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Development of a novel gamma probe for detecting radiation direction

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Abstract: Spatial localization of radioactive sources is currently a main issue interesting different fields, including nuclear industry, homeland security as well as medical imaging. It is currently achieved using different systems, but the development of technologies for detecting and characterizing radiation is becoming important especially in medical imaging. In this latter field, radiation detection probes have long been used to guide surgery, thanks to their ability to localize and quantify radiopharmaceutical uptake even deep in tissue. Radiolabelled colloid is injected into, or near to, the tumor and the surgeon uses a hand-held radiation detector, the gamma probe, to identify lymph nodes with radiopharmaceutical uptkake.

The present work refers to a novel scintigraphic goniometric probe to identify gamma radiation and its direction. The probe incorporates several scintillation crystals joined together in a particular configuration to provide data related to the position of a gamma source. The main technical

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characteristics of the gamma locator prototype, i.e. sensitivity, spatial resolution and detection efficiency, are investigated. Moreover, the development of a specific procedure applied to the images permits to retrieve the source position with high precision with respect to the currently used gamma probes. The presented device shows a high sensitivity and efficiency to identify gamma radiation taking a short time (from 30 to 60 s). Even though it was designed for applications in radio-guided surgery, it could be used for other purposes, as for example homeland security.

Keywords: Intra-operative probes; Gamma camera, SPECT, PET PET/CT, coronary CT angiography (CTA); Medical-image reconstruction methods and algorithms, computer-aided software

Contents

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1 Introduction

The detection of radioactivity and its localization has become a main issue interesting nuclear industry (nuclear power plants dismantling, radioactive waste management, radiation protection, etc.), environmental services, public health, homeland security as well as applications in medical imaging diagnosis and treatment [1]. Instruments dedicated to spatial radioactivity localization can be divided into two main categories: imaging detectors and gamma probes. On one hand, position sensitive imaging detectors provide information about radioactive sources in a given field of view by measuring the spatial distribution and the energy spectrum of γ-ray emissions. Usually, these systems are designed to be used in a fixed position for monitoring a continuous flow of people, vehicles, luggage, packages and cargo. On the other hand, collimated gamma probes are hand-held devices which are used to detect and/or identify a radioactive source usually with a greater sensitivity.

In the field of imaging detection, several devices have been proposed that essentially differ for the employed systems and for the image reconstruction methods. Among these systems, some instruments are based on Compton imaging: the position of a radioactive source is identified by reconstructing the direction of incident photons that interact via Compton scattering [2, 3]. The Compton scattering imaging is a technique widely used in many fields such as nuclear medicine, astrophysics and recently counterterrorism. A classical detector technology that exploits the physics of Compton scatter is a parallel-plate pixellated semiconductor CdZnTe detector, which have to be depth-sensitive for employing Compton imaging [4]. The main limitations of this system still remain the finite size of anode pixels which leads to uncertainty in the cone axis, thus in lateral interaction position, and the electronic noise which leads to uncertainty in interaction depth and deposited energy, thus in the cone angle. As alternative to Compton imaging, another approach for the detecting radiation direction is the use of collimated detectors. For homeland security purposes, the spatial localization of radioactive sources is currently performed by using detectors based on coded apertures masks. Coded masks are spatial configurations of shielding material (e.g., small squares formed from plates of lead or tungsten) placed in front of a detector array to modulate the radiation distribution. Conceptually, a coded mask system would provide the capability of imaging the radiation source location in 5-15 minutes. Even thought coded masks are currently used for security applications, they have not been successfully migrated to medicine, because medical images behave as distributed sources (near-to-source imaging), and coded mask imaging is optimal when applied to images that behave as point sources [5]. Therefore, for medical imaging, coded masks for γ-ray detection are not used as three-dimensional imaging performed by the use of gamma camera is still substantially superior.

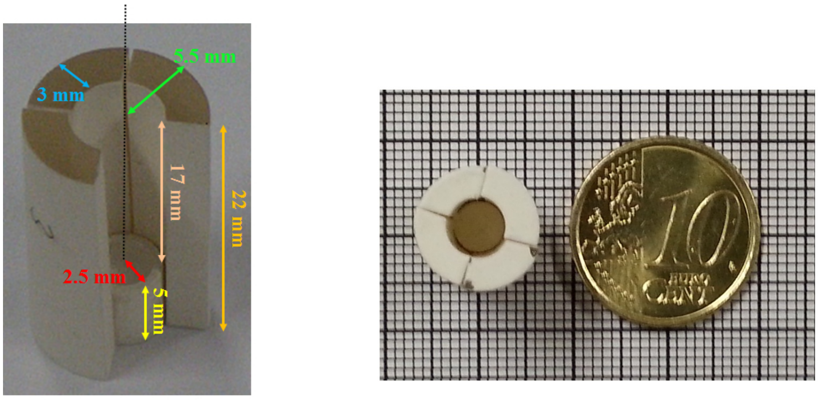
Detection systems based on gamma probes were developed in radio-guided surgery to locate lymph nodes by their radioactivity after the interstitial injection of a radionuclide. The surgical management of cancer patients based on radio-guided surgery actually provides real-time information on the location and extent of disease, as well as on the assessment of resection margins. Therefore, it makes the surgeon able to minimize the surgical invasiveness of many diagnostic and therapeutic procedures, while still maintaining maximum benefit to the cancer patient [6]. Currently, the most frequent clinical application of radio-guided surgery is the sentinel lymph node (SLN) biopsy, with the aim to find those lymph nodes which directly drain a tumor site and to remove them for pathological examination [7]. Gamma probe detection systems used for radio-guided sentinel lymph node procedures require exceptional spatial resolution in order to allow for more precise localization of small lymph node candidates. Moreover, they also require high sensitivity in order to guide the surgeon to the specific sites of disease while rapidly searching over a relatively large surgical field. Over the last decade, several gamma probes based on different detector technologies have been developed, some of which are now commercially available. Scintillation-based cameras use various scintillators and photodetectors to position gamma events. These cameras have good detection efficiency, relatively low cost, but sub-optimal energy resolution. In contrast, semiconductor cameras have higher energy resolution and are more compact but they have the disadvantage of lower detection efficiency [8]. Anyhow, the presence of a passive collimation shielding for the appropriate selection of the gamma radiation and for preventing radiation from unintended locations (i.e., scatter) is a common feature to these systems which still limits their detection efficiency. Therefore, on one hand, even though position sensitive imaging detectors are currently used for detecting radiation direction, they are severely limited in sensitivity, which implies a high time-to-image. On the other hand, the main limitation of currently used gamma probes is the low efficiency and the limited Field of View (FOV) due to the presence of the collimation shield.

In order to overcome these limitations, a portable hot spot radiation imaging gamma probe is proposed with the aim to precisely and rapidly identify gamma radiation and its direction. It is based on the replacement of the passive collimator with and active collimation shield able to provide indication on the radiation direction with high efficiency and wide FOV.

2 Materials and methods

The presented device, developed for nuclear medicine application, is a scintigraphic probe which consists of different scintillation crystal elements joined together in a particular configuration for providing the direction of a radioactive source. The probe comprises an external scintigraphic detecting element, i.e. a tubular body, provided with a proximal opening and divided in four sectors, each one constituted by a Lutetium Yttrium Orthosilicate (LYSO) scintillation crystal (figure 1).

It has a whole diameter of 1.1 cm with a thickness of 3 mm and a height of 22 mm. This external component also acts as active shield of the lateral surface of a Sodium-doped Caesium



(a) Side view.

(b) Top view.

Figure 1. Configuration of the scintigraphic probe.

Iodide (CsI(Na)) scintillation crystal, 5 mm ⌀ and 5 mm thick, housed inside the tubular body [9].

This configuration will make the probe able to directly provide to the operator indications related not only to the position, but even to the direction to be followed towards the radioactive source. The active shield has to be constituted by high-density crystals to make the prototype compact and to ensure the adequate shielding of the central detector. Therefore, one of the best scintillation materials to realize the mentioned active shield is the LYSO ($Lu_{2(1-x)}Y_{2x}SiO_5$), which has a density of 7.10 g/cm^3 and a light emitting efficiency of 32000 photons/MeV, suitable for the absorption of gamma radiation emitted by the radioisotopes currently used in clinical practice, i.e. ^{99m}Tc, ^{131}I, ^{111}In. The central CsI(Na) scintillation crystal has a higher light yield (38000 photons/MeV) respect to the LYSO ones, so that the amplitude response generated by this detector will be distinct from that of the active shield. This prototype was designed for clinical scintigraphic examinations, as for example the localization of the sentinel lymph node, using the technique of the local administration of a radiopharmaceutical near the tumour. The height of 22 mm fits the typical size of commercial probes (2 to 3 cm), to enable the subcutaneous use. The thickness of 3 mm is necessary to ensure the adequate shielding of the central crystal, by attenuating from 95% to 92% of photons at 140 keV (^{99m}Tc emission) that pass through it transversely. Even thought these dimensions have been designed for applications in radio-guided surgery, for detecting photons emitted by ^{99m}Tc, they could be modified in order to use the device for other applications.

In order to test the working principles of the device, it was optically coupled to a Multi Anode Photo-Multiplier Tubes (MA-PMT) Hamamatsu H10966A-100. It has a SuperBiAlkali photocathode (SBA), in 8 × 8 array configuration (64 anodes), with an active area of 49 × 49 mm^2 and high quantum efficiency (38.7% at 380 nm) [10]. A 64 independent channels electronics read-out is used, which allows to collect the charge coming from each anode of MA-PMT for each scintillation event (list mode procedure). All the anodes are independently read and digitalized (with 14 bit ADCs) with a maximum sampling frequency of 250 ksample/second [11].

As the probe dimensions are limited, only the four central anodes of the MA-PMT are used for the data acquisition. It is important to specify that the described read-out electronics was non specifically developed for the presented probe, but it was only used to preliminary evaluate the probe characteristics and to validate its working principle. The MA-PMT allows to perform imaging through the use of Anger logic, thus identifying each crystal responses. Moreover, the system provides the pulse height distributions corresponding to each scintillation crystal in order to retrieve, through a proper selection in energy window, the number of events within the full energy peak. In other word, this system is able to determine the counts recorded by each crystal and the corresponding deposited energy. The main technical characteristics of the gamma locator prototype are also determined. In particular sensitivity, spatial resolution and detection efficiency are investigated operating a transverse scanning of an acrylic breasts phantom containing a different point sources (^{57}Co or ^{137}Cs) in front of the device. The breast phantom is used to simulate a real situation where the probe is used for the detection of SLN and scattering occurs. The overall sensitivity (efficiency) is evaluated by detecting the count rate (photons detected) per unit of activity (photons emitted) and it is determined at the tip of the probe profile. Spatial resolution (radial sensitivity distribution) is described by the width of the resultant measurement cone out of which radiation is being detected at a defined distance. It is evaluated at two different energies, 122 keV and 662 keV. Moreover, the working principle of the prototype regarding the determination of source position is investigated. In order to verify the effectiveness of the technique, experimental measurements are performed by moving in steps of 15 degrees a collimated ^{99m}Tc source (0.5 mCi activity), placed at fixed distance (9 cm), around longitudinal and transversal axis of the device.

A specific procedure applied to the acquired images permits to retrieve the position of the source, providing an indication on radiation direction through the calculation of the angle ϕ_{calc}. To each scintillation crystal an angle ϕ_i is assigned. The procedure is based on a simple calculation of the weighted counts average associated to the three crystals which register the higher amount of counts.

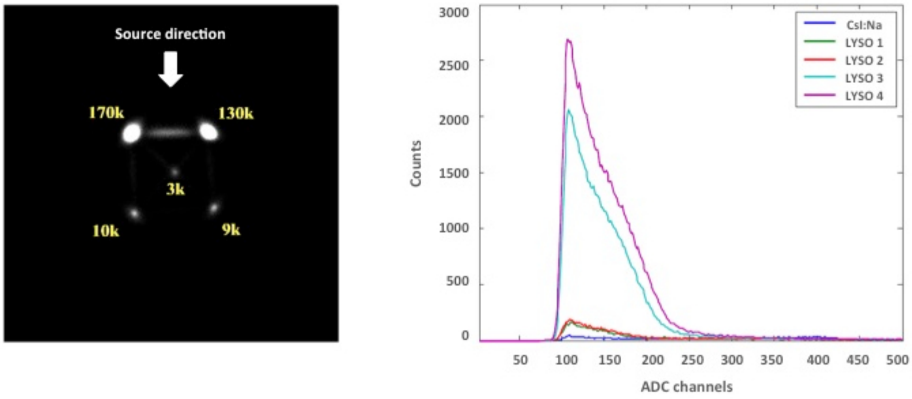
$$\phi_{\text{calc}} = \frac{\sum_{i=1}^{3} \phi_i \cdot c_i}{\sum_{i=1}^{3} c_i}, \qquad \sigma_{\phi_{\text{calc}}} = \sqrt{\sum_{i \neq j \neq k = 1}^{3} \left(\left[\frac{(\phi_i - \phi_j) \cdot c_j + (\phi_i - \phi_k) \cdot c_k}{(c_i + c_j + c_k)^2} \right] \cdot \sigma_i \right)^2} \tag{2.1}$$

where c_i represent the events recorded by each single crystal, calculated as integral of photoelectric peak derived from the corresponding pulse height distributions. $\sigma_{\phi_{\text{calc}}}$ represents the statistical error associated to the retrieved angle, where $\sigma_i = \sqrt{c_i}$. It is expected that the radiation source will be identified and localized in few steps. Firstly, the detector is positioned in a generic point of the observation field; secondly, a scout acquisition is performed in order to identify the dial from which the radiation originates and the probe approaches the source based on the counts collected by the external detectors. Finally, the localization of the radioactive source is performed on the basis of central detector counts as, when the source is in front of the probe head, the central crystal counts are strongly increased allowing the accurate localization of the source.

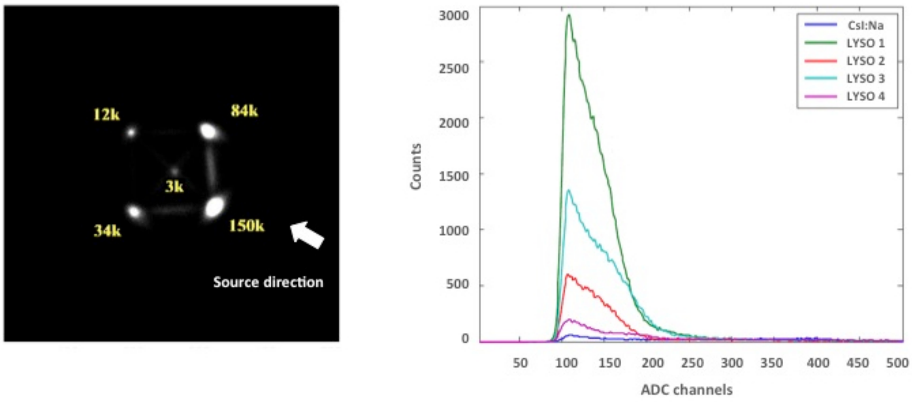
3 Results and discussion

For sake of simplicity, only few images acquired with a collimated ^{99m}Tc source at different angles respect to the longitudinal axis of the device will be presented in the following.

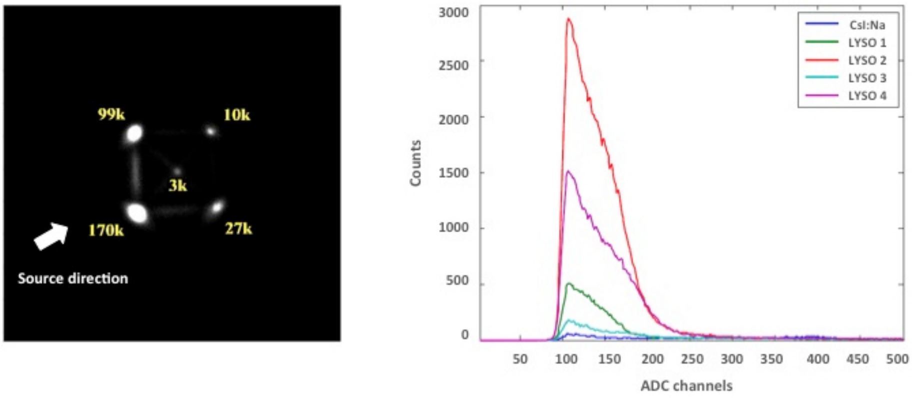
Figure 2 shows an example of the system ability in performing imaging for identifying each crystal responses. Moreover, for each image spectrometric information, i.e. the pulse height distributions corresponding to each scintillation crystal, are reported. The images in figure 2 demonstrate



(a) 0 degree.



(b) 120 degree.



(c) 240 degree.

Figure 2. Images acquired with a collimated ^{99m}Tc source, placed at fixed distance, at different angles (indicated by an arrow in the figures) respect to the longitudinal axis of the device. The reported pulse height distributions correspond to each scintillation crystal.

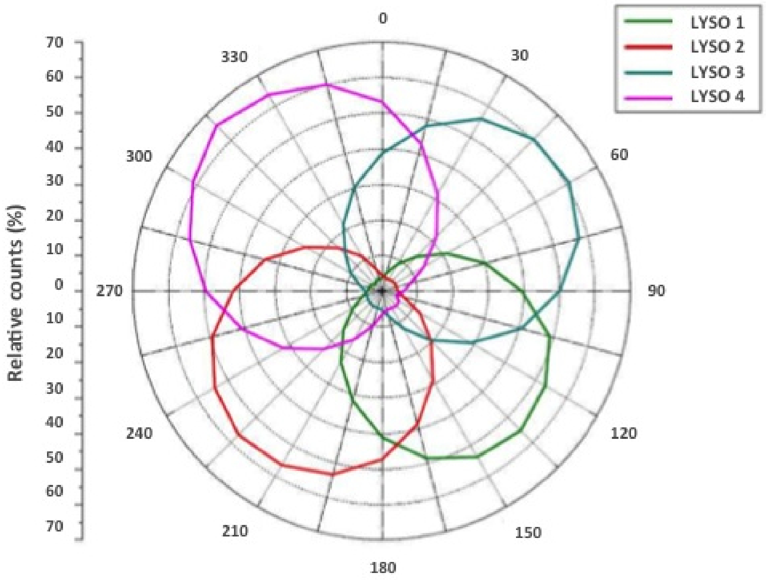


Figure 3. Angular distribution of counts registered by each external crystal.

that the device is highly sensitive to the directional change of the radioactive source, while the associated spectrometric information are fundamental for categorizing the radioactive source and for determining the counts recorded by each crystal. A way to represents the crystals counts is the angular distribution of counts registered by each external crystal (figure 3).

This distribution shows that each crystal is sensitive over a wide angular range. Slight differences in the amplitude of the angular distribution are due to small differences in the LYSO scintillation crystals sizes. By applying the formulas 2.1, our tests clearly designate that a very high precision in determining the emission direction can be obtained, as the device is able to measure the gamma ray incident direction with an error less than 7°. The statistical error is less than 1° for $100k$ counts, anyhow staying less than 3° when counts become of the order of 1000.

Apart from requesting a separate evaluation of the scintillation for each crystal, the source direction can be simply and precisely determined. Moreover, as the curves of the angular distribution mutually intersect, the data related to the source localization can be retrieved without requesting a high number of scintillation crystals which would require more complicated, bulkier and heavier photo-detection systems.

Figures 4 shows the sensitivity curves for the overall probe at ^{57}Co and at ^{137}Cs respectively. The overall detection efficiency at 122 keV, evaluated at the center of the probe, was 1.7×10^{-2}. The spatial resolution, calculated as FWHM of counting rate distribution for the central element as function of source position, was about 7 mm. The overall sensitivity curve at ^{57}Co shows that the system covers a wide field of view, about 30 cm, when the source is almost in contact with the top side of the detector (5 mm source-to-detector distance). The system sensitivity was 17 counts/s/kBq, while the central crystal sensitivity is a factor of 10 less. Even though the probe dimensions were designed for low energy application (140 keV photons), the prototype works even for higher energy (662 keV photon of ^{137}Cs). In this case, the overall sensitivity curve shows that the system covers

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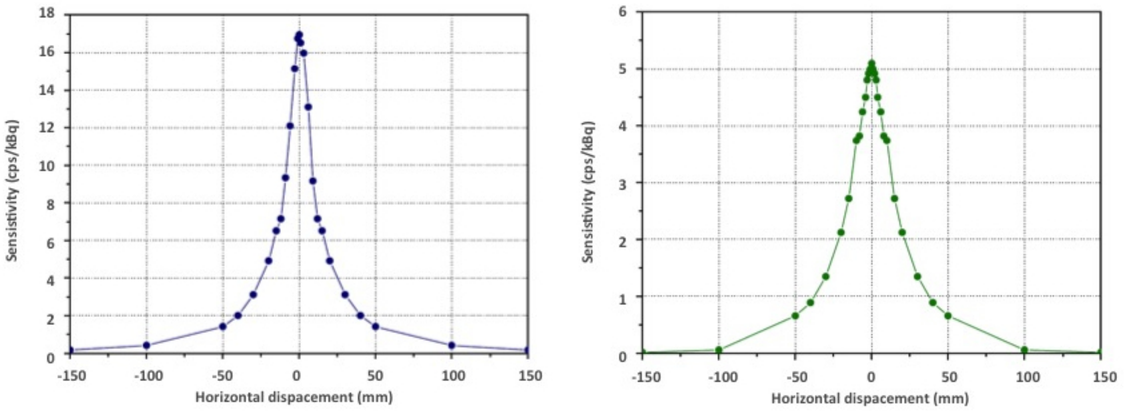

(a) Overall probe sensitivity curve at ^{57}Co.

(b) Overall probe sensitivity curve at ^{137}Cs.

Figure 4. Sensitivity curves at ^{57}Co and at ^{137}Cs.

again a wide field of view, about 20 cm. The system sensitivity was 5 counts/s/kBq, less than for ^{57}Co but still appreciable. The spatial resolution, was about 19 mm, while the overall detection efficiency at 662 keV, evaluated at the centre of the probe, was 0.1×10^{-2}.

4 Conclusion

Our target was to evaluate the performance parameters of the proposed prototype and to optimize its design for scintigraphic application in radio-guided surgery. The main advantage of the presented scintigraphic goniometric probe lies in the possibility of a quick identification of the radiant source in a scintigraphic examination, by using a simple and small size instrument. The presented device showed a high sensitivity and efficiency to identify gamma radiation taking a short time (few minutes per kBq at the distance of 1 m). In comparison with existing systems, which do not provide information about the radiation direction, the presented apparatus allows to obtain directional information with similar counting rates (about 1 kHz). The so-constructed probe offers a high sensibility and efficiency, at least 100 times higher than imaging systems such as small gamma chambers for scintigraphy. Moreover, the entire prototype presents compact overall dimensions, making it suitable for portable and hand held devices. These characteristics makes it suitable for the localization of tumoral tissues or lesions showing a high specificity to the radiomedicine, in particular for the applications of radio-guided surgery.

Obviously, alternative probe uses are possible, in order to identify any radioactive source, for example with the purpose of higher safety in sensible areas such as the airport, in thermonuclear plants or in sites with radioactive contamination risk, even to detect radioactive waste disposed in a not correct or improper way. In conclusion, the presented probe could constitute a direction guiding system by integrating it with a manoeuvrable robot for rapid detection of radioactive sources over a wide area or by a connection to a telecamera in order to visually and dynamically localize a radioactive object (a person, a moving suitcase).

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