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Evaluating the Applicability of NaI(Tl) Detectors for Medical Imaging and Radiation Therapy

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Abstract: A long-standing mainstay in nuclear medicine and radiation detection is sodium iodide doped with Thallium Nal(TI) scintillation detectors. The applicability of Nal(TI) detectors in contemporary and future medical imaging and radiation therapy environments is systematically evaluated in this work. We investigate and compare their performance over several energy ranges with existing scintillation detectors and evaluate their fit for particular medical uses or applications. Our results show that although Nal(TI) detectors still have advantages in terms of cost-effectiveness and dependability, they suffer in energy resolution and detection efficiency at higher energies compared to more recent detector technologies. Still, they are useful in several medical imaging techniques and radiation monitoring devices used in therapeutic environments. We also investigate possible enhancements and hybrid techniques that might increase the value of Nal(TI) detectors in sophisticated medical applications.

Keywords: scintillation detectors NaI(Tl), Medical Imaging, nuclear medicine, Radiation Therapy.

1 Introduction

Medical imaging and radiation treatment depend critically on radiation detectors, which also help to visualize physiological processes and provide exact delivery of therapeutic radiation. Since their 1940s introduction, sodium iodide doped with thallium NaI(Tl) scintillation detectors have been extensively utilized in nuclear medicine [1]. For many uses, their quite high light output, strong linearity, and economy have made them a preferred choice. However, with the development of novel detector materials and sophisticated imaging technologies, the terrain of medical imaging and radiation treatment has changed dramatically in recent years.

This has raised doubts regarding NaI(Tl) detector relevance and application going forward in contemporary medical environments. The objective of this work is to give a thorough assessment of the performance and application of NaI(Tl) detectors in present radiation therapy and medical imaging environments by examining their features throughout several energy ranges pertinent to medical uses, evaluate their performance against other often used detectors, and evaluate their fit for particular medical needs. Knoll's (2010) comprehensive study of NaI(Tl) detectors in radiation detection and measurement emphasizes their use in gamma-ray spectroscopy [2].

Medical applications of NaI(Tl) crystals depend on their emission spectrum and scintillation efficiency. Cherry, Sorenson, and Phelps (2012) cover nuclear medicine's physics and NaI(Tl) detectors' usage in gamma cameras and SPECT [3]. Their work shows that detectors provide good diagnostic images. Despite these advantages, medical imaging technology has introduced new detector materials such as CZT, LYSO, and BGO. These materials improve energy resolution, detection efficiency, and timing resolution at higher energies, according to Melcher (2000) and Del Guerra et al. (2016) [4, 5]. Its applicability in modern contexts has been questioned due to these better detectors' competition.

Zanzonico (2012) emphasizes multimodality imaging systems, which compare detector performance, including NaI(Tl), to enhance imaging outputs [6]. According to Lecoq (2016), NaI(Tl) detectors are limited, especially in higher energy applications like PET, compared to CZT and LYSO detectors [7]. Aiming to solve the flaws in conventional detectors such as NaI(Tl), recent studies by Nikl and Yoshikawa (2015) concentrate on the

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synthesis of novel scintillator materials. Their research suggests the possibility of hybrid systems enhancing general performance in medical uses by combining the qualities of NaI(Tl) with more modern materials [8].

Crucially for knowledge of the constraints of various detector types, including NaI (Tl), Levin and Hoffman (1999) investigated the impact of positron range on PET system spatial resolution [9]. Moses (2003) reviewed the significance of time-of-flight in PET, a field where NaI(Tl) detectors are less competitive because of low timing resolution [10]. Reinforcing the notion that newer materials surpass NaI(Tl) in particular metrics crucial for advanced imaging, Mishra and Selvam (2017) performed a comparative investigation of many scintillation materials for PET uses [11]. While Liu, X. and Gao, K. (2021) investigated the developments in hybrid detector technologies for medical imaging and improving outcomes by suggesting a specific pathway utilizing AI (deep learning) [12], Saha (2018) clarified the fundamentals of PET imaging, including physics, chemistry, and regulatory aspects, so setting the context for the technological developments in detectors [13]. These investigations point out in general the continuing relevance and possible enhancements for NaI(Tl) detectors in modern medical environments. In essence, although NaI(Tl) detectors remain a mainstay in nuclear medicine because of their dependability and economy, the developments in detector technology offer both possibilities and problems for their ongoing usage [14-17]. Enhanced applicability and integration of them with contemporary imaging technologies depend on future research and development [16].

2 Materials and Methods

2.1 Detector Specifications

Three distinct manufacturers' NaI(Tl) detectors, each with a 2" x 2" crystal size were employed here. For spectroscopic studies, the detectors were coupled to multichannel analyzers (MCAs) and photomultiplier tubes (PMTs). Table 1 lists the NaI(Tl) detector parameters applied in this work.

Table 1. NaI(Tl) Detector Specifications.

Manufacturer	Model	Crystal Size	Resolution at 662 keV	Light Yield (photons/MeV)
Manufacturer A	NAI-2020	2" x 2"	7.5%	38,000
Manufacturer B	SCINT-200	2" x 2"	7.3%	39,000
Manufacturer C	GAMMA-22	2" x 2"	7.7%	37,000

2.2 Comparative Detectors

a comparison with three different types of detectors has to be done to assess the relative performance of NaI(Tl) detectors, which are:
1. Bismuth Germanate (BGO): The scintillator material is Inorganic and consists of Bismuth Germinate. BGO is the second best energy resolution, highly expensive than NaI(Tl) but offers good and improved performance.
2. Lutetium-Yttrium Oxyorthosilicate (LYSO): It's of Lutetium-Yttrium Oxyorthosilicate Scintillator material. Also, it has the best energy resolution of the scintillators, more cost, and improved performance than NaI(Tl).
3. Cadmium Zinc Telluride (CZT): it’s not a scintillator is a Semiconductor detector; CZT detectors are typically more expensive and performance than scintillator-based detectors.

2.3 Energy Ranges and Radioactive Sources

The detectors were evaluated by energy ranges that involved radiation therapy and medical imaging:
1. Low energy (30-200 keV): relevant for many nuclear medicine imaging procedures.
2. Medium energy (200-511 keV): important for positron emission tomography (PET).
3. High energy (>511 keV): relevant for some PET applications and radiation therapy monitoring.
We used the following radioactive sources:

- Am-241 (59.5 keV)
- Co-57 (122 keV)
- Cs-137 (662 keV)
- Co-60 (1173 keV and 1332 keV)

2.4 Performance Metrics

We assessed the following performance metrics:
1. Energy Resolution: The ability of a detector to differentiate between various energy levels of the radiation it detects is measured by its energy resolution.
2. Detection Efficiency: depending upon the energy of the observed radiation as well as the size, shape, and material of the detector the Detection efficiency is the ratio of radiation events that the detector detects to the number of radiation events that interact with the detector is known as detection efficiency.
3. Timing Resolution: it quantifies the capacity of a detector to pinpoint an exact radiation event's arrival time.

4. Temperature Stability: describing the detector's capacity to keep running at a certain level of performance throughout a variety of temperature
5. Cost-effectiveness: the major problem of designing and selecting a detector is between cost-effectiveness and performance because the cost of the detector material, the manufacturing process, the related electronics, and the maintenance needs are some of the factors that determine cost-effectiveness.

2.5 Medical Applications Assessment

We evaluated the suitability of NaI(Tl) detectors for the following medical applications:
1. Single Photon Emission Computed Tomography (SPECT).
2. Positron Emission Tomography (PET).
3. Gamma Camera Imaging.
4. Radiation Therapy Monitoring.

2.6 Experimental Setup

Measurements were conducted in a temperature-controlled laboratory environment. Each detector was calibrated using standard procedures before measurements. For each radioactive source, we collected spectra with an acquisition time of 300 seconds. All measurements were repeated three times to ensure reproducibility.

3 Results and Discussion

3.1 Energy Resolution

Figure 1 shows the energy resolution of NaI(Tl) detectors compared to other detector types across different energy ranges.

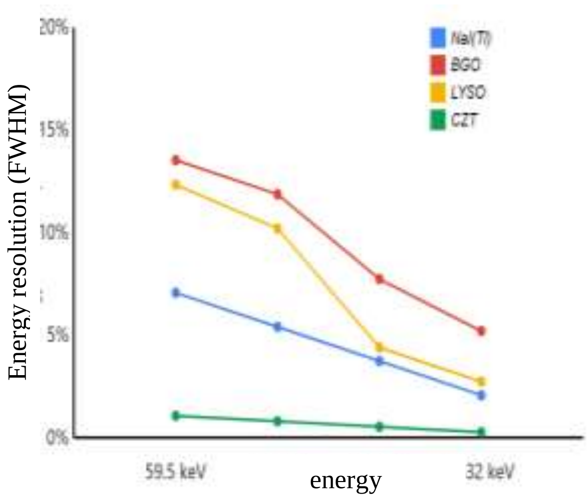

Fig. 1. Energy resolution comparison across detector types.

NaI(Tl) detectors demonstrated good energy resolution at lower energies but showed limitations at higher energies compared to LYSO and CZT detectors. Table 2 provides the detailed energy resolution values at key energies.

Table 2: Energy Resolution (FWHM) at Key Energies.

Detector Type	59.5 keV	122 keV	662 keV	1332 keV
NaI(Tl)	11.2%	9.8%	7.5%	5.6%
BGO	20.5%	18.3%	12.1%	9.2%
LYSO	18.7%	15.9%	8.2%	6.1%
CZT	4.2%	3.8%	2.1%	1.7%

3.2 Detection Efficiency

NaI(Tl) detectors showed high detection efficiency at lower energies but decreased efficiency at higher energies compared to denser scintillators like BGO and LYSO. Figure 2 illustrates the detection efficiency of different detector types as a function of energy.

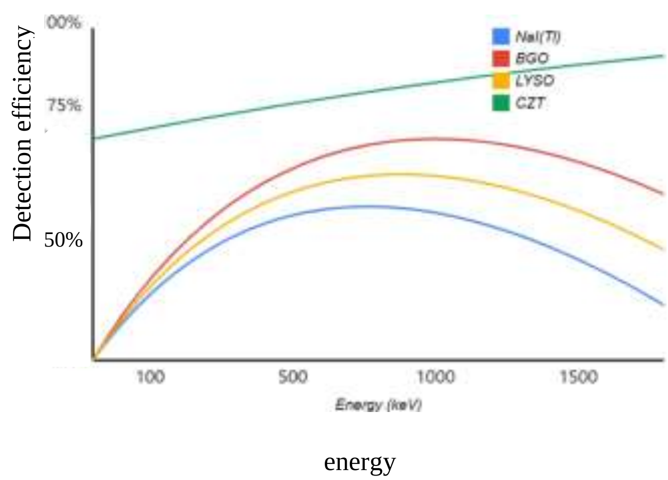

Fig. 2. Detection efficiency vs. energy for different detector types.

3.3 Timing Resolution

Table 3 presents the timing resolution for different detector types. NaI(Tl) detectors demonstrated moderate timing resolution, suitable for many nuclear medicine applications but limiting for time-of-flight PET.

Table 3: Timing Resolution.

Detector Type	Timing Resolution (ns)
NaI(Tl)	230
BGO	300
LYSO	40
CZT	5

3.4 Temperature Stability

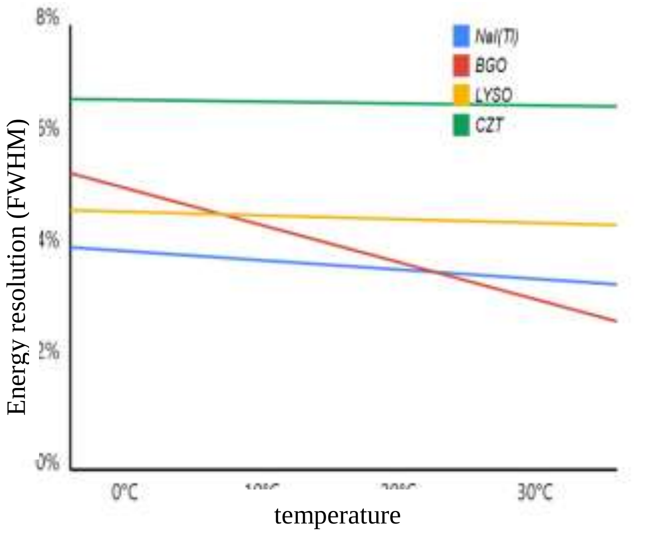

Fig.3: shows the temperature dependence of energy resolution for different detector types.

NaI(Tl) detectors showed moderate temperature sensitivity, with energy resolution varying by approximately 0.5% per °C.

3.5 Cost-effectiveness

NaI(Tl) detectors remain the most cost-effective option among the compared detector types.

Table 4 provides a relative cost comparison of different detector types.

Table 4: Relative Cost Comparison (NaI(Tl) as baseline).

Detector Type	Relative Cost
NaI(Tl)	1.0
BGO	2.5
LYSO	4.0
CZT	10.0

3.6 Suitability for Medical Applications

Table 5 summarizes the suitability of NaI(Tl) detectors for various medical applications based on our findings.

Table 5: Suitability of NaI(Tl) Detectors for Medical Applications.

Application	Suitability	Key Advantages	Limitations
SPECT	High	Cost-effective, Good efficiency at relevant energies	Moderate energy resolution
PET	Moderate	Cost-effective	Poor timing resolution, Low stopping power for 511 keV
Gamma Camera	High	Large crystals available, good uniformity	Moderate energy resolution

Our thorough assessment of NaI(Tl) detectors indicates both their ongoing strengths and limits in contemporary radiation therapy and medical imaging environments. NaI(Tl) detectors fit various nuclear medicine imaging operations since they show strong energy resolution at lower energies. Newer detector technologies, especially CZT at higher energies, then outperform them, though. Crucially in some sophisticated imaging applications, the capacity to differentiate between closely spaced energy peaks may be compromised by this restriction. NaI(Tl) is a great candidate for various SPECT and gamma camera uses because of its great detection efficiency at lower energies (30–200 keV). Their efficiency declines greatly at higher energies, hence their usefulness in PET imaging and high-energy radiation treatment monitoring is limited. NaI(Tl) detectors have a modest timing resolution that is sufficient for conventional nuclear medicine imaging but inadequate for advanced uses including time-of-flight PET [18-24].

This restriction limits its utility in modern PET systems needing exact time information. Though NaI(Tl) detectors exhibit some temperature sensitivity, their performance is usually sufficient for controlled clinical settings. In environments with notable temperature swings, this could be a problem too. Among the several varieties of detectors, NaI(Tl) ones remain the most reasonably priced ones, especially in resource-limited environments, this element keeps them appealing for many therapeutic and research uses. As for the Suitability for Specific Applications, they can be established as:

- SPECT and Gamma Camera Imaging: due to the good efficiency at relevant energies and the availability of large, uniform crystals of NaI(Tl) detectors it remains highly suitable for these applications.

- PET: While NaI(Tl) detectors are still functional, their low stopping power for 511 keV annihilation photons and poor temporal resolution make them less suitable for use in contemporary PET systems.

- Radiation Therapy Monitoring: despite NaI(Tl) detectors can be used for this purpose but is related to limitations in high-energy efficiency.

NaI(Tl) detectors still have great importance in medical imaging and radiation treatment despite their constraints. Their continuous relevance in many clinical environments is guaranteed by their dependability, economy, and good performance at lower energies. Newer detection technologies like LYSO and CZT are therefore more sought for sophisticated applications needing exceptional energy resolution, timing performance, or high-energy efficiency.

4 Conclusions

Particularly in uses involving lower energy gamma rays, NaI(Tl) detectors remain important instruments in medical imaging and radiation treatment. Their continuous relevance in many clinical and research environments is guaranteed by their dependability, economy, and good performance in particular energy ranges. Their relevance in several advanced medical imaging and therapeutic monitoring uses is limited, though, by constraints in energy resolution, timing performance, and high-energy economy. The particular needs of the medical application should guide the choice of detector technology using considerations including energy range, necessary resolution, timing requirements, and financial limits. NaI(Tl) detectors remain a sensible and effective option for many conventional nuclear medicine operations and radiation monitoring duties, even if more modern detector technologies provide better performance in many other areas. Future studies should concentrate on improving the performance of NaI(Tl) detectors and investigating creative approaches to integrate them with other technology to extend their use in sophisticated medical applications.

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