

Review article

Development of Scintillators in Nuclear Medicine

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Abstract

High-quality image is necessary for accurate diagnosis in nuclear medicine. There are many factors in creating a good image and detector is the most important one. In recent years, several detectors are studied to get a better picture. The aim of this paper is comparison of some type of these detectors such as thallium activated sodium iodide bismuth germinate cesium activated yttrium aluminum garnet (YAG: Ce) YAP: Ce "lutetium aluminum garnet activated by cerium" CRY018 "CRY019" lanthanum bromide and cadmium zinc telluride. We studied different properties of these crystals including density, energy resolution and decay times that are more important factors affecting the image quality.

Keywords: Decay time, density, detector, energy resolution, fwhm, image quality, single photon emission computed tomography, the after glow

Introduction

The history of nuclear medicine is rich with contributions from gifted scientists across different disciplines in physics, chemistry, engineering, and medicine. The multidisciplinary nature of nuclear medicine makes it difficult for medical historians to determine the birthdate of nuclear medicine. This can probably be best placed between the discovery of artificial radioactivity in 1934 and the production of radionuclides by Oak Ridge National Laboratory for medicine related use, in 1946.^[1] Nuclear medicine imaging technologies are viewed in the context of anatomy, physiology and molecular level to diagnosis of disease, assessment of response to treatment and determination of drug's distribution throughout the body.^[2-4] The concept of emission and transmission tomography, later developed into a single photon emission computed tomography (SPECT), was introduced by David E. Kuhl and Roy Edwards in the late 1950s.^[1]

Single photon emission computer tomography is a computerized three-dimensional image processing for demonstration of acquisitioned image by gamma camera.^[5] The function of the scintillation crystals in the nuclear medicine imaging systems is production visible light from hitting high energy γ -rays.^[6] Many physical factors degrade SPECT images, qualitatively and/or quantitatively. Researching on quality improvement is proceeding on the gamma camera and SPECT system for assessment the quality and quantity of images.^[7]

Growing interest in the development of new scintillator materials is pushed by increasing the number of medical, industrial and scientific application.^[8] Detectors are the heart of a SPECT system and are responsible for collecting the high-energy photons emitted by the patient, estimating the photon energy and location of interaction, and generating count data for subsequent image reconstruction.^[9] A scintillation crystal with high luminous efficiency, short decay time, low cost, high density, short radiation length, good spectral match to photodetectors and without afterglow is more favorable.^[9-11]

The luminous efficiency can reduce the radiation absorbed dose to patients by decreasing radiopharmaceutical injection dosage as concerns about patient safety.

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Short decay time is important for special resolution and photon detection. The afterglow is also a critical parameter and is often induced by some traps from crystal defects.^[6,12] Afterglow in halides is believed to be intrinsic and correlated to certain lattice defects. Bismuth germinate (BGO) and cadmium tungstate crystals are examples of low after glow scintillation materials. Despite the acknowledge advantages of the CsI: Tl in many scintillator applications, a characteristic property that undermines its use in high-speed radiographic and radionuclide imaging is the presence of a strong afterglow component in its scintillation decay. This causes pulse pileup in high count rate applications, reduced energy resolution in radionuclide imaging, and reconstruction artifacts in computed tomography applications.^[13] Materials with high atomic numbers and high density are important for detector efficiency. The materials shown in Table 1 have comparable effective densities. Both energy resolution and spatial resolution depend on the size of the signal generated with each detected event.^[14,15] Studies continue to get good crystals with different materials for obtaining of an image with the best quality.

Scintillation Crystal Materials

Research and development of new scintillator materials are mainly triggered by the growing needs of modern medical imaging and high energy physics.^[16] The first and most common crystal which was introduced in 1948 was thallium activated sodium iodide (NaI: Tl).^[17] NaI: Tl is a crystal with reasonable price, a proper luminance efficiency and an acceptable energy range, which it makes a common crystal for use in most nuclear medicine imaging equipment. Studies continue to get a good image quality for an accurate diagnosis.^[18] NaI: Tl properties include: The density of 3.47 g/cm³, a decay time of 230 ns and an energy resolution of 7.2 [Table 1].

Derenzo *et al.* (1990) compared NaI: Tl and BGO [Table 1] and found that later is more sensitive mainly due to its higher density. BGO with a density of 7.13 g/cm³, proper absorption of γ -rays, decay time of 300 ns and an energy resolution of 12 was proposed as a proper candidate.^[19,20] Chewpraditkul *et al.* (2009) compared voltage of 662 kilo electron volte in terms of energy

resolution in lutetium-yttrium oxyorthosilicate, cesium activated yttrium aluminum garnet (YAG: Ce) and lutetium aluminum garnet activated by cerium (chemical formula Lu₃Al₅O₁₂), (LuAG: Ce). YAG: Ce is a crystal's material with high-speed oxidation and its effects on atomic number and density. YAG: Ce has a density 4.55 g/cm³, decay time of 70 ns and energy resolution 7.2.^[16,21] LuAG: Ce has energy resolution of 6.7 and 70 ns decay time is better than BGO.^[22] As well as LuAG: Ce has better detection rate than YAG: Ce because of higher density (6.76 g/cm³) and atomic number (58.9).^[16]

Another crystal is cesium activated yttrium aluminum YAP: Ce has high density of 5.37 g/cm³ and decay time of 25 ns is a good time. Energy resolution (6.7) YAP crystal is better than YAG.^[23] Figure 1 shows a diagram of YAG energy resolution.

Crystal, Mixed Rare-Earth Silicate

These are two different types of new crystals with suitable characteristics in nuclear medicine; CRY018 and CRY019. CRY018 crystal has a density of 4.5 g/cm³, decay time of 45 ns and detection of 425 nm wavelength. CRY018 scintillation detectors are intended and preferred for use in electron microscopy, β - and X-ray counting, as well as for electron and X-ray imaging screens.^[24] CRY019 crystal has density of 7.4 g/cm³, 46 ns decay time and detection of 4.2 nm wavelength and preferably used for γ -ray detectors (positron emission tomography and SPECT system) and high spatial resolution imaging screens for X-ray, γ - and β -rays.^[25]

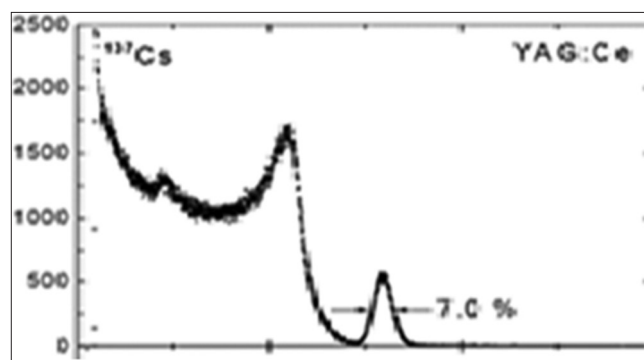


Figure 1: ^{99m}Tc spectrum from cesium activated yttrium aluminum garnet detector^[16]

Table 1: Comparison of the characteristics of nuclear medicine used - detectors in different case of studies

	NaI:Tl	BGO	YAG:Ce	YAP:Ce	CRY019	LuAG:Ce	CRY018	CZT	LaBr ₃
Density (g/cm ³)	3.67	7.13	4.55	5.37	7.4	6.76	4.50	5.78	5.08
Light output (%NaI:Tl)	100	15-20	40	60	40-75	20	80	-	160
Decay time (ns)	230	300	70	25	46	70	45	1	26
Energy resolution (%at661 keV)	7.2	12	7.2	6.7	8.5	6.7	7	0.5	2.7

NaI:Tl: Thallium-activated sodium iodide; BGO: Bismuth germinate; YAG:Ce: Cesium activated yttrium aluminum garnet; LuAG:Ce: Lutetium aluminum garnet activated by cerium; CZT: Cadmium zinc telluride; LaBr₃: Lanthanum bromide; ns: Nano second

Development of Crystal

Mirela angela *et al.* (2011) evaluated cerium-activated lanthanum bromide (LaBr₃) and LaCl₃ as new nuclear medicine detectors, in terms of energy resolution, processing speed of light (decay time), the high temperature stability, high γ -ray detection efficiency and crystal size. The LaBr₃ was used in *in vivo* for administration of I-131 in the thyroid to obtain acceptable results and consequently was enunciated as appropriate detector. The properties that make the LaBr₃:Ce scintillator detector attractive for different applications based on γ -ray spectrometry are very good energy resolution, very fast light output decay, enabling high count rate applications, high temperature stability, high gamma detection efficiency, operation at room temperature, promising technology for manufacturing crystal at larger sizes.^[26] LaBr₃ is good a crystal material and has an excellent energy resolution and short decay time (16 ns) and the best gamma radiation detection rate. The crystal shows excellent energy resolution values good radiation absorption properties and speed.^[22,27-30] Figure 2 shows a comparison of LaBr₃ and NaI: Tl.

The most recent introduction crystal is cadmium zinc telluride (CZT) with the ability in different energies X-ray photon detection.^[31,32] CZT is grown as a single crystal at a temperature of around 110°C in a hermetically sealed container to prevent chemical contamination. High effective atomic number (Z_{eff} ~50) gives it high stopping power for typical energies of interest in SPECT. The spatial resolution of today's CZT detectors is 2.5 mm independent of energy more better than the 4.0 mm typically achieved with NaI at ^{99m}Tc energies (140 keV), and much better again than the resolution obtained with ²⁰¹Tl (5–6 mm). One of the most striking things about the CZT detector is its size. Specifically, in an Anger camera it is difficult to resolve the position of events beyond the center of the last (edge) PMT. This results in a significant dead space all around the detector being direct-conversion based, has no such dead space. CZT detectors have reached a level of maturity that permits their use in

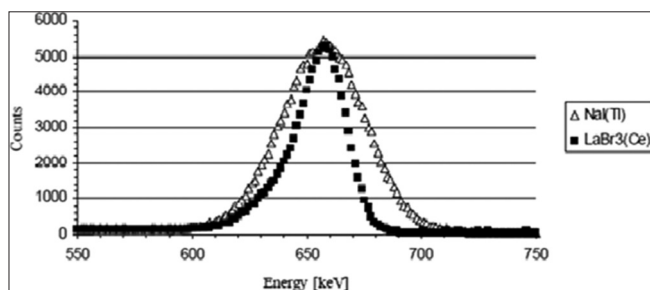


Figure 2: Illustration of Cs-137 spectrum from lanthanum bromide and NaI detector^[7]

specific applications that take advantage of their unique properties: High spatial resolution, low dead space, and excellent energy resolution.^[32,33]

Cadmium zinc telluride has relatively high density and atomic number that puts in suitable radiation energy range for diagnostic imaging. Other advantag of CZT are very low decay time.^[3,33,34] In 2013 Jenny Oddstig studied CZT with NaI: Tl detector in the field of cardiac imaging using simulation system Simind and get suitable results and images.^[35] Figure 3 shows a graph comparing the peak energy of NaI: Tl and CZT.

Conclusion

Single photon emission computed tomography detector has more important effect to get a good image. Utilization of a suitable detector is necessary in obtaining high-quality images for better diagnosis. Many crystals have been evaluated in preclinical studies, and some of them have advantage in comparison with others due to chemical structure characteristics. For example, BGO is a crystal with the highest density and YAP: Ce has high density, and decay time of 25 ns is a good time, expressed a suitable detector than YAG: Ce. CRY018 and CRY019 crystals have high density and suitable decay time, but they haven't good energy resolution. Moreover, LaBr₃ is one of the most excellent detectors in nuclear medicine, this detector has high energy resolution that good proportionality characteristic and also CZT is a detector with good density, high energy resolution and lowest decay time in comparison with other detectors. Thus, until now, collected data from studies demonstrated that CZT can be the best detector. Research and studies continue about advantages and disadvantages of detectors, and also the best application of them in diagnostic imaging in the future.

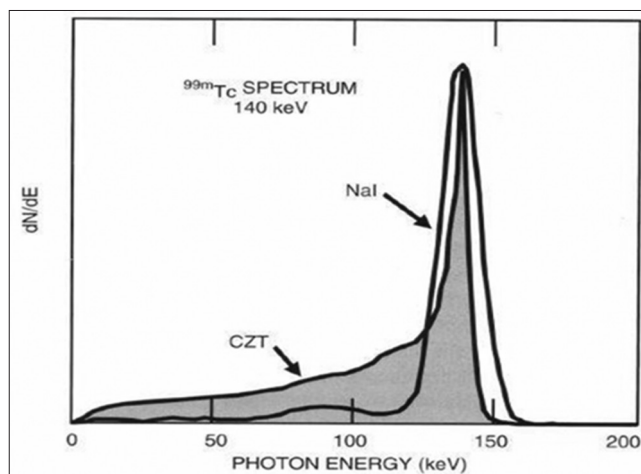


Figure 3: Illustration of ^{99m}Tc spectrum from cadmium zinc telluride and thallium activated sodium iodide detector^[35]

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