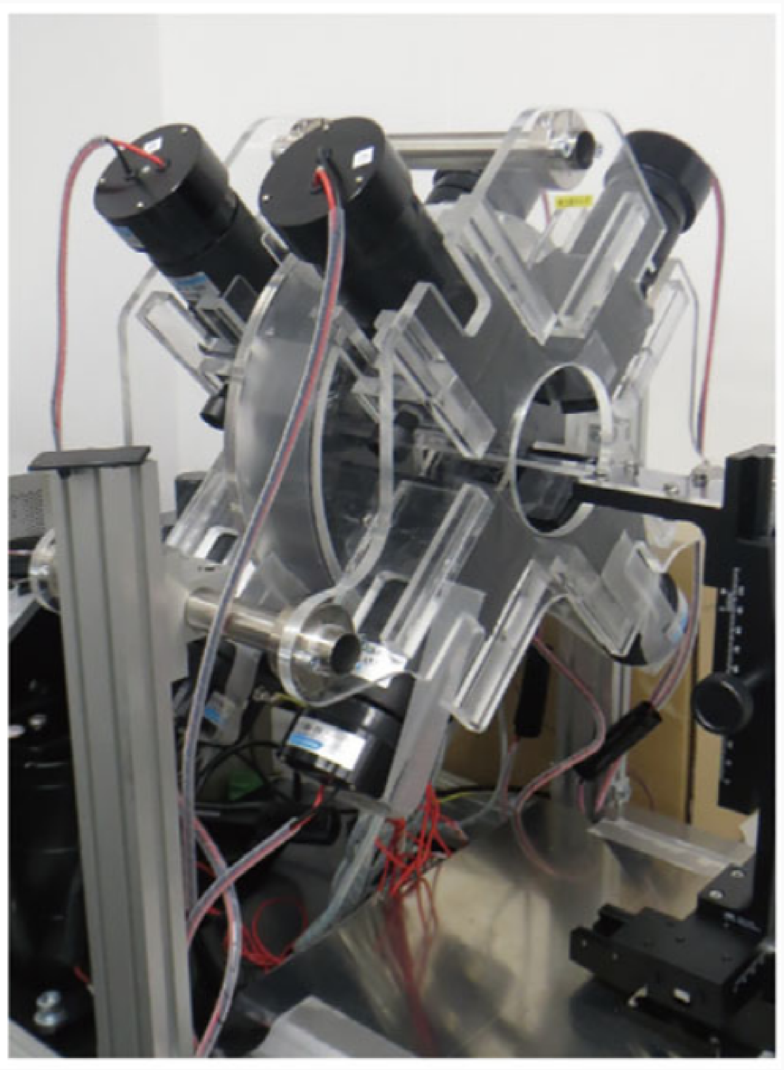

Figure 1: MI-PET Machine at RIKEN-Kobe

GATE Simulations

GEANT4 Application for Emission Tomography (GATE) is a Monte Carlo simulation toolkit. The detector system, source, and if applicable, the patient or phantom can be described in GATE user code. GATE is an open-source application, making it easy for users to add functionality required for their simulations. In our case, we have added a new type of radiation source, *twogamma*, to simulate a pair of emissions from ^{43}K. The *twogamma* source emits a 617 keV and a 373 keV gamma-ray in two random directions which mimics the isotropic spatial correlations of ^{43}K decay emissions. The cross-talk between the detectors for various collimator designs will be evaluated using the GATE toolkit.

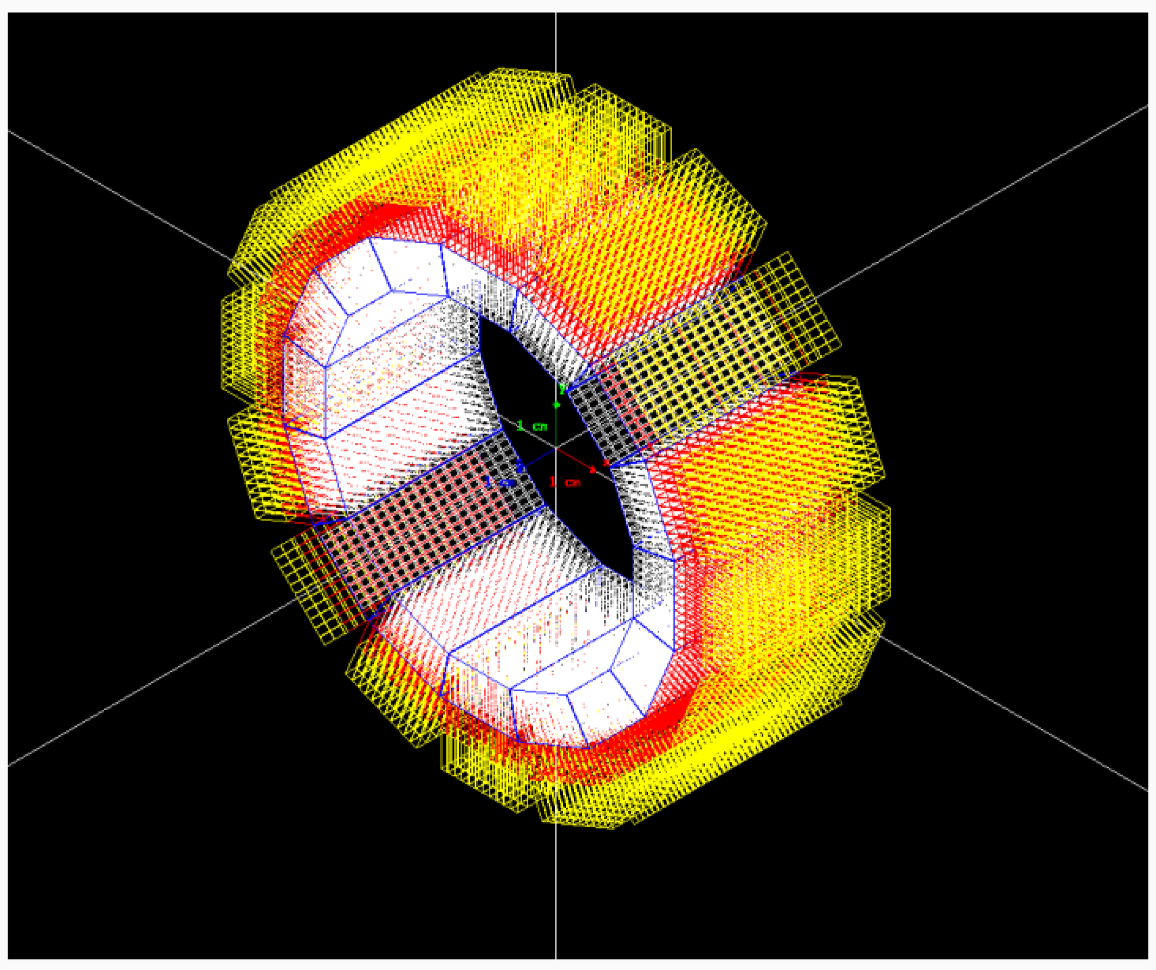

Figure 2: MI-PET Modules (Red, Yellow) and Collimators (White) in the GATE Toolkit

Next Steps

Currently, the GATE simulations are being carried out for the collimator geometry and choice of materials. The results of the simulations will be used to finalize the collimator design. Several candidate manufacturers for the collimators have been identified; once the design is finalized, the collimators will be procured. Initial measurements with the collimators will take place at RIKEN-Kobe in early 2022. The results of the simulations and experiment will be compared to PET and SPECT imaging modalities. We are also contemplating ^{111}In as the next candidate isotope, which emits a cascade of gamma-rays of 117 & 243 keV energies for which a 2 mm thick collimator system would be adequate.