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ARTICLE

Precise Numerical Simulation of Gamma-ray Pulse Height Spectrum Measured with a CdTe Detector Designed for BNCT-SPECT

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Boron neutron capture therapy (BNCT) is a new radiation therapy which can destroy tumor cells. In order to know the actual treatment effect directly in real time, we are developing a spectatorial system, which is called BNCT-SPECT. In the present study, we examined the feasibility of BNCT-SPECT by use of a CdTe detector taking into account the real BNCT scene. Precise calculations were carried out with MCNP5 to evaluate the pulse height spectra, which is to be measured by the CdTe detector. It was confirmed from the calculation results that at the energy of 478 keV, the S/N ratio is greater than unity and the number of counts exceeds 1000.

KEYWORDS: BNCT, CdTe detector, SPECT, gamma-ray pulse height spectrum

I. Introduction

Boron neutron capture therapy (BNCT) is a new radiation therapy which can destroy tumor cells, simultaneously suppressing influence against healthy cells. BNCT is expected to spread over the world because it has such specific advantage that healthy cells are not damaged and only the tumor cell can be destroyed, compared with other radiation therapies.

It is known, however, that there are some problems in BNCT. One of them is that it is difficult to determine the irradiation time exactly in BNCT. This is caused by the fact that exact boron concentration and neutron flux intensity in tumor cells cannot be known easily.

To solve the problem, we measure 478 keV prompt gamma-rays emitted from $^{10}B(n,\alpha)^{7}Li$ reaction in BNCT. Three dimensional treatment effect of BNCT can thus be estimated with a spectatorial system by measuring 478 keV gamma-rays. The spectatorial system for BNCT is called BNCT-SPECT in this paper. Studies on the BNCT-SPECT have been carried out by some researchers. Though utilization of scintillators and semiconductor detectors has been investigated for years[1,2,3,4)], BNCT-SPECT is not in practical use yet even as a prototype one.

In the present study, a CdTe[5)] detector was selected as the basic device to detect 478 keV gamma-rays. We tested the performance of the elemental CdTe detectors[6)]. Before producing a prototype detector having array structure for BNCT-SPECT, we plan to confirm numerically whether the present CdTe detector could be utilized in a real scene of BNCT. In the following sections, the pulse height spectrum to be measured with the detector is precisely calculated in the real scene of BNCT. From the calculation result, we discuss the S/N ratio at 478 keV and the number of counts to be detected during BNCT. In addition, with the obtained numerical calculation result, we simultaneously examine the intactness of the detector under a heavy irradiation circumstances of the BNCT.

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II. BNCT-SPECT

The principle of BNCT–SPECT is as follows. In BNCT, boron is accumulated in a tumor cell by use of medicine(BPA or BSH). When neutrons are irradiated, the following nuclear reactions are induced:

$$\mathbf{^{10}B + n \rightarrow \alpha + {^{7}Li} + 2.79\ MeV \quad (6.1\%)}$$
$$\mathbf{\rightarrow \alpha + {^{7}Li} + 2.31\ MeV + \gamma\ (478\ keV)\ (93.9\%)\ \text{-}[1]}$$

Emitted ^{7}Li and α particles destroy the tumor cell. Out of produced ^{7}Li, the amount of 94 % is left in an excited state, from which 478 keV gamma-ray is emitted via a transition from the first excited to the ground state in about 10^{-14} sec. The attenuation coefficient of this photon in tissues is about 0.1 cm^{-1}. Thus, this gamma-ray escapes from a human body to a large extent. The schematic position and intensity of the gamma-ray are measured by a SPECT device in this present study shown in **Figure 1**. This information is directly related to the (n,α) reaction amount distribution in the tumor, which becomes the treatment effect of BNCT. Three-dimensional image of the BNCT effect can be estimated through unfolding process. In addition, we will employ the Bayes's theorem for this process to realize real time image reproduction.

The requirements to realize BNCT-SPECT are summarized as follows:

(1) It is necessary to complete a measurement in about 30 minutes, because the treatment time in BNCT is normally less than one hour.
(2) The spatial resolution in the obtained BNCT-SPECT image should be less than several mm from the viewpoint of medical requirement.

(3) Annihilation gamma-rays of 511 keV are an unavoidable background in a real site of BNCT. This is quite a troublesome radiation, because the energy is very close to 478 keV. Therefore, it is necessary for the detector to have a good energy resolution of less than 15 keV so as to separately measure gamma-rays of 478 and 511 keV.

We have finally selected a CdTe semiconductor detection device as an elemental detector for BNCT-SPECT to meet the above three requirements for the following reasons. With the CdTe crystal, the size of the detector element can be downsized compared to HpGe, and the spatial resolution can thus be improved. The energy resolution can be improved by employing a Schottky type CdTe crystal compared to scintillator. Also a larger wafer can be produced recently which can enhance the efficiency at the same time keeping a good spatial resolution. The practical idea will be presented later in this section.

As the design target of the present CdTe detector, we set two items. One is the number of counts. For the statistical accuracy, at least the number above 1000 is necessary. The other is signal to noise ratio, S/N ratio, at 478 keV. Around this energy there are a lot of background gamma-rays emitted from the structural materials surrounding the detector assembly. The S/N ratio should thus be at least larger than unity.

For the former, we employed an idea of using the detector as a side-surface entrance to make the detector thickness larger, at the same time to make the spatial resolution acceptably small[5,6]. For the latter, an appropriate collimator necessarily used and the detector assembly should be heavily shielded at the same time.

Before producing the prototype detector with an array structure for BNCT-SPECT, it is quite important to confirm its feasibility considering the real BNCT scene to meet the design target above by precise three-dimensional (3-d) calculations. Simultaneously, we discuss the intactness of the detector under heavy irradiation, because the CdTe detector is not resistant against radiations. If the detector is exposed with strong radiations, it could be damaged and deteriorated in the performance.

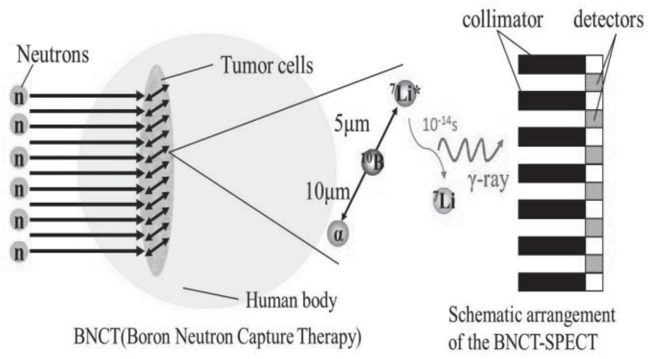

Fig. 1 Conceptual figure of BNCT-SPECT.

III. Precise Monte Carlo Calculation

As calculation code we used 3-d Monte Carlo code MCNP5, because for the present purpose, precise 3-d modeling is essential. The cross section library for the calculation is ENDF/B-6 with appropriate thermal scattering kernels for D_2O and graphite. As for other calculation conditions, we employ a 10 keV broad parallel neutron beam as neutron source. 10 keV is the upper energy of epi-thermal neutrons to be utilized for BNCT, which is a conservative calculation condition. Three variance reduction techniques of cell importance, forced collision, and point detector are used.

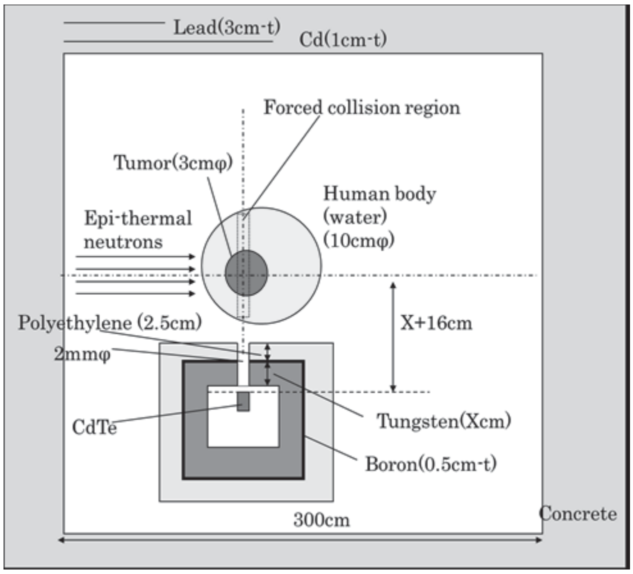

Fig. 2 Calculation model of the actual BNCT spot.

As shown in **Figure 2**, the CdTe detector is heavily shielded and 478 keV gamma-rays are entering through a quite narrow collimator. It is thus inevitable to use various variance reduction techniques to obtain an acceptably and reasonably good statistical result. As tally, we employed F4, F5 and F8, which were used for estimating reaction rate, neutron flux and pulse height spectrum, respectively. **Figure 2** indicates the calculation model in the actual BNCT spot. The calculation model is composed of an irradiation room, detection assembly and human body phantom. The CdTe detector is heavily shielded with polyethylene, tungsten, boron and so on. The tungsten thickness is a parameter to search the optimal shielding condition in the calculations later.

Calculations are divided into two steps, source term and pulse height spectrum calculations.

First, we calculate source terms, concerning following 4 items:

(1)^{10}B(n,α) reaction rate in the tumor,
(2)^{113}Cd(n,γ) reaction rate in the detector,
(3)Neutron spectrum at the detector, and
(4)Gamma-ray spectrum at the detector except (1) and (2).

^{1}H(n,γ) reaction in and around the tumor being quite crucial is included in (4).

Second, we calculate four pulse height spectra with F8 tally by using the calculated source terms:

(1)478 keV gamma-ray source in the tumor,
(2)^{113}Cd capture gamma-ray source in the detector,
(3)Neutron source at the detector, and
(4)Gamma-ray source at the detector.

Considering the source intensity of 10^9 n/sec/cm^2 at the tumor and summing up (1)~(4), the pulse height spectrum to

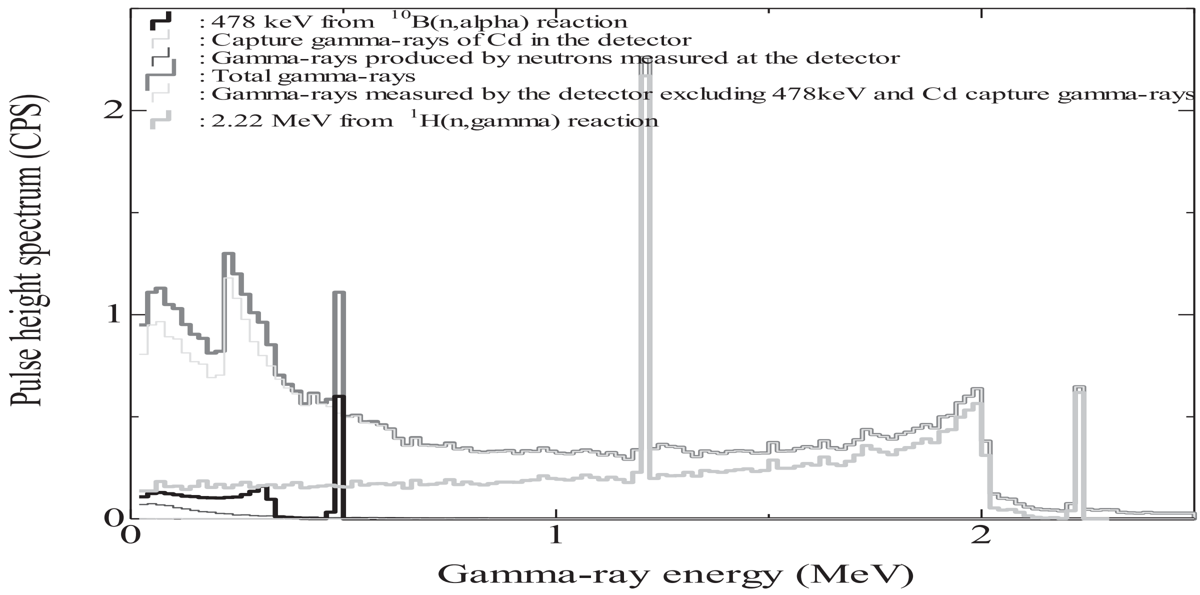

Fig. 3 Gamma-ray pulse height spectrum in the whole energy range up to 10 MeV.

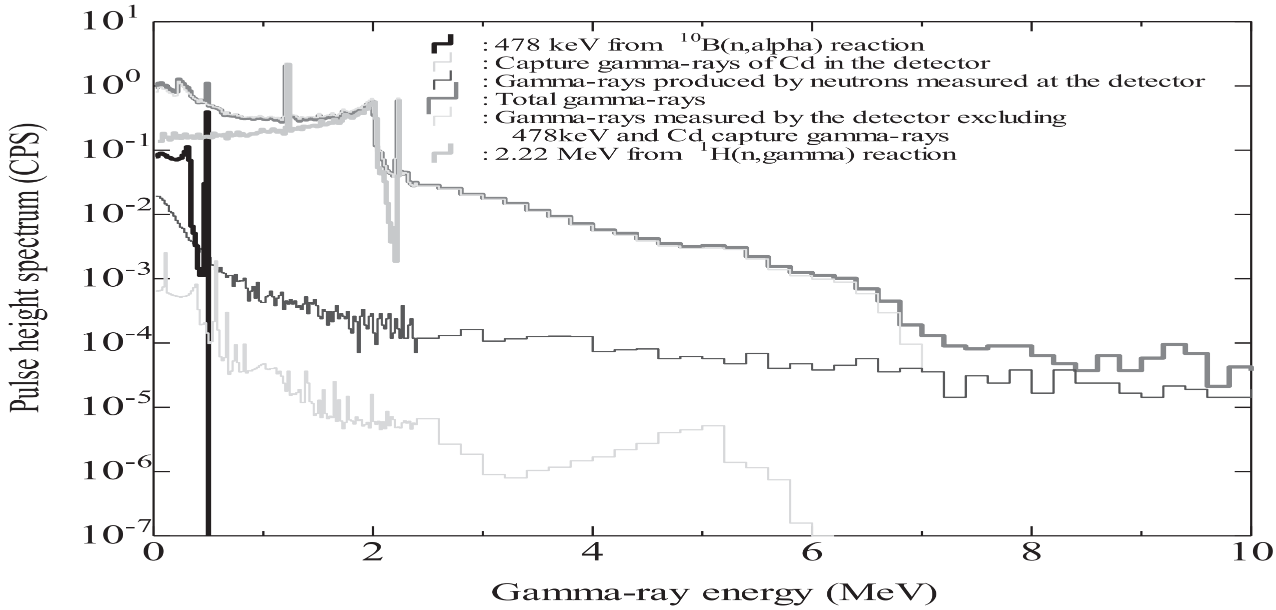

Fig. 4 Gamma-ray pulse height spectrum in the lower energy region.

be measured by the present CdTe detector during BNCT irradiation can be estimated.

IV. Results and Discussion

The calculated pulse height spectra are shown in **Figure 3**. Capture gamma-rays are created in the material of the detector assembly and the wall. In the higher energy region, the capture gamma-rays and their scattering contributions are dominant. In the lower energy region, unexpectedly ^{113}Cd capture gamma-rays and neutron induced gamma-rays at the detector are not large. Surprisingly, it is found that hydrogen capture gamma-rays are not so large. Consequently, penetrating gamma-rays through the tungsten shield are dominant in the pulse height spectrum, meaning it is quite crucial to examine the pertinent tungsten shield thickness.

Figure 4 stands for the same pulse height spectra as in **Figure 3,** but the expanded one in the lower energy region to present the precise structure around 478 keV. From the figure, the 478 keV gamma-rays show the largest contribution. The penetrating gamma-rays are the second largest one, followed by the ^{113}Cd capture gamma-rays and the neutron induced gamma-rays. The S/N ratio is calculated by making the ratio of 478 keV counts to other gamma-rays in the pulse height spectrum at the energy bin containing 478 keV.

Figure 5 shows the S/N ratio and number of counts in the 478 keV bin for thirty minutes. The x-axis is the thickness of tungsten in the detector assembly. In the figure, results for three CdTe detectors having different dimensions are summarized. The S/N ratio is improved with increase of the

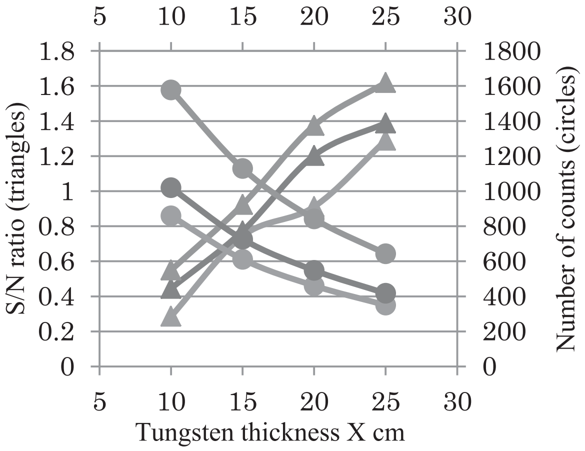

Fig. 5 S/N ratio and number of counts in 30 min. at 478 keV. Green line; 1.5×2×30 mm, red line; 1×2×30 mm and blue line; 1×2×20 mm. Also triangles show S/N ratio and closed circles show number of counts.

tungsten thickness from 10 to 25 cm. The number of counts increases with decreasing thickness. These two have an opposite trend, which means that the point meeting the design requirements could exist at around the middle thickness of tungsten.

When tungsten of 16~17 cm in thickness and CdTe of 1.5 × 2 × 30 mm are used, it is confirmed that 478 keV gamma-rays could be measured in an S/N ratio greater than unity and the count rate would be enough high to obtain the total count above 1000 for 30 minutes.

V. Conclusion

To realize BNCT-SPECT, a CdTe crystal was selected as an elemental detection device to measure 478 keV gamma-rays under a severe background condition. Before producing the prototype detector, precise numerical calculations were conducted with MCNP5 code taking into account the real environment of BNCT. As a result of calculation, it was confirmed that S/N ratio of 478 keV gamma-rays is higher than unity and the number of counts is greater than 1000 for 30 minutes at 478 keV in the pulse height spectrum, if adopting a combination of 1.5×2×30 mm CdTe and appropriately thick tungsten shield. In addition, since the count rate is not so large, the integrity of the CdTe detector could be maintained during the irradiation. In conclusion, the prospect of realization of BNCT-SPECT was confirmed. Now we are producing a larger elemental CdTe detector of 1.5×2×30 mm. After testing the characteristics thereof, the detection performance of 478 keV gamma-rays will be checked by a phantom experiment using a neutron source of Osaka University. Then test measurement will be done in a real BNCT scene in hospitals under the collaboration with the Department of Dentistry, Osaka University. Finally an array type CdTe detector will be produced as an elemental array device for BNCT-SPECT.

References

1) Kobayashi T. et al., "A noninvasive dose estimation system for clinical BNCT based on PG-SPECT – Conceptual study and fundamental experiments using HPGe and CdTe semiconductor detectors" Med. Phys., 27(9), 2124-2132 (2000).
2) Minsky D.M. et al., "Experimental feasibility studies on a SPECT tomograph for BNCTdosimetry" Appl Radiat Isot. 67(7-8), S179-82(2000).
3) Munck af Rosenschöld P. et al.,"Prompt gamma tomography during BNCT – A feasibility study" J. Instrum. 1, 1–10(2006).
4) Verbakel W. et al., "γ-ray telescope for online measurements of low boron concentrations in a head phantom for BNCT. Nucl. Instrum" Methods Phys. Res. Sect. A 394 (1–2), 163–172(1997).Ibaraki-ken, Japan, JAEA-Conf 2010-005, pp.75-80 (2010).
5) I. Murata, T. Mukai, M. Ito, H. Miyamaru, S. Yoshida, "Feasibility study on BNCT-SPECT using a CdTe detector," Progress in Nucl. Sci. Technol., **1**, pp. 267-270 (2011).
6) T. Mukai, I. Murata, M. Ito, H. Miyamaru, "Development of CdTe detector for BNCT-SPECT," Proc. of the 2009 Annual Symposium on Nucl. Data, Nov. 26-27, 2009, RICOTTI, Tokai-mura