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Investigation of luminescent properties of LSO:Ce, LYSO:Ce and GSO:Ce crystal scintillators under low-energy γ-ray excitation used in nuclear imaging

Ioannis Valais[a,b], Stratos David[b], Christos Michail[b], Anastasios Konstantinidis[b], Ioannis Kandarakis[b], George S. Panayiotakis[a,*]

[a]*Department of Medical Physics, Medical School, University of Patras, 265 00 Patras, Greece*
[b]*Department of Medical Instruments Technology, Technological Educational Institution of Athens, Ag. Spyridonos, Aigaleo, 122 10 Athens, Greece*

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Abstract

LSO:Ce, LYSO:Ce and GSO:Ce single-crystal scintillator light emission characteristics were studied in the low γ-ray energy range (^{99m}Tc source) used in nuclear medical imaging. The absolute luminescence efficiency and the optical emission spectrum of the three scintillators were measured, under γ-ray excitation using an integration sphere coupled to a photomultiplier and an optical spectrometer, respectively. Spectral compatibility of all scintillators to optical sensors was also estimated. The absolute luminescence efficiency of all crystals was found adequately high (8.7 μW m^{-2}/μGy s^{-1} for GSO:Ce, 15.3 μW m^{-2}/μGy s^{-1} for LYSO:Ce and 20.0 μW m^{-2}/μGy s^{-1} for LSO:Ce). Their emission spectra were found compatible (57–94%) to currently employed optical photon detectors.

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Keywords: X-ray imaging; LSO:Ce radiation detectors; Luminescence efficiency

1. Introduction

Inorganic scintillators coupled to optical detectors are employed in most medical imaging modalities, e.g., PET, SPECT, X-ray CT, planar scintigraphy, projection radiography, etc. [1,2]. Cerium-doped scintillators have a much faster response than most currently employed materials (e.g., NaI:Tl, CsI:Tl or Gd_2O_2S:Pr.) [3] with decay time of a few nanoseconds (⩽30 ns) [4]. Ce^{3+} doped lutetium oxyorthosilicate (Lu_2SiO_5:Ce or LSO:Ce) scintillator shows fast response (40 ns) and high light yield (⩾26,000 photons/MeV). However, one factor worth considering is its high price in relation to some commonly employed scintillators [5]. Gadolinium oxyorthosilicate (Gd_2SiO_5:Ce or GSO:Ce) crystal exhibits fast response (60 ns) and it is of low cost as compared to LSO [6]. Cerium doped lutetium yttrium oxyorthosilicate, $(Lu,Y)_2SiO_5$:Ce or LYSO:Ce, is a mixed LSO/YSO (5–10%Y) non-hygroscopic crystal with high density (7.1 g/cm^3), high light output (⩾30,000 photons/MeV), good energy resolution (~10%) and short decay time (40 ns) [7,8].

The aim of the present work was to evaluate the light emission efficiency of LSO:Ce, LYSO:Ce and GSO:Ce single-crystal scintillators under ^{99m}Tc (140 keV) γ-ray excitation often used in nuclear imaging.

2. Materials and methods

LSO:Ce, LYSO:Ce (supplied by Photonic Materials Ltd., Scotland, UK) and GSO:Ce (supplied by Hitachi Chemical Co. Ltd. Japan) scintillators with dimensions 10 × 10 × 10 mm^3 were excited by 140 keV γ-rays emitted by ^{99m}Tc sources of varying activity (Fig. 1). A specific lead vial container was used for the accommodation of the ^{99m}Tc sources. The ^{99m}Tc sources were positioned at a distance $L = 10$ cm from the top surface of the crystals in order to establish a uniform irradiation. The γ-ray

*Corresponding author. Tel./fax: +302610996113.
E-mail address: panayiot@upatras.gr (G.S. Panayiotakis).

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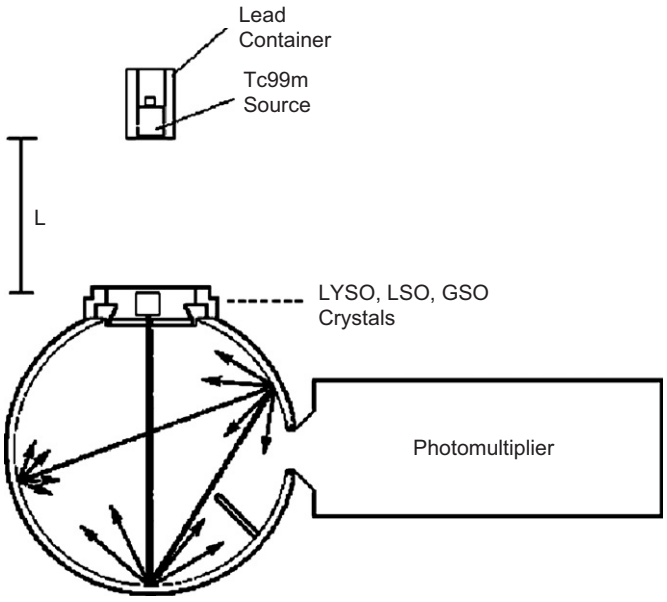

Fig. 1. Experimental setup used for measuring the light energy flux emerging from the γ-ray excited scintillator using an integration sphere.

radioactivity of the source was measured using a well type Biodex Atomlab 100 dose calibrator (Biodex Medical Systems Inc., NY). From these data, the air kerma at the surface of the crystal was calculated for each ^{99m}Tc source. The light energy flux emitted by the excited scintillators was measured by a light integration sphere (Oriel 70451) coupled to a photomultiplier (EMI 9798B) [9,10].

The absolute luminescence efficiency η_A was determined by these measurements according to the relation [11]

$$\eta_A = \frac{\dot{\Psi}_\lambda}{\dot{K}_{air}} \quad (1)$$

where $\dot{\Psi}_\lambda$ is the light energy flux, emitted by the scintillator and $\dot{K}_{air}$ is the air KERMA. The optical emission spectrum of LSO:Ce, LYSO:Ce and GSO:Ce was measured, under γ-ray excitation using an optical spectrometer (Ocean Optics Inc., S2000). Optical spectrum data were used to determine the spectral compatibility of the three scintillators to the spectral sensitivities of various optical photon detectors incorporated in detectors of nuclear medicine imaging systems. Spectral compatibility may be estimated by the spectral matching factor (SMF), which is defined by the ratio [12]

$$SMF = \frac{\int S_P(\lambda) S_D(\lambda)\,\mathrm{d}\lambda}{\int S_P(\lambda)\,\mathrm{d}\lambda} \quad (2)$$

where $S_P(\lambda)$ is the spectrum of the light emitted by the scintillator and $S_D(\lambda)$ is the spectral sensitivity of the optical photon detectors coupled to the scintillator. The optical photon detectors examined in our study were: (i) GaAs photocathode, (ii) extended S20 EMI photocathode with quartz window, (iii) avalance photodiode (APD), Hamamatsu S5343, (iv) a-Si:H/108 H amorphous silicon photodiode, corresponding to intrinsic layer thickness of 800 nm (108 H), (v) H8500 Hamamatsu Position Sensitive Photomultiplier (PSPMT) and (vi) CCD S100AB SITe® (Table 1). The efficiency corresponding to a specific scintillator–optical photon detector combination has been defined [12] as the effective efficiency (η_{eff}), given as the absolute luminescence efficiency (η_A) multiplied by the corresponding SMF,

$$\eta_{eff} = \eta_A \times SMF. \quad (3)$$

Table 1
Spectral matching factors of LSO:Ce, LYSO:Ce and GSO:Ce with optical detectors

Optical detectors	LSO:Ce	LYSO:Ce	GSO:Ce
GaAs photocathode	0.93	0.93	0.93
Extended S-20 photocathode	0.94	0.94	0.90
APD Hamamatsu S5343	0.63	0.60	0.76
a-Si:H 108H photodiode	0.58	0.57	0.70
PSPMT Hamamatsu 8500	0.85	0.86	0.71
CCD S100AB SITe®	0.88	0.88	0.88

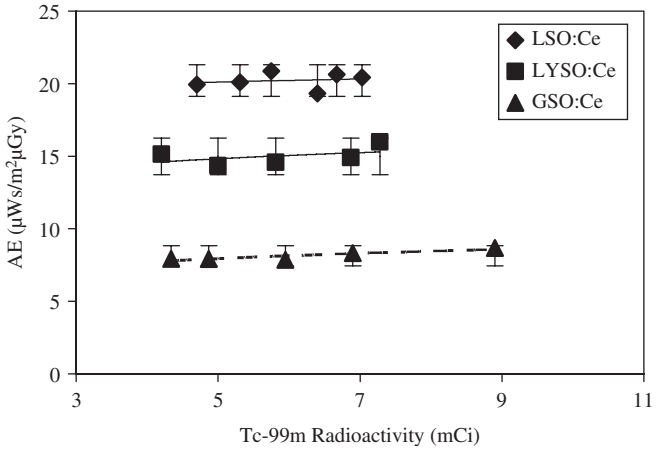

Fig. 2. Variation of the absolute luminescence efficiency (AE) of LSO:Ce, LYSO:Ce and GSO:Ce crystals with radioactivity for 140 keV γ-rays. AE units: $\mu W\,m^{-2}/\mu Gy\,s^{-1}$. Points: measured data, line: fitted curve.

3. Results and discussion

Fig. 2 shows the variation of the absolute luminescence efficiency of LSO:Ce, LYSO:Ce and GSO:Ce single-crystal scintillators with increasing radioactivity (mCi) at 140 keV (^{99m}Tc). Absolute efficiency is expressed in units of ($\mu W\,m^{-2}/\mu Gy\,s^{-1}$).

The fitted curve crossing through the measured data points is an almost straight line, which denotes that absolute luminescence efficiency is almost independent from the radioactivity of the source and depends mainly on the energy of the γ-photons incident on the scintillator.

Fig. 3 shows the variation of the voltage readout from the photomultiplier with the radioactivity of the ^{99m}Tc sources used. The measured crystals show a linear response with increasing activity with LSO:Ce exhibiting higher slope than the others.

Fig. 4 illustrates the normalized light emission spectrum of GSO:Ce, LYSO:Ce and LSO:Ce single-crystal scintillators under γ-ray excitation. Measurements were conducted at room temperature. Maximum spectral values were found within the spectral range 410–435 nm, depending on the scintillator crystal. Each spectrum covered a wide spectral range from approximately 380 to about 550 nm, extending from the blue region into the green spectral region.

Table 1 summarizes the calculated SMFs of LSO:Ce, LYSO:Ce and GSO:Ce scintillators with six optical photon detectors, using relation (2). The spectral sensitivities of the optical photon detectors (S_D), in Table 1, were taken from manufacturer's datasheets. Since LSO:Ce and LYSO:Ce have the same peak in their spectral response (Fig. 4), it is expected to have identical matching factor values.

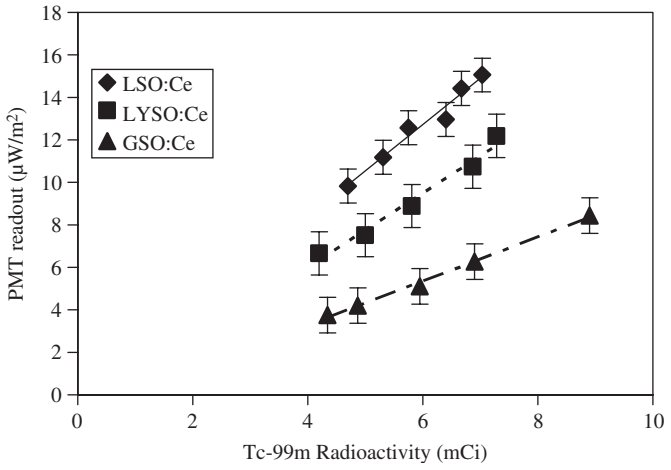

Fig. 3. Variation of the photomultiplier voltage output with radioactivity for 140 keV γ-rays.

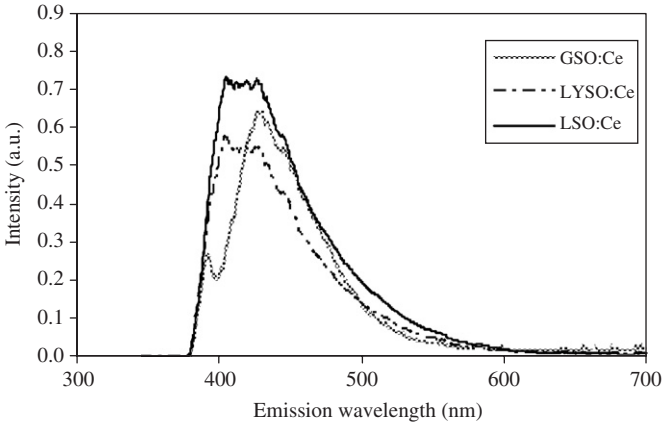

Fig. 4. Normalised spectral response of GSO:Ce, LYSO:Ce and LSO:Ce single crystal scintillators under γ-ray excitation. Line: fitted curve.

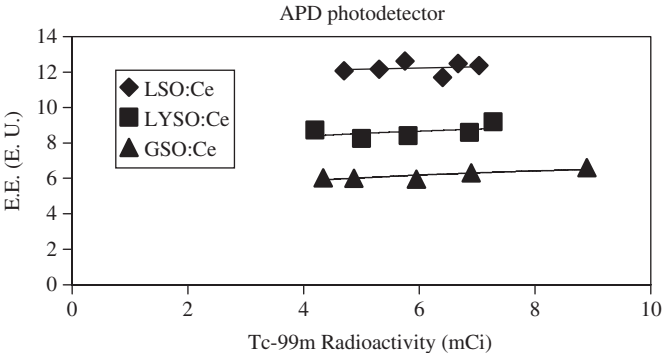

Fig. 5. The effective efficiency of LSO:Ce, LYSO:Ce and GSO:Ce single crystal scintillators, when combined with APD photodetector.

Although in Table 1, for the same optical detector, a slight variation between these two scintillators in the matching factor values is noted probably due to different intensities and acreages of the two spectra. All three scintillators had the same matching factor value when combined with GaAs photocathode and CCD. The highest spectral compatibility for GSO:Ce was found when combined with GaAs photocathode (matching factor: 0.93) and for LSO:Ce and LYSO:Ce was found when combined with extended S-20 photocathode. High compatibility was also exhibited with two optical detectors of interest in γ-ray imaging, namely the APD photodiode and the PSPMT photomultiplier. Considering the matching factor values in Table 1, GSO:Ce had better compatibility than LSO:Ce and LYSO:Ce when combined with APD. On the contrary, LSO:Ce and LYSO:Ce had better compatibility than GSO:Ce when combined to PSPMT.

Fig. 5 shows the effective efficiency (EE) of LSO:Ce, LYSO:Ce and GSO:Ce when combined with APD photodetector. As one can observe in Fig. 5 the effective efficiency curves of the three scintillators are similar to the corresponding absolute efficiency curves, only shifted lower in Y-axis. This was expected since η_{eff} is calculated using relation (3), and the SMF values in Table 1 are all lower than 1.0. Although GSO:Ce has higher SMF value for the APD photodetector than LSO:Ce and LYSO:Ce (Table 1), the overall efficiency, i.e., the effective efficiency of the two scintillators is better than the efficiency of GSO:Ce for the γ-photon energy examined in this study.

4. Conclusions

The emitted light energy flux of the aforementioned scintillators was found to be a linear function of radioactivity. LSO:Ce exhibited the higher absolute luminescence efficiency than LYSO:Ce and GSO:Ce at 140 keV. This result is not in agreement with the light yield data of LSO and LYSO scintillators published elsewhere, which however corresponded to higher incident photon energies [3]. Emission spectra (380 to about 550 nm), peaking at 440 nm for GSO:Ce and at 420 nm for LYSO:Ce and LSO:Ce were found compatible (57—94%) to optical

photon detectors examined in this study. All crystals were found to have increased performance in the 140 keV (^{99m}Tc) energy employed in nuclear imaging applications.

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