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Dzhelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE INTEREST PROGRAMME

“Application of semiconductor pixel detectors from the Timepix family in nuclear medicine tasks (SPECT, CT).”

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Abstract

Single Photon Emission Computed Tomography (SPECT) is a nuclear imaging technique that utilizes radioactive tracers to visualize the distribution of radiopharmaceuticals within the body. SPECT is an essential tool in nuclear medicine for diagnosing a wide range of conditions, guiding treatment decisions, and monitoring patient outcomes. This technology allows healthcare professionals to accurately identify medical issues, plan specific treatments, and perform surgical interventions with greater safety and efficacy. One of the key advantages of semiconductor detectors is their high sensitivity and energy resolution, which enables them to accurately differentiate between different types of radiation and detect low-energy photons. In this review, we discuss the use of semiconductor pixel detectors from the Timepix family for nuclear medicine tasks.

Introduction

The integration of semiconductor pixel detectors from the Timepix family into nuclear medicine tasks, particularly in Single Photon Emission Computed Tomography (SPECT) and Computed Tomography (CT), represents a significant advancement in medical imaging technology. Semiconductor detectors offer high sensitivity, energy resolution, and versatility, making them promising candidates for enhancing imaging modalities crucial for diagnosing and treating various medical conditions.

CT, a cornerstone of modern medical imaging, relies on X-rays to produce detailed cross-sectional images of the body. Reconstruction methods such as filtered back projection (FBP) and iterative reconstruction have been instrumental in generating three-dimensional representations of internal structures. While FBP excels in computational efficiency, it often introduces artifacts, prompting the exploration of iterative methods and emerging approaches like deep learning to improve image quality.

SPECT, another vital nuclear imaging technique, focuses on the distribution of radiopharmaceuticals within the body to assess organ function and detect abnormalities. The principles of SPECT imaging leverage the detection of gamma rays emitted by radioactive tracers, highlighting areas of abnormal function or disease activity. As SPECT imaging evolves, advancements aim to enhance image quality, reduce scan times, and improve diagnostic accuracy.

Semiconductor detectors, utilizing materials like silicon and germanium, offer advantages such as high sensitivity, energy resolution, and fast response times. These detectors play a crucial role in radiation detection and measurement, finding applications in medical imaging, environmental monitoring, and nuclear physics research. Their integration into nuclear medicine tasks holds promise for enhancing imaging capabilities, enabling more accurate diagnoses and effective treatment planning.

In this report, we investigate the application of semiconductor pixel detectors from the Timepix family in CT and SPECT tasks. Through practical experiments and analysis, we aim to explore the performance of these detectors in image acquisition and reconstruction, comparing them against traditional methods. By assessing factors such as reconstruction accuracy, efficiency, and artifact reduction, we seek to evaluate the potential of semiconductor detectors to improve the quality and efficacy of nuclear medicine imaging techniques.

Materials and Methods

CT

Computed Tomography (CT) is an advanced medical imaging technique that uses X-rays to obtain detailed images of the interior of the body. As shown in Figure 1, during a CT scan, multiple X-ray images are taken from different angles around the body, and then these images are combined through a computerized process to create a three-dimensional representation of internal structures. This technology allows doctors to clearly and accurately visualize organs, tissues, and bones, helping them diagnose a wide variety of diseases and injuries, such as fractures, tumors, and vascular disorders [1].

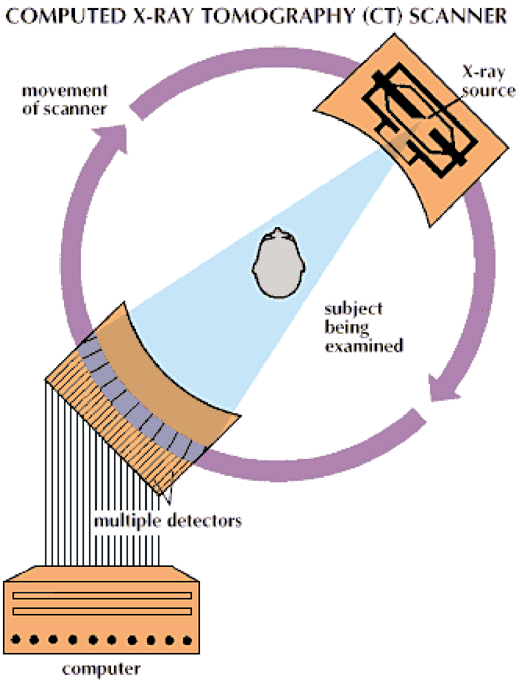


Figure 1. CT Scanner Schematic [2]

CT scanners are widely used in medicine for their ability to provide detailed, real-time images of internal anatomical structures. The information obtained through CT images is essential for clinical decision-making, as it allows healthcare professionals to accurately identify medical issues, plan specific treatments, and perform surgical interventions with greater safety and efficacy. Additionally, CT is an invaluable tool in monitoring the progression of chronic diseases, tracking response to treatment, and evaluating the effectiveness of medical therapies [3].

There are several reconstruction methods in computed tomography (CT) that are used to generate three-dimensional images from projection data obtained by the scanner. One of the most common methods is filtered back projection (FBP), which involves applying a filter to the projected data before performing back projection to obtain the final image. An important advantage of FBP is its speed and computational efficiency, making it ideal for clinical applications where rapid reconstruction is needed. However, FBP can produce artifacts in the image due to noise and lack of attenuation correction, which can affect diagnostic quality [4,5].

Another reconstruction method used in CT is iterative reconstruction, which includes algorithms such as maximum likelihood algorithm (MLE) and regularized least squares algorithm (SIRT). The main advantage of iterative methods is their ability to reduce noise and improve image quality by considering the physical model of the data acquisition process. This can result in sharper images with fewer artifacts compared to FBP. However, iterative methods are more computationally intensive and require more processing time, which may limit their application in clinical settings where fast reconstruction is required [6].

An emerging approach in CT reconstruction is deep learning, which uses convolutional neural networks to learn complex patterns directly from the projected data and generate high-quality images. A significant advantage of deep learning in CT is its ability to enhance image quality and reduce noise without the need for explicit physical models. Additionally, deep learning can adapt to different types of data and clinical scenarios, making it highly versatile. However, training neural networks requires large amounts of data and computational resources, which can be a limitation in resource-constrained environments [7].

In addition to the mentioned methods, advanced techniques such as algebraic geometry-based reconstruction and partial X-ray-based reconstruction aim to improve the quality and efficiency of CT reconstruction. These techniques can offer advantages such as improved spatial resolution, reduced acquisition time, or increased robustness against artifacts. However, their implementation may require specialized knowledge and careful parameter tuning to achieve optimal results.

SPECT

Single Photon Emission Computed Tomography (SPECT) is a nuclear imaging technique that utilizes radioactive tracers to visualize the distribution of radiopharmaceuticals within the body. During a SPECT scan, a gamma camera rotates around the patient, capturing emitted gamma rays from the radioactive tracer (view Figure 2). These gamma rays are then processed by a computer to create three-dimensional images that show the concentration and distribution of the radiopharmaceutical in specific tissues or organs. By analyzing these images, healthcare professionals can assess organ function, detect abnormalities, and diagnose various medical conditions [8].

SPECT imaging is particularly valuable in nuclear medicine for its ability to provide functional information about the body's physiological processes. Unlike traditional anatomical imaging techniques, such as X-rays or CT scans, SPECT focuses on the metabolic activity and blood flow within tissues and organs. This functional perspective allows doctors to evaluate organ function, assess the severity of diseases, and monitor treatment response in conditions such as heart disease, cancer, and neurological disorders. SPECT scans are commonly used in conjunction with other imaging modalities to provide a comprehensive understanding of a patient's health status.

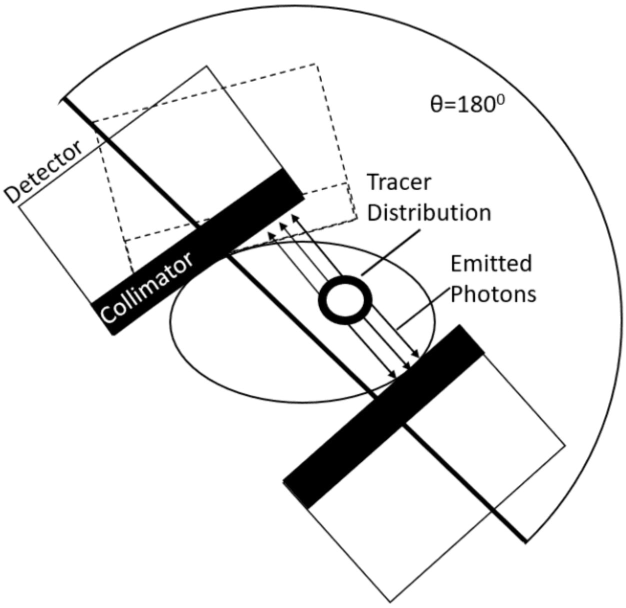


Figure 2. Schematics of the SPECT imaging [9]

The principles of SPECT imaging rely on the detection of gamma rays emitted by the radioactive tracer as it decays within the body. By measuring the intensity and distribution of these gamma rays, SPECT cameras can generate detailed images that highlight areas of abnormal function or disease activity. The versatility and sensitivity of SPECT make it an essential tool in nuclear medicine for diagnosing a wide range of conditions, guiding treatment decisions, and monitoring patient outcomes. As technology continues to advance, SPECT imaging techniques are constantly evolving to improve image quality, reduce scan times, and enhance diagnostic accuracy in clinical practice [10].

Collimators

Collimators are devices used in various fields such as medical imaging, nuclear physics, and astronomy to control the direction and spread of radiation or particles. They consist of a series of collimating elements that help limit the field of view and focus the radiation or particles onto a specific area of interest. By using collimators, researchers and practitioners can improve the quality and accuracy of their measurements and images, as well as reduce unwanted background noise or scatter.[11]

In medical imaging, collimators are commonly used in X-ray machines to ensure that only the desired area of the patient's body is exposed to radiation, while minimizing exposure to surrounding tissues. In nuclear physics experiments, collimators help define the path of particles and prevent unwanted interactions with other materials, thus allowing researchers to study specific properties or behaviors of particles more effectively. In astronomy, collimators are used in telescopes to block out unwanted light and improve the resolution and clarity of celestial images.[12, 13]

Semiconductor detectors

Semiconductor detectors are a type of radiation detector that utilize semiconductor materials to detect and measure ionizing radiation. These detectors operate based on the principle that when ionizing radiation interacts with the semiconductor material, it generates electron-hole pairs, leading to the creation of electrical signals that can be measured. The energy deposited by the radiation in the semiconductor material determines the number of electron-hole pairs produced, allowing for the quantification of the radiation dose [14].

One of the key advantages of semiconductor detectors is their high sensitivity and energy resolution, which enables them to accurately differentiate between different types of radiation and detect low-energy photons. This capability makes semiconductor detectors particularly useful in applications where precise measurements of radiation energy are essential, such as in medical imaging, environmental monitoring, and nuclear physics research. Additionally, semiconductor detectors offer fast response times and can operate at room temperature, making them convenient and versatile tools for a wide range of radiation detection tasks.

Semiconductor detectors come in various forms, including silicon and germanium detectors, each with specific characteristics and applications. Silicon detectors are commonly used in portable radiation detection devices and medical imaging equipment due to their compact size and efficiency. On the other hand, germanium detectors are known for their superior energy resolution and are often employed in high-precision spectroscopy applications, such as gamma-ray spectroscopy in nuclear physics research. Overall, semiconductor detectors play a crucial role in radiation detection and measurement by providing accurate, reliable data that is essential for various scientific, medical, and industrial purposes.

Medipix and Timepix detectors are cutting-edge technologies used in particle physics research and medical imaging. These detectors are pixelated semiconductor devices that can detect and track individual particles with high precision and efficiency. Medipix detectors are particularly used in X-ray imaging applications, while Timepix detectors are used in a wide range of scientific and industrial applications. These detectors have revolutionized the way researchers study and image particles, leading to significant advancements in various fields of science and technology. [15, 16]

Results

The first part of our practical work was aimed at studying methods of acquisition and reconstruction of CT Projections. We used the skimage library in Python and ImageJ.

To determine the differences between the various CT projection reconstruction methods, we considered backprojection, filtered backprojection and fast Fourier transform methods.

First, we decided to determine a sufficient number of projections for image reconstruction. We consider that on average 200 projections are enough for good reconstruction of an uncomplicated image.

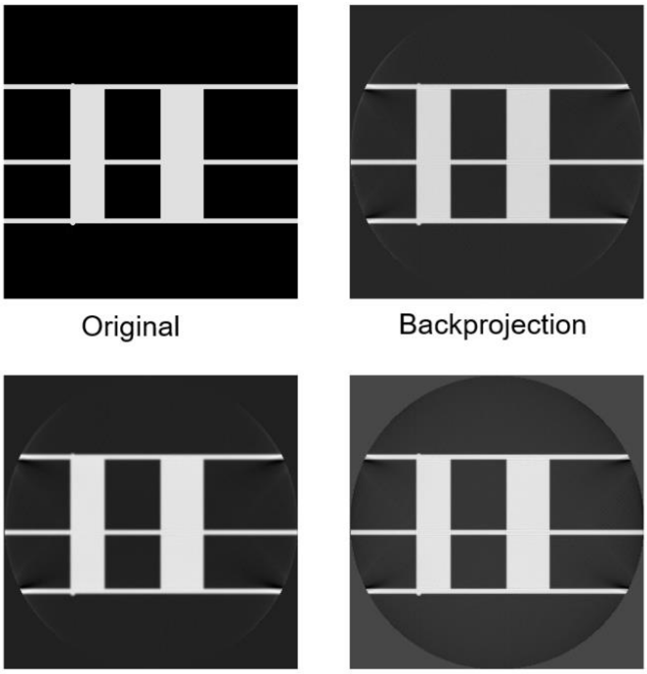
When an image is simple and contains less detail, a smaller number of projections (such as 200) may be sufficient to capture essential information and reconstruct the image appropriately. However, as the complexity and level of detail of the image increases, more projections are required to accurately capture all the nuances and complexities present.

This is because each projection provides a different perspective of the object being depicted, and by increasing the number of projections, we can get a more complete view of the object from multiple angles. By increasing the number of projections for highly detailed images, we can improve the accuracy and quality of the reconstructed image by capturing more information and reducing artifacts or distortions that can occur with fewer projections.

Therefore, when the reconstruction was carried out, we increased the number of projections until reaching 2000, and obtaining a much better quality image.

Let's review each of the CT projection reconstruction methods(view Figure 3). The back-projection method is easy to understand. It reduces artifacts and requires rather few projections, but it is time-consuming to reconstruct complex images. In addition, the back-projection method is sensitive to noise. To reduce noise and artifacts, it is necessary to use a filter in the frequency domain before back projection, i.e. apply the filtered back projection method. This method allows you to select filtering suitable for a particular image. All filters work well, but give a little different results. Examples of the line filter and Hahn filters are shown in Figures 4 and 5. The ramp filter adds noise but preserves edges well, while the Hahn filter adds less noise but blurs edges. We also considered the fast Fourier transform method. This method decomposes space information into frequency components, which makes it easier to analyze and interpret the image. However, it can also be sensitive to noise, resulting in blurred images.

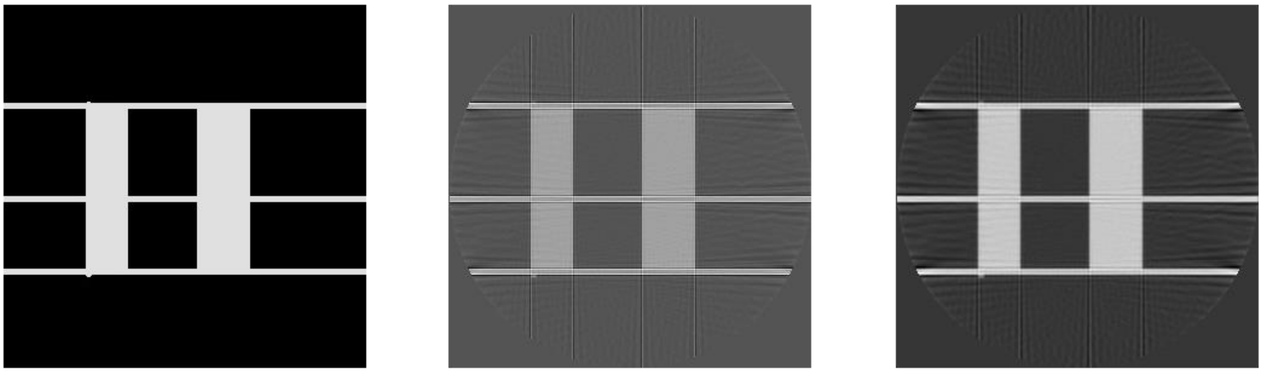
Thus, if we compare the above methods of CT projection reconstruction, the result of filtered back projection is more versatile and efficient.



Original Backprojection

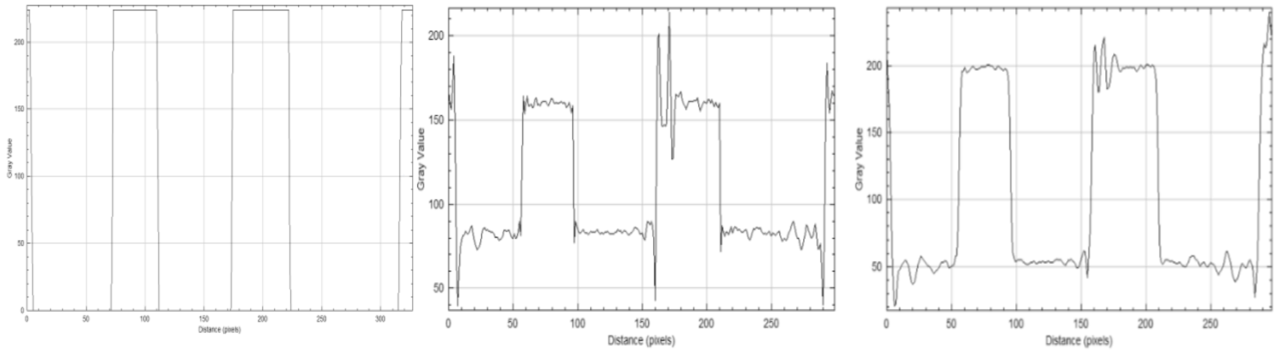
Filtered backprojection Fast Fourier transform

Figure 3. Example of using different methods of image reconstruction



Original Ramp Hann

Figure 4. Filtered back projection.



Original Ramp Hann

Figure 5. Plot profile for filtered back projection.

The second part of our work consists of the processing of SPECT images, through the use of pinhole cameras, whose advantage is that they have an infinite depth of field and do not suffer chromatic aberration, which can be used to form images from X-rays. and other high energy sources, which are typically difficult or impossible to focus on. The fundamental thing for working with this technology is that if the hole pattern is carefully chosen, it is possible to reconstruct the original image with a resolution equal to that of a single hole.

For image processing, a MURA pattern was generated, which is built on a square network whose side length p is prime; each element of the MURA, A i,j, where i and j go from 0 to p − 1, is:

0 if i = 0,

1 if j = 0, i != 0,

1 if CiCj = +1,

0 otherwise

Where Cq = +1 if q is a quadratic residue modulo p, and −1 otherwise. C q is also known as Jacobi symbol. If x2 mod p = q mod p, we say that q is a quadratic remainder of p.

To perform the decoding, a matrix Gij is constructed, whose elements are constructed from the elements Ai,j of the MURA and are equal to:

+1 if i + j = 0,

+1 if Ai,j = 1 (i + j != 0),

−1 if Ai,j = 0 (i + j != 0)

Figure 6 shows an image of the MURA mask generated using a code in Python language.

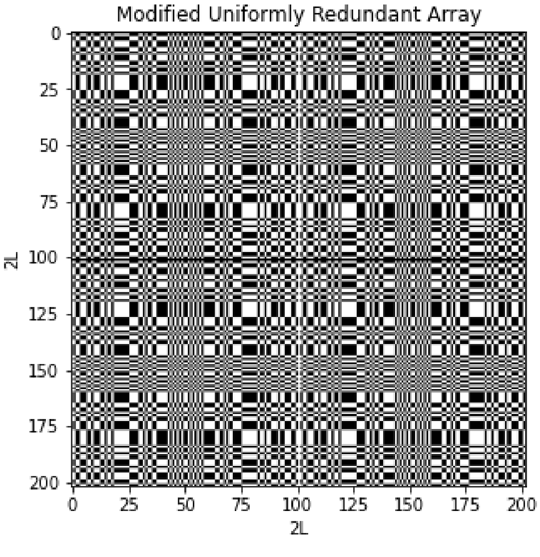


Figure 6. MURA mask generated.

Coded aperture micro-SPECT is an imaging technique that uses a coded aperture mask to improve the spatial resolution and sensitivity of single-photon emission computed tomography (SPECT) images. This technology features a coded aperture mask, which consists of a pattern of open and closed apertures that are arranged in a pseudorandom or known pattern, such as that shown in Figure 6.

This mask is placed in front of the detector to create an encoded image of the radiation source. When gamma rays are emitted by the animal's radioactive tracer, they pass through the coded aperture mask and interact with the detector, as shown in Figure 7.

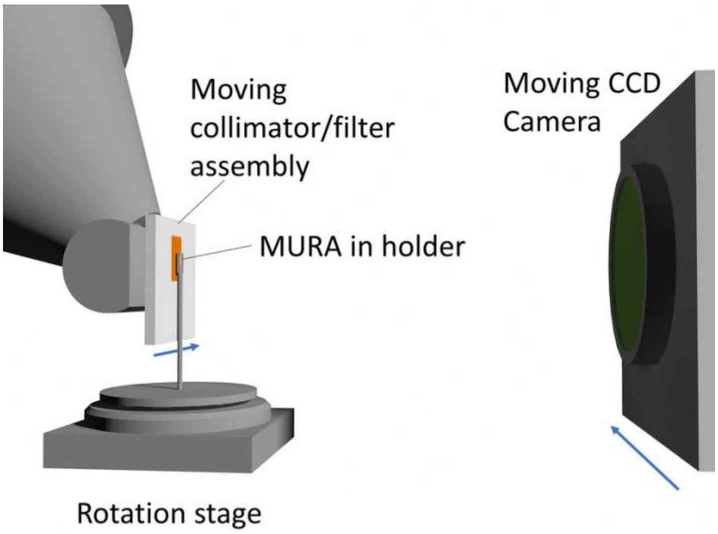


Figure 7: Detector array with MURA mask added.
Fountain: Davis, G.R., Beckenbach, T. & Meyer, P. Imaging a microfocus X-ray focal spot with a thin coded aperture. *Sci Rep* **12**, 18635 (2022). https://doi.org/10.1038/s41598-022-23338-y

The coded aperture mask casts a unique shadow on the detector based on the pattern of the apertures. By measuring the intensity of the detected gamma rays, and using the known pattern of the encoded aperture mask, it is possible to reconstruct the encoded image and create a high-resolution image of the distribution of the radioactive tracer within. the little animal The reconstructed image can be processed and analyzed to visualize specific organs, tissues or structures of interest within the small animal. This allows studying physiological processes, disease progression or the effects of treatments in preclinical studies.

Conclusion

In summary, our investigation highlights the significant potential of semiconductor pixel detectors from the Timepix family in revolutionizing nuclear medicine imaging, particularly in Computed Tomography (CT) and Single Photon Emission Computed Tomography (SPECT). By leveraging the superior sensitivity, energy resolution, and versatility of semiconductor materials, these detectors offer promising avenues for enhancing both CT and SPECT imaging modalities.

In CT imaging, our analysis of reconstruction methods such as filtered back projection (FBP), iterative reconstruction, and emerging deep learning approaches underscores the importance of balancing artifact reduction and computational efficiency. Semiconductor detectors present an exciting opportunity to optimize CT reconstruction processes, potentially resulting in clearer images with fewer artifacts.

Likewise, in SPECT imaging, semiconductor detectors demonstrate the capability to improve sensitivity and resolution, facilitating more precise detection and visualization of radiopharmaceutical distribution within the body. This advancement has significant implications for diagnosing medical conditions and guiding treatment decisions.

Overall, the integration of semiconductor pixel detectors into nuclear medicine tasks holds promise for advancing medical imaging technology, ultimately enhancing patient care and outcomes. Continued research and development efforts in this field are essential to fully realize the potential benefits of semiconductor detectors in improving diagnostic accuracy and treatment efficacy in clinical practice.

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