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Investigation of single, random, and true counts from natural radioactivity in LSO-based clinical PET

Seiichi YAMAMOTO,*,*** Hitoshi HORII,** Mitsuru HURUTANI,**
Keiichi MATSUMOTO*** and Michio SENDA***

*Department of Electrical Engineering, Kobe City College of Technology
**Division of Nuclear Medicine, Nishijin Hospital
***Department of Image Based Medicine, Institute of Biomedical Research and Innovation

Objective: Lutetium oxyorthosilicate (LSO) contains natural radioactivity that emits beta particles and three gamma photons simultaneously. These beta particles and gamma photons increase the single and random rates in a positron emission tomography (PET) system while a beta particle and gamma photon produced in the same decay of Lu-176 and detected by another detector can be beta-gamma coincidence true events. The purpose of this work is to measure the single, random, and true count rates due to the natural radioactivity in LSO and determine the optimum lower energy threshold level for an energy window in an LSO-based clinical PET. ***Methods:*** First, we measured the energy spectra of these beta particles and gamma photons in LSO using a single crystal to obtain the basic data. Then, we measured single, random, and true count rates of an LSO-based clinical PET from the natural radioactivity as a function of the lower energy threshold. ***Results:*** In the PET, single and random count rates due to the natural background activity were gradually decreased as the lower energy threshold level increased. The true count rates due to the beta-gamma coincidence were more than 10 kcps below a lower energy threshold of 250 keV. However, these true count rates due to the natural radioactivity in LSO can be decreased to less than 1 kcps at a lower energy threshold level set at more than 350 keV. ***Conclusion:*** With these considerations, in an LSO-based clinical PET, a lower energy threshold level set at above 350 keV is recommended.

Key words: LSO, natural radioactivity, coincidence, PET

INTRODUCTION

IT IS WELL KNOWN that lutetium oxyorthosilicate (LSO) contains natural radioactivity, Lu-176, that emits beta particles.[1,2] However, it is not well known that LSO also emits three gamma photons simultaneously with the beta particles.[3,4] Figure 1 shows the decay diagram of Lu-176. The radioisotope emits beta particles whose mean energy is 420 keV. It also emits three gamma photons whose energies are 307 keV, 202 keV, and 88 keV simultaneously to the beta particles. The beta particles emitted in LSO increase the single count rate of the detector and also increase the random coincidence rate in a positron emission tomography (PET) system. In addition, if a beta particle produced in one detector, and the escaped gamma photon from the LSO is detected by another detector, the event can be recognized as a true coincidence (Fig. 2). This true event due to the natural radioactivity increases the baseline counts similarly to scatter events in PET. These single, random, and true count rates depend on the lower energy threshold level of the energy window (lower energy threshold) of the system. Although some of these phenomena were already reported for an LSO-based animal PET[3] and LSO-based research PET,[4] there is no report for a clinical PET. These phenomena also caused

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For reprint contact: Seiichi Yamamoto, Ph.D., Department of Electrical Engineering, Kobe City College of Technology, 8–3 Gakuen-Higashi-machi, Nishi-ku, Kobe 651–2194, JAPAN.

E-mail: s-yama@kobe-kosen.ac.jp

problems in performance evaluation using NEMA standard and were recently reported for a LSO based PET/CT scanner.[5,6]

Consequently, we first measured the energy distribution of the beta particles and gamma photons from LSO for the basic data. Next, using an LSO-based clinical PET system, ACCEL (CTI/Siemens, Knoxville, TN, USA), we measured the single, random, and true count rates from the natural beta particles and gamma photons by changing the lower energy threshold. Using these results, we estimated the optimum lower energy threshold of the LSO-based clinical PET system.

MATERIALS AND METHODS

(1) Energy distribution of the beta particles from LSO
Using a 3.7 mm × 3.7 mm × 10 mm LSO (CTI, Knoxville, TN, USA), the energy distribution of the beta particles from the natural radioactivity in the LSO was measured. The LSO was wrapped in white Teflon, and a 3.7 mm × 10 mm surface was optically coupled to a 3-inch round photo-multiplier tube (PMT). A 10 mm thick lead was placed on the LSO to reduce the detection of environmental radiations from the LSO. Measurement was performed without any radioisotopes around the LSO. Pulses from the PMT were amplified by a standard Nuclear Instrumentation Module (NIM) and were fed to a multi-channel analyzer (1125P, Clear Pulse, Tokyo, Japan). Accumulation time was 1,000 sec. For comparison, a 511 keV gamma source (Na-22) was positioned on the LSO; the energy spectrum was also measured in the same set up as the measurement of the beta particles. The acquisition time for this measurement was 100 sec.

(2) Pulse height distribution of gamma photons from LSO
Using the same LSO, the energy distribution of the gamma photons from the LSO was measured. The LSO was positioned on a 23.5 mm × 40 mm × 7 mm size gadolinium orthosilicate (GSO) with aluminum plate of a 1-mm thick inserted between the LSO and GSO. The 23.5 mm × 40 mm side of the GSO was optically coupled to a 3-inch round PMT. With this configuration, the gamma photons from the LSO were detected by the GSO while the beta particles were absorbed by the aluminum plate, because the aluminum plate is thick enough to absorb beta particles of less than 1 MeV. To reduce the background counts from environmental radiation detected by the GSO, the LSO and GSO were covered with lead. Measurements were performed without any radioisotopes around the LSO and GSO. Pulses from the PMT were amplified by the standard NIM and were fed to the multichannel analyzer. The accumulation time was 1,000 sec. For comparison, the 511 keV gamma source (Na-22) was positioned on the GSO, and the energy spectrum was also measured. The acquisition time for this measurement was 100 sec.

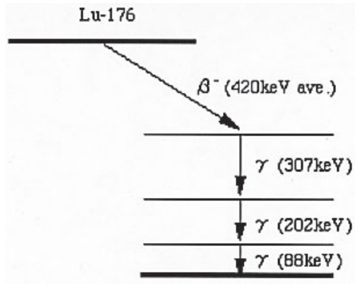

Fig. 1 Decay diagram of Lu-176. The isotope emits a beta particle and three gamma photons.

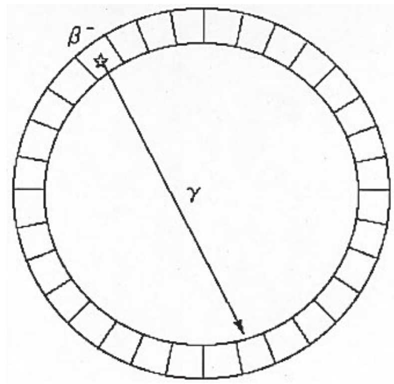

Fig. 2 Schematic diagram of the beta-gamma coincidence due to the natural radioactivity contained in the Lu-176.

(3) Single, random, and true count rates due to the natural radioactivity in an LSO-based PET
Using an LSO-based clinical PET (ACCEL, CTI/Siemens, Knoxville, TN, USA), single, random, and true count rates due to the natural radioactivity in the LSO were measured. This PET was the first commercially available LSO-based PET which has a better count rate capability compared with bismuth-germanate (BGO) based PET of similar dimension.[7,8] The LSO-based PET has 48 block detectors per ring and three block rings in total. The size of a single block detector is 51 mm × 51 mm × 25 mm divided into 8 × 8 matrices that are optically connected to four PMTs. The total volume of the LSO used in the PET was estimated to be approximately 9,500 m*l*.

We measured count rates in two conditions: one without any radioactivity in the field of view (FOV) of the PET, and the other with a 20-cm diameter, 20-cm height cylindrical phantom containing 32 MBq of Ge-68 solution. The former is for the measurement of the single, random, and true count rates of the PET due to the natural radioactivity in the LSO. The latter is for the measurement of the true and random count rates for a rough estimation of the sensitivity of the PET. In all cases, the total count rates in the PET were measured.

Measurements were performed by changing the lower energy threshold from 150 keV to 400 keV in 50 keV

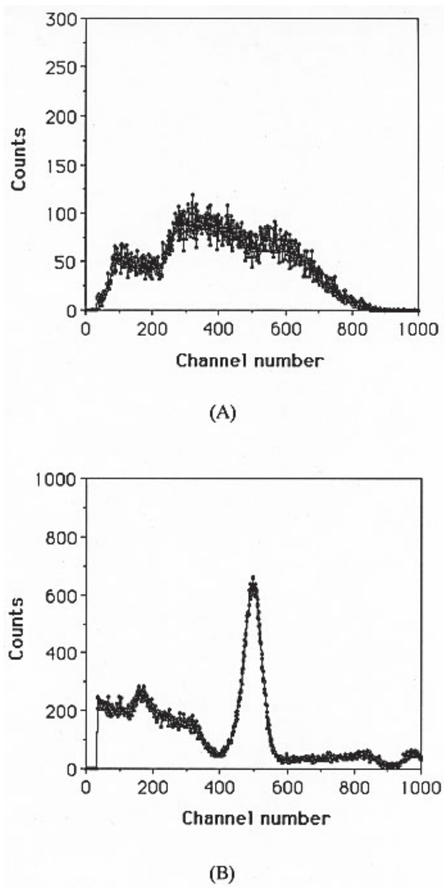

Fig. 3 Energy spectra of the beta particles from the natural radioactivity in the LSO (A) and 511 keV gamma photons (B).

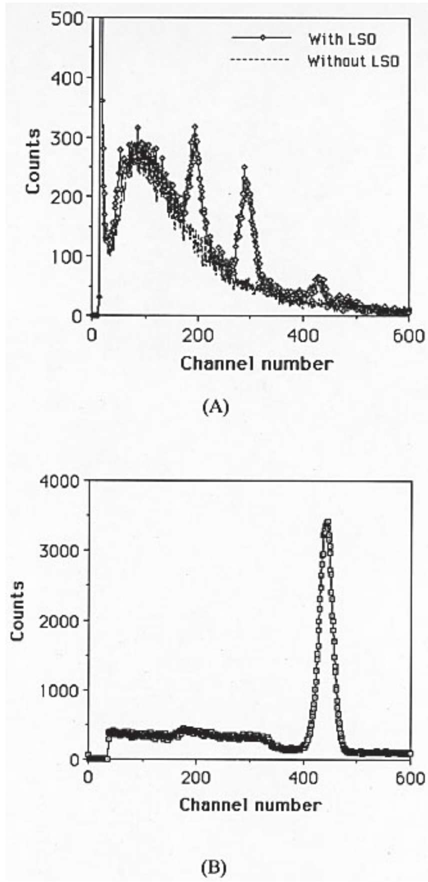

Fig. 4 Energy spectra of the gamma photons from the natural radioactivity in the LSO (A) and 511 keV gamma photons (B) measured using GSO.

steps. The upper energy threshold was fixed to 650 keV in all measurements. Count rates were monitored from the operation console display of the PET.

We also measured energy distribution of LSO for 511-keV gamma photons of which the width to height (H/W) ratio is similar to the crystal size of the LSO-based clinical PET to validate the optimum lower threshold for clinical PET. Because the light output from the scintillator depends on the H/W ratio,[9] the measurement was used for the estimation of the energy distribution for the detector of the LSO-based clinical PET. The size of the LSO used for the measurement was 3.7 mm × 3.7 mm × 10 mm. The size of the scintillator (one cell of the detector block) of the LSO-based clinical PET is approximately 6.4 mm × 6.4 mm × 25 mm. The H/W ratio of the scintillator of the LSO-based clinical PET is 3.9 while the LSO used for the experiment was 2.7. A white Teflon tape was used for the reflector. The 3.7 mm × 3.7 mm side was optically coupled to the PMT and 511-keV gamma photons were irradiated from the top of the LSO. Energy spectrum was measured in the same set-up as was used for the other energy distribution measurements.

RESULTS

(1) Energy distribution of the beta particles from the LSO
In Figure 3-(A), we show the energy spectrum for the beta particles of the natural radioactivity contained in the LSO. The distribution was broad and three broad peaks were observed. The three peaks probably correspond to beta plus 88 keV gamma photon, beta plus 202 keV gamma photon, and beta plus 307 keV gamma photon simultaneously detected events, respectively. In Figure 3-(B), we also show the energy spectrum for the 511 keV gamma photons measured by the same LSO. Energy resolution was 12.2% full width at half maximum (FWHM). The photo-peak channel for the 511 keV gamma photons was approximately 2/3 of the maximum peak channel of that for the beta particles. This means that a significant fraction of the signal from the beta particles can be detected as single events even with a high energy threshold level setting by the detector electronics.

(2) Pulse height distribution of gamma photons from the LSO
In Figure 4-(A), we show the energy spectrum for gamma photons from the natural radioactivity of the LSO

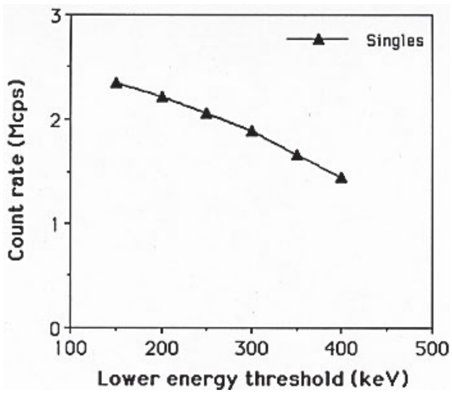

Fig. 5 Single count rate as a function of a lower energy threshold level setting without any radioactivity in the FOV measured for LSO-based PET (CTI/Siemens ACCEL).

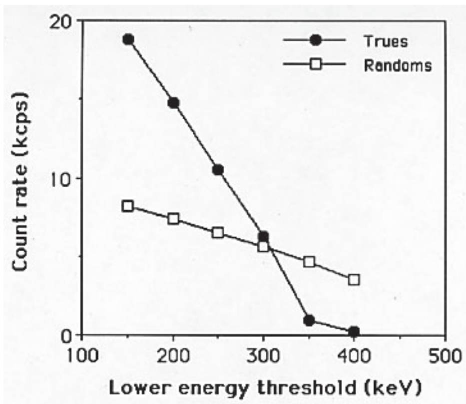

Fig. 6 True and random count rates as a function of a lower energy threshold level setting without any radioactivity in the FOV measured for LSO-based PET (CTI/Siemens ACCEL).

measured by the GSO. We see three clear peaks in the distribution that correspond to the photo-peaks of the 202 keV gamma photons, 307 keV gamma photons, and the sum peak of the 202 keV and 307 keV gamma photons. We did not detect a clear photo-peak of 88 keV gamma photons. In Figure 4-(B), we show the energy spectrum for the 511 keV gamma photons measured by the GSO. Comparing these two figures, it became obvious that these photo-peaks from the gamma photons from LSO's natural radioactivity except sum peak were below the photo-peak of the 511 keV gamma photons. Thus, it became clear that most of these gamma photons could be rejected by the adequate setting of a lower energy threshold of the PET.

(3) Single, random, and true count rates due to the natural radioactivity in an LSO-based PET

In Figure 5, we show the single count rates due to the natural radioactivity in an LSO-based PET as a function of a lower energy threshold level setting. The single count rates were quite high, more than 1 Mcps in all of the energy threshold levels. The single count rates were

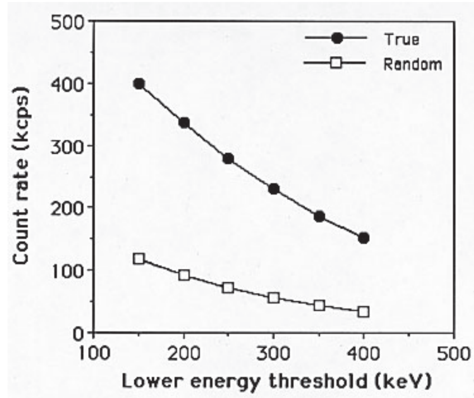

Fig. 7 True and random count rates as a function of a lower energy threshold level setting with a 32 MBq of 20-cm cylindrical phantom in the FOV measured for LSO-based PET (CTI/Siemens ACCEL).

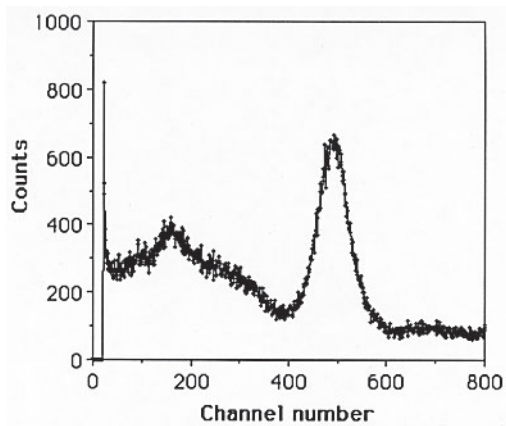

Fig. 8 Energy spectra of the LSO for 511-keV gamma photons of whose height to width ratio (W/H) is similar to that of the LSO-based clinical PET (CTI/Siemens ACCEL).

slightly decreased as the lower energy threshold level was increased.

In Figure 6, we show true and random count rates due to the natural radioactivity in the LSO-based PET as a function of a lower energy threshold level setting. True count rates due to the beta-gamma coincidence were more than 10 kcps in a low energy threshold level below 250 keV and the true count rates dramatically dropped to less than 1 kcps more than 350 keV. This is because the energies of the gamma photons due to the natural radioactivity in the LSO are 202 keV and 307 keV, significantly smaller than the 511-keV gamma photons. The random count rates were more than 5-kcps at the low energy threshold level and gradually decreased as the lower energy threshold increased. This is because the random coincidence is proportional to the square of the single rates that are shown in Figure 5.

In Figure 7, we show the true and random coincidence rates for the LSO-based PET with 20-cm cylindrical phantom containing 32 MBq of Ge-68 solution. The true count rates gradually decreased as the lower energy threshold increased. The true count rate at a low energy threshold level of 350 keV became almost half of the count rate at 250 keV. However, a significant fraction of this decreased true count rate is probably due to the decrease in scatter coincidence. The random rates were also decreased as the lower energy threshold increased.

Figure 8 shows the energy spectra of the LSO for 511-keV gamma photons of which H/W ratio is similar to that of the LSO-based clinical PET. The energy resolution was 18.4% FWHM. The energy resolution was lower than that shown in Figure 3-(B) because the optically coupling side to PMT was different. In Figure 8, the 3.7 mm × 3.7 mm side was optically coupled to PMT, while the 3.7 mm × 10 mm side was coupled in Figure 3-(B). The scintillation light in the latter case could more easily reach PMT than the former, and thus the self absorption of the scintillation light in the LSO as well as the light loss in the reflection processes was smaller.

DISCUSSION AND CONCLUSION

We measured the energy spectra for beta particles and gamma photons from the natural radioactivity in LSO, and found that the beta particles and gamma photons really exist and are detectable. In addition, we measured the single, true, and random count rates due to the natural radioactivity in the LSO-based PET. The radioactivity in the LSO was reported to be 241 cps/m*l*.[10] The 9,500 m*l* of LSO will produce 2.3 Mcps of a single count rate that is almost identical to the measured single count rate at a 150 keV lower energy threshold. The slight difference can be explained by the dead-time and events loss due to the lower energy threshold.

The results indicate that the lower energy threshold setting was not sufficient to reject either the single rate or random rate from the natural radioactivity in LSO. That is because the energy spectrum of the beta particles from the natural radioactivity in the LSO has a wider distribution than the lower energy threshold, as shown in Figure 3. However, this random rate was around 5 kcps, approximately 10% of that with the 20-cm diameter cylindrical phantom of 32 MBq which will not be a serious problem in high count rate studies because the random can be corrected by measuring the delayed coincidence or use of some other correction methods.

The true count rate due to the beta-gamma coincidence from the natural radioactivity of the LSO was relatively high, more than 10 kcps at the lower energy threshold level of less than 250 keV. The count rate is around 10% of that with the phantom. This will be a serious problem for the quantitative measurement in the PET because this true count will be an offset value in reconstructed images. At the end of dynamic studies using C-11 or O-15, in which the count rate is low because of the decay of these radioisotopes, a true count of around 10 kcps will not be ignored in the quantitative measurements. However, with the lower energy threshold level of 350 keV, the true count rate due to the beta-gamma coincidence dramatically decreased to less than 1 kcps. With this level of true count rates, most studies will be possible by adopting minimum considerations of the offset counts.

The sensitivity of the PET decreased as the lower energy threshold increased. However, taking into account the true count rate due to the beta-gamma coincidence, optimum lower energy threshold level will be more than 350 keV. In this case, there will be the advantage of some reduction of the scatter and random. The recommended lower energy threshold for the LSO-based PET or LSO-based PET/CT by the manufacturer is 350-keV. The threshold value may be determined by considering the beta-gamma coincidence in the system as well as scatter fraction of the system.

The energy resolution for the LSO with similar H/W ratio to LSO-based clinical PET was 18.4% FWHM. With this energy resolution, the lower energy threshold seems to be set higher than 400-keV. However, because of the deviation of energy responses in block detectors and the accuracy of the energy window settings of the electronics, the energy threshold may be limited to 350-keV. In the future, the lower energy threshold may be set at a higher level when these limitations are overcome.

This beta-gamma coincidence may be more important for animal PET systems using LSO or scintillators containing Lu such as LYSO, LGSO, and MLS. These systems are sometimes used with a lower energy threshold level of less than 350-keV because they employ smaller sized scintillators that make the sensitivity small due to the small photo-fraction of the detectors as well as relatively poor energy resolution.

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