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Abstract: The aim of this study is to evaluate the suitability of crystalline scintillator LaCl₃:Ce for possible use in hybrid medical imaging systems, such as PET/CT and SPECT/CT scanners. For this purpose, a single crystal (10 × 10 × 10 mm³) was irradiated by X-rays within the tube voltage range from 50 to 150 kVp, and the absolute efficiency (AE) was measured experimentally. The energy absorption efficiency (EAE), quantum detection efficiency (QDE), and the spectral compatibility with various optical detectors were also calculated with the use of mathematical formulas. The results were compared with published data for Bi₄Ge₃O₁₂ (BGO), Lu₂SiO₅:Ce (LSO), and CdWO₄ single crystals of equal dimensions, commonly used in medical imaging applications. The luminescence efficiency values of the examined crystal were found to be higher than those of LSO, BGO, and CdWO₄ crystals, within the whole X-ray tube voltage range. In the matter of EAE, LaCl₃:Ce demonstrated reduced performance with respect to LSO and CdWO₄ crystals. The emission spectrum of LaCl₃:Ce was found to be compatible with various types of photocathodes and silicon photomultipliers (SiPMs). Considering these properties, LaCl₃:Ce crystal could be considered suitable for use in hybrid medical imaging systems.

Keywords: scintillators; single crystals; radiation detectors; LaCl₃:Ce

1. Introduction

Scintillators are materials particularly important in medical imaging systems, because their use may reduce the ionizing radiation dose to the patient. Scintillation detectors are usually connected to optical sensors, such as film, photocathodes, photodiodes, CCD, a-Si/TFT, and CMOS [1–4]. The latter setup has been widely employed in several technological fields, from industry up to nuclear physics, but with a prominent application in medical imaging applications such as X-ray imaging, computed tomography (CT), single photon emission computed tomography (SPECT), and positron emission tomography (PET) [4–8]. The sensitivity, which is antagonistic to patient dose, of these systems increases remarkably when more efficient and faster scintillation crystals are utilized [5,8].

Crystal scintillator’s investigation is of major importance in nuclear medicine systems. As an example, crystalline scintillators with halogenated impurities, such as lanthanum chloride (LaCl₃) activated with cerium (Ce), has been widely studied in nuclear medicine applications [9–11] because of its physical properties, such as a density of 3.86 g/cm³ suitable for radiation absorption, a high light output reported from 40,000 photons/MeV to 49,000 photons/MeV, a decay time of 28 ns, and good energy resolution, which depends upon the crystal physical and chemical properties such as size and cerium concentration [10,12–18].
The LaCl$_3$:Ce crystal has a hexagonal symmetry in the UCl$_3$ type lattice in the space group $P6_3/m$ or $C_3h$, with point symmetry $C_3h$ at the lanthanide site. The lanthanide coordination polyhedron consists of nine chloride ligands arranged in a tricapped trigonal prism configuration [15,19]. The lattice constant of the crystal is 0.6196 nm [13]. The concentration of cerium in the crystal has been reported in the literature to be from 0.1% to 30% [11,12,15,20].

Current nuclear medicine instrumentation includes hybrid systems where contemporary imaging systems such as SPECT and PET are combined with X-ray computed tomography scanners (CT) and form hybrid systems such as SPECT/CT and PET/CT. A breakthrough of such a hybrid modality could be the use of the same detector type for CT and SPECT or PET.

Under this consideration, in the current work, the response of a commercially available LaCl$_3$:Ce single crystal scintillator [13] excitation was experimentally examined for X-ray tube voltages in the range from 50 kVp to 150 kVp. The response was examined via (a) the absolute luminescence efficiency ($AE$), describing the light output power per incident exposure, (b) the spectral matching factor ($\alpha_s$) and the overall efficiency ($EE$), investigating the suitability of various photodetectors attached to LaCl$_3$:Ce, and (c) the radiation absorption properties of the crystal. After research into the relevant literature, excitation of LaCl$_3$:Ce crystal with X-rays to investigate some of its properties was carried out in specific energy ranges. The crystal’s emission spectrum, after X-ray excitation produced by X-ray tube at 35 kV with 25 mA, has been studied by Guillot-Noel et al. [15]. This study was supplemented by the usage of LaCl$_3$:Ce crystals of different concentrations of cerium, under the same experimental conditions [12]. The emission spectrum of the crystal was also measured at 30 kV with 25 mA [20]. In order to investigate the crystal suitability, mainly for X-ray counting applications, studies of the proportionality of response and the energy resolution of the crystal have also been carried out in the energy ranges 10.5–100 keV [21] and 5–60 keV (X-rays from radioactive sources Fe-55: 5.9 keV, Cd-109: 22 keV, and Am-241: 60 keV) [22]. This work extends the current LaCl$_3$:Ce literature and presents a combined examination of LaCl$_3$:Ce performance in terms of measuring absolute efficiency in clinical utilized X-ray tube voltages, calculating the X-ray energy absorption efficiency and estimating the suitability of LaCl$_3$:Ce in conjunction with commercially available photoreceptors, with the scope of using LaCl$_3$:Ce in hybrid medical imaging systems.

The results of this study were compared with calculated and previously published results for Bi$_4$Ge$_3$O$_{12}$ (BGO), Lu$_2$SiO$_5$:Ce (LSO), and CdWO$_4$ single crystals that are commonly used in several imaging systems [23,24], and the specific LaCl$_3$:Ce crystal absolute efficiency was found comparable or better.

High light yield (i.e., $AE$) as well as satisfactory spectral matching to optical sensors ($\alpha_s$ and $EE$) yields scintillator–photodetector combinations which can provide higher signal output and better image quality for a given level of patient exposure. Accordingly, a required quality of output image can be obtained with less radiation burden to the examinee. The latter is important in CT examinations where a lot of X-ray projections are obtained per gantry rotation and scan.

2. Materials and Methods

A single cubic-shaped crystal was purchased from Advatech UK Limited [13]. The cube dimensions were $10 \times 10 \times 10$ mm$^3$. The light yield ($LY$) of the crystal was 49,000 photons/MeV (provided by the supplier), its density 3.86 g/cm$^3$, and its max emission peak is at 350 nm [13]. The surfaces of the crystal were polished. In addition, the crystal was purchased encapsulated in a thin aluminum protective layer, due to its hygroscopicity, where only one crystal surface, i.e., output, was not encapsulated. Energy absorption efficiency ($EAE$), quantum detection efficiency ($QDE$), absolute luminescence efficiency ($AE$), spectral matching factors ($SMF$), and effective efficiency ($EE$) with several optical detectors were determined experimentally or with the use of mathematical formulas. The X-ray flux needed for absolute efficiency calculation was obtained by an X-ray tube coupled with a
CPI, series CMP 200DR 50 kW generator. The high voltage ranged from 50 to 150 kVp and the current–time product was kept constant at 63 mA s. The inherent filtration of the X-ray tube was 1.5 mm Al. Furthermore, an additional Al filtration of 20 mm was placed at the tube exit [7,23–25].

The quantum detection efficiency (QDE) describes the ability of a scintillator to detect photons and is defined as the fraction of the incident X-rays interacting with the scintillator [26]. The fraction of the incident X-ray energy absorbed in the crystal is described through the energy absorption efficiency (EAE) [26]. EAE and QDE can be calculated as [23,26]:

\[
EAE(E) = \frac{\int_0^{E_0} \Phi_0(E) E \left( \frac{\mu_{\text{att}}(E)/\rho}{\mu_{\text{en}}(E)/\rho} \right) \left( 1 - e^{-\left( \frac{\mu_{\text{att}}(E)/\rho}{\rho} \right) T} \right) dE}{\int_0^{E_0} \Phi_0(E) E dE}
\]

and

\[
QDE = \frac{\int_0^{E_0} \Phi_0(E) \left( 1 - e^{-\left( \frac{\mu_{\text{att}}(E)/\rho}{\rho} \right) T} \right) dE}{\int_0^{E_0} \Phi_0(E) dE}
\]

where \( \Phi_0(E) \) is the incident X-ray photon fluence on the scintillator, \( E \) is the photon energy, \( \mu_{\text{att}}(E)/\rho \) is the radiation photon total mass attenuation coefficient, and \( \mu_{\text{en}}(E)/\rho \) is the corresponding total mass energy absorption coefficient. \( T \) is the detector thickness and \( \rho \) is the density (in g/cm\(^3\)) [23,26]. The coefficients used in Equations (1) and (2) were obtained from XMudat software [27], and the X-ray fluence from TASMIP Spectra Calculator [28].

The absolute luminescence efficiency is defined as the ratio of the energy flux \( \Psi_\lambda \) (units \( \mu W \cdot m^{-2} \)) of the optical photons emitted by a stimulated crystal to the rate of exposure \( \dot{X} \) (units \( \text{mR} \cdot \text{s}^{-1} \)) of the X-rays incident on it [29]. The instrumentation necessary for measuring the optical photon flux comprised an Oriel light integration sphere, an EMI photomultiplier tube, and a Cary electrometer. More details regarding the measurement of \( AE \) can be obtained in the literature [7,23–25]. According to its definition [24,25],

\[
AE = \frac{\Psi_\lambda}{\dot{X}}
\]

The units of \( AE \) are known as efficiency units (EU), where 1 EU = 1 \( \mu W \cdot m^{-2} \)/(mR·s\(^{-1}\)).

Crystal scintillators are always combined with optical photon detectors. The performance of such a combination can be estimated by the spectral matching factor \( \alpha_s \), which expresses the spectral compatibility of the scintillator’s emitted light to the spectral sensitivity of the photodetector, and it can be defined as [23]

\[
\alpha_s = \frac{\int S_p(\lambda) S_D(\lambda) d\lambda}{\int S_p(\lambda) d\lambda}
\]

where \( S_p(\lambda) \) is the spectrum of the emitted light by the scintillator, \( S_D(\lambda) \) is the spectral sensitivity of the photodetector coupled to the scintillator, and \( \lambda \) is the wavelength of the light emitted [30]. The spectral sensitivity of various photodetectors was obtained from manufacturers’ data and the literature [25,31–34].

The overall efficiency of a scintillator–photodetector combination has been expressed by the effective efficiency (EE) [35] and is calculated as [8,25]

\[
EE = AE \cdot \alpha_s
\]

3. Results and Discussion

Figure 1 shows values for the energy absorption efficiency of the LaCl\(_3\):Ce crystal. These values were compared with calculated data for BGO, LSO, and CdWO\(_4\) single crystals of equal dimensions. The \( EAE \) values of LaCl\(_3\):Ce crystal were lower than BGO, LSO, and CdWO\(_4\) in the low-energy range (50 kVp) (0.497 for LaCl\(_3\):Ce, 0.840 for BGO, 0.871 for LSO, and 0.714 for CdWO\(_4\)) as a consequence of the significantly higher density of these
The deviation between the absorption efficiency values of LaCl$_3$:Ce and those of BGO, LSO, and CdWO$_4$ decreases as the X-ray energy increases. At 70 kVp, LaCl$_3$:Ce shows a tendency to increase, but remains lower than the EAE of LSO and CdWO$_4$ crystals. At 150 kVp, the EAE values of LaCl$_3$:Ce, BGO, LSO, and CdWO$_4$ are approximately 0.584, 0.698, 0.566, and 0.587, respectively. The highest values for LaCl$_3$:Ce were calculated at 140 and 150 kVp, demonstrating that the use of LaCl$_3$:Ce of this thickness favors higher energy radiographic applications such as computed tomography.

**Figure 1.** EAE of the LaCl$_3$:Ce, BGO, LSO:Ce, and CdWO$_4$ single crystals.

The attenuation coefficients, as well as the ratio of the attenuation coefficients $\mu_{en}/\mu_{att}$ used in Equations (1) and (2), are shown in Figures 2 and 3, respectively, for all four materials.

**Figure 2.** Attenuation coefficients of the LaCl$_3$:Ce, BGO, LSO:Ce, and CdWO$_4$ single crystals.

**Figure 3.** Attenuation coefficients ratio $\mu_{en}/\mu_{att}$ of the LaCl$_3$:Ce, BGO, LSO, and CdWO$_4$ single crystals.
As shown in Figure 1, the EAE generally decreases when increasing the voltage across the X-ray tube. The ability of a crystal to absorb photons is expressed through the attenuation coefficient $\mu_{\text{att}}$ and the absorption coefficient $\mu_{\text{en}}$. $\mu_{\text{att}}$ expresses the probability of interaction of the radiation with the crystal, which is manifested mainly through photoelectric effect, based on the energies and the effective atomic number ($Z_{\text{eff}}$) of these crystals. $\mu_{\text{en}}$ expresses the probability of absorbing radiation inside the crystal. With increasing voltage in the X-ray tube, the emitted radiation spectrum moves to higher energies. As the energies of the emitted photons increase, the $\mu_{\text{att}}$ coefficients decrease, as shown in Figure 2, except for some energy values at which some discontinuities occur. These discontinuities are called absorption edges and correspond to binding energies of the K, L, M, and N shells, where the probability of photon absorption through the photoelectric effect is greatly increased due to resonance. In addition, as shown in Figure 3, the ratio $\mu_{\text{en}}/\mu_{\text{att}}$ at some energy values decreases sharply, and, as a consequence, the EAE of the crystal decreases. This reduction for BGO and LSO:Ce crystals occurs at the K-edges energy values of 90 keV and 63 keV, respectively, and, consequently, the EAE of these crystals decreases after 90 kVp and 63 kVp, respectively, while stabilizing after 110 kVp for both crystals at about the same levels as shown in Figure 3. For LaCl$_3$:Ce crystal, the reduction is at 38 keV and the effect in the corresponding curve in Figure 1, although not clearly visible, explains the reduction of EAE from 50 kVp to 60 kVp. The increase of EAE after 60 kVp and its stabilization after 110 kVp, at the same levels as the LSO:Ce and CdWO$_4$ crystals, is explained by the high increase of the $\mu_{\text{en}}/\mu_{\text{att}}$ ratio of the crystal after 38 keV and its tendency to equate with the values of the $\mu_{\text{en}}/\mu_{\text{att}}$ ratio of the other two crystals.

Figure 4 illustrates the fluctuation of QDE values with X-ray tube voltage. It is apparent from these values that LaCl$_3$:Ce of thickness 10 mm exhibits almost perfect efficiency to detect the incident photons, as the values range from 0.996 to 1.
The variation of the purchased LaCl\(_3\):Ce absolute efficiency with X-ray tube voltages 50 to 150 kVp is shown in Figure 5. In Figure 5, the corresponding AE values for LSO, BGO, and CdWO\(_4\) crystals of equal dimensions (10 × 10 × 10 mm\(^3\)) are also demonstrated \([23,24]\). The AE values of all crystals demonstrate a tendency to increase with increasing of the kVp. However, LaCl\(_3\):Ce values were in all cases higher than those of the other crystals. For example, at the tube voltages applied of 70 kVp and 130 kVp, the absolute efficiencies were (a) for 70 kVp: 24.38 EU for LaCl\(_3\):Ce, 18.7 EU for CdWO\(_4\), 12.4 EU for LSO, and 2.3 EU for BGO; and (b) for 130 kVp: 38.7 EU for LaCl\(_3\):Ce, 26.9 EU for CdWO\(_4\), 17.7 EU for LSO, and 3.7 EU for BGO \([23,24]\). The AE results confirm the suitability of LaCl\(_3\):Ce crystal for possible use in medical imaging applications, since it exhibits higher values than LSO and BGO single crystals, which are commonly used in such applications. Furthermore, the AE values in higher energies verify the efficiency of LaCl\(_3\):Ce crystal in nuclear medicine applications.

It is worth commenting that the increased efficiency of LaCl\(_3\):Ce, compared to CdWO\(_4\), LSO, and BGO, cannot be attributed only to its radiation absorption properties. A reason that can explain its increased absolute efficiency is the additional effect of its higher light yield \((LY)\) 49.000 photons/MeV compared to the 8.900 photons/MeV for BGO crystal, 30.000 photons/MeV for LSO crystal, and 28.000 photons/MeV for CdWO\(_4\) scintillator. The total number of the optical photons produced per incident X-ray, \(L_y\), are due to the combined effect of \(EAE\) and \(LY\). In order to theoretically estimate the total number of optical photons produced for several X-ray tube voltages, we calculated the mean energy \(E\) for the X-ray spectra at 50 kV, 60 kV, 80 kV, 140 kV, and 150 kV as \(E = \int \Phi(E)EdE/\int \Phi(E)dE\). The corresponding mean energies were calculated as 41.5 keV, 47.2 keV, 56.7 keV, 74.8 keV, and 75.9 keV, respectively. The total number of optical photons produced was calculated as \(EAE \cdot \frac{LY}{EN}\)-\(LY\).

In Table 1, the \(L\) values of LaCl\(_3\):Ce, compared to CdWO\(_4\), LSO, and BGO, at 50 kV, 60 kV, 80 kV, 140 kV, and 150 kV are shown.
It may be seen that for low X-ray energies, LaCl₃:Ce is inferior to LSO in terms of optical photon production, because of the low EAE, due to its low density and despite its higher light yield compared to LSO. For higher energies though, where the EAE differences between LaCl₃:Ce and LSO are reduced, as shown in Figure 1, LaCl₃:Ce produces more optical photons. In each case, however, the AE values of LaCl₃:Ce are superior to the scintillators at the X-ray tube voltages under investigation. This indicates that the optical photon propagation properties, such as transmission through the material and optical escape from the crystal, also play an important role in the total scintillation efficiency. The BGO, LSO, and CdWO₄ crystals were wrapped with Teflon layers as part of the irradiation procedure [38]. According to the literature, the reflectivity of the surfaces of polished crystals alone, or in contact with Teflon or specular surfaces, is close to 100% for optical photon angle of incidence over 30 degrees [39].

Figures 6–9 illustrate the normalized optical spectrum of LaCl₃:Ce crystal along with the spectral sensitivities of various optical sensors [25,31–34]. The LaCl₃:Ce spectrum, obtained from the vendor’s website [13], shows the main luminescence peak at 350 nm [13,14].

The spectral matching factor values for LaCl₃:Ce, along with several optical detectors, were calculated according to Equation (4). These optical detectors, which are shown in Figures 6–9, were silicon photomultipliers (SiPMs) utilized in nuclear medicine techniques, charge-coupled devices (CCD), and complementary metal–oxide semiconductors (CMOS) used in imaging applications, as well as various photocathodes. It was found that LaCl₃:Ce exhibits excellent compatibility with multialkali photocathode (0.99), GaAs photocathode (0.93), and bialkali photocathode (0.94). Moreover, it exhibits exceptional compatibility when coupled with various flat panel (FP) photocathodes, with the SMF values fluctuating
from 0.91 to 0.99 (0.99 for H8500D-03 and H10966A). On the other hand, poor compatibility was registered with the GaAsP phosphor photocathode, since the SMF value was only 0.27. LaCl₃:Ce also showed good compatibility with most of the silicon photomultipliers used in our experiments, as it showed SMF values in the range from 0.62 to 0.67 (0.67 for Si PM S10985-050C and Si PM S10362-11-025U). On the contrary, LaCl₃:Ce was found to be incompatible with CCDs and CMOS detectors. Specifically, the lowest SMF values were registered for CCD with polygates (0.002), for CMOS RadEye HR (0.0), for CMOS Pgate (0.0002), and for CCD with traditional polygates and CCD no polygates (both at 0.0003). The combinations with SMF greater than 0.60 are shown in Table 2.

![Figure 6. Normalized emitted light spectrum of the LaCl₃:Ce crystal and spectral sensitivity of various charge-coupled devices.](image)

![Figure 7. Normalized emitted light spectrum of the LaCl₃:Ce crystal and spectral sensitivity of various complementary metal–oxide semiconductors.](image)
Crystals 2022, 12, x FOR PEER REVIEW 9 of 15

Figure 7. Normalized emitted light spectrum of the LaCl₃:Ce crystal and spectral sensitivity of various complementary metal–oxide semiconductors.

Figure 8. Normalized emitted light spectrum of the LaCl₃:Ce crystal and spectral sensitivity of various photocathodes.

The spectral matching factor values for LaCl₃:Ce, along with several optical detectors, were calculated according to Equation (4). These optical detectors, which are shown in Figures 6–9, were silicon photomultipliers (SiPMs) utilized in nuclear medicine techniques, charge-coupled devices (CCD), and complementary metal–oxide semiconductors (CMOS) used in imaging applications, as well as various photocathodes. It was found that LaCl₃:Ce exhibits excellent compatibility with multialkali photocathode (0.99), GaAs photocathode (0.93), and bialkali photocathode (0.94). Moreover, it exhibits exceptional compatibility when coupled with various flat panel (FP) photocathodes, with the SMF values fluctuating from 0.91 to 0.99 (0.99 for H8500D-03 and H10966A). On the other hand, poor compatibility was registered with the GaAsP phosphor photocathode, since the SMF value was only 0.27. LaCl₃:Ce also showed good compatibility with most of the silicon photomultipliers used in our experiments, as it showed SMF values in the range from 0.62 to 0.67 (0.67 for SiPMs10985-050C and SiPMs10362-11-025U). On the contrary, LaCl₃:Ce was found to be incompatible with CCDs and CMOS detectors. Specifically, the lowest SMF values were registered for CCD with polygates (0.002), for CMOS RadEye HR (0.0), for CMOS Pgate (0.0002), and for CCD with traditional polygates and CCD no polygates (both at 0.0003). The combinations with SMF greater than 0.60 are shown in Table 2.

Table 2. LaCl₃:Ce photodetector combinations with SMF above 0.60.

| Optical Detectors | LaCl₃:Ce | Extended photocathode (E-S20) | 0.83 |
|-------------------|---------|-------------------------------|------|
|                   |         | Bialkali Photocathode         | 0.94 |
|                   |         | Multialkali Photocathode      | 0.99 |
|                   |         | (FP) PS-PMT H8500C-03         | 0.93 |
|                   |         | (FP) PS-PMT H8500D-03         | 0.99 |
|                   |         | (FP) PS-PMT H10966A           | 0.99 |
|                   |         | (FP) PS-PMT H8500C            | 0.91 |
|                   |         | SiPM MicroFC-30035-SMT        | 0.66 |
|                   |         | SiPM S10985-050C              | 0.67 |
|                   |         | SiPM S10362-11-025U           | 0.67 |

Figures 10–13 illustrate the effective luminescence efficiency of the LaCl₃:Ce crystal with the optical detectors shown in Figures 6–9. The optimum effective efficiency values were attributed to photocathodes and silicon photomultipliers (SiPMs). The lowest values are obtained when coupled with CCDs and CMOS optical sensors. In detail, EE values almost equal to the AE ones are obtained (~15 EU at 50 kVp and ~39 EU at 150 kVp) when LaCl₃:Ce is coupled with GaAs photocathode, bialkali photocathode, multialkali photocathode, flat panel PS-PMT H8500D-03, and flat panel PS-PMT H10966A. On the contrary, the decrease (with kVp) in the detected luminescence signal varied from 99.7% to 100% when LaCl₃:Ce was combined with CMOS RadEye HR, CMOS Pgate, CCD with polygates, CCD no polygates LoD, and CCD with traditional polygates.
Table 2. LaCl$_3$:Ce photodetector combinations with SMF above 0.60.

| Optical Detectors                                    | LaCl$_3$:Ce |
|------------------------------------------------------|-------------|
| Extended photocathode (E-S20)                        | 0.83        |
| Bialkali Photocathode                                | 0.94        |
| Multialkali Photocathode                             | 0.99        |
| (FP) PS-PMT H8500C-03                                | 0.93        |
| (FP) PS-PMT H8500D-03                                | 0.99        |
| (FP) PS-PMT H10966A                                  | 0.99        |
| (FP) PS-PMT H8500C                                   | 0.91        |
| SIPM MicroFC-30035-SMT                               | 0.66        |
| SIPM S10985-050C                                     | 0.67        |
| SIPM S10362-11-025U                                  | 0.67        |
| SIPM S10362-11-050U                                  | 0.62        |
| SIPM S10362-11-100U                                  | 0.65        |
| GaAs Photocathode                                    | 0.93        |

Figures 10–13 illustrate the effective luminescence efficiency of the LaCl$_3$:Ce crystal with the optical detectors shown in Figures 6–9. The optimum effective efficiency values were attributed to photocathodes and silicon photomultipliers (SiPMs). The lowest values are obtained when coupled with CCDs and CMOS optical sensors. In detail, EE values almost equal to the AE ones are obtained (~15 EU at 50 kVp and ~39 EU at 150 kVp) when LaCl$_3$:Ce is coupled with GaAs photocathode, bialkali photocathode, multialkali photocathode, flat panel PS-PMT H8500D-03, and flat panel PS-PMT H10966A. On the contrary, the decrease (with kVp) in the detected luminescence signal varied from 99.7% to 100% when LaCl$_3$:Ce was combined with CMOS RadEye HR, CMOS Pgate, CCD with polygates, CCD no polygates LoD, and CCD with traditional polygates.

Figure 10. Effective efficiency of the LaCl$_3$:Ce crystal combined with various charge-coupled devices.

Figure 11. Effective efficiency of the LaCl$_3$:Ce crystal combined with various complementary metal–oxide semiconductors.
4. Conclusions

The absolute luminescence efficiency and the spectral matching of a LaCl\(_3\):Ce crystal were examined within the tube voltage range (50–150 kVp) employed in X-ray imaging applications. The results were compared with previously published data for LSO, BGO, and CdWO\(_4\) single crystals of equal dimensions, commonly utilized in commercial imaging systems. Peak absolute luminescence efficiency of LaCl\(_3\):Ce crystal was obtained at 150 kVp (39.9 EU) The luminescence efficiency values of the examined crystal were found to be higher than those of LSO, BGO, and CdWO\(_4\) crystals, within the whole X-ray tube voltage range. In terms of EAE, LaCl\(_3\):Ce demonstrated reduced performance with respect to LSO and CdWO\(_4\) crystals. The spectral compatibility with several commercial optical detectors was also investigated. The emission spectrum of LaCl\(_3\):Ce was found to be compatible with various types of photocathodes and silicon photomultipliers (SiPMs).
A high-efficiency detector for hybrid medical imaging systems such as SPECT/CT and PET/CT would require reduced pharmaceutical administered activity for a given signal output. In addition, for the X-ray part of the system, reduced radiation translated to reduced current in the CT generator circuit, would be required. More specifically, if absolute efficiency measurements are considered, for the 140 kV X-ray irradiation conditions, LaCl$_3$:Ce can provide the same output as LSO and BGO with 46% and 10% of radiation exposure, respectively. Thus, a scintillator such as LaCl$_3$:Ce with optimized exposure conditions is expected to reduce patient exposure as well as the aforementioned operational costs of the medical installation.

Considering these properties and the previous studies examining LaCl$_3$:Ce crystal for use in nuclear medicine applications, LaCl$_3$:Ce crystal could be considered suitable for use in hybrid medical imaging systems, such as PET/CT and SPECT/CT scanners.

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