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Study on measuring device arrangement of array-type CdTe detector for BNCT-SPECT

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ABSTRACT

Aim: To design the measuring device arrangement of array-type CdTe detector for BNCT-SPECT.

Background: In a boron neutron capture therapy, a very serious unsolved problem exists, namely that the treatment effect for BNCT cannot be known during irradiation in real time. Therefore, we have been developing a so-called BNCT-SPECT with a CdTe detector, which can obtain a three-dimensional image for the BNCT treatment effect by measuring 478 keV gamma-rays emitted from the excited state of ^{7}Li nucleus created by the ^{10}B(n,α) reaction. However, no practical uses were realized at present, because BNCT-SPECT requires very severe conditions for spatial resolution, measuring time, statistical accuracy and energy resolution.

Materials and methods: The design study was performed with numerical simulations carried out by a 3-dimenaional transport code, MCNP5 considering the detector assembly, irradiation room and even arrangement of arrayed CdTe crystals.

Results: The estimated count rate of 478 keV gamma-rays was sufficiently large being more than the target value of over 1000 counts/h. However, the S/N ratio did not meet the target of S/N > 1. We confirmed that deterioration of the S/N ratio was caused by the influence of Compton scattering especially due to capture gamma-rays of hydrogen. Theoretical calculations were thereafter carried out to find out whether anti-Compton measurement in an array-type CdTe detector could decrease the noise due to Compton scatterings.

Conclusions: The calculation result showed that the anti-coincidence would possibly increase the S/N ratio. In the next phase, an arrayed detector with two CdTe crystals will be produced to test removal possibility of the anti-coincident event.

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1. Background

Recently, BNCT (boron neutron capture therapy) has attracted many scientists in a medical field as a new radiation therapy. BNCT can destroy tumor cells by alpha particles (α) and lithium nuclei (^{7}Li) emitted by the reaction of thermal neutrons or epithermal neutrons with boron (^{10}B). Ranges of emitted α and ^{7}Li particles are as long as the size of a human body cell. Hence, if ^{10}B would be accumulated only in tumor cells, it would be expected that only the tumor cells would be killed with low damage of the healthy cells.

However, this therapy has not been established yet as a commonly utilized therapy, because no medical neutron sources are available and, in addition, there are some other serious problems to be solved as early as possible. One of them is that the treatment effect cannot be known during BNCT in real time. The present study describes a SPECT system for BNCT named BNCT-SPECT, which we are now developing. This is a three dimensional imaging device to monitor the local BNCT dose (treatment effect) around the tumor in real time. The BNCT-SPECT device is shown in Fig. 1. ^{10}B(n,α)[7] Li reaction is expressed by the next two nuclear reactions:

$$\begin{aligned} {}^{10}\mathrm{B} + \mathrm{n} &\rightarrow \alpha + {}^{7}\mathrm{Li} + 2.79\,\mathrm{MeV} \quad (6.1\%) \\ &\rightarrow \alpha + {}^{7}\mathrm{Li}^{*} + 2.31\quad \mathrm{MeV} + \gamma \quad (478\,\mathrm{keV}) \quad (93.9\%) \end{aligned} \tag{1}$$

94% of residual ^{7}Li is in the first excited state, i.e., ^{7}Li*. ^{7}Li* decays in its half-life of 10^{-14} s to emit a 478 keV gamma-ray via transition from the first excited state to the ground state. If the intensity distribution of 478 keV gamma-rays could be measured three-dimensionally, we could obtain the three-dimensional distribution of ^{10}B(n,α)[7] Li reaction rate in the tumor. The result of the measurement can then be regarded as the treatment effect of BNCT. Emitted 478 keV gamma-rays are collimated by the collimator and measured by many measuring devices in the array detector in order to make an image of gamma-ray intensity. The BNCT treatment effect (local tumor dose) can be estimated from the obtained three-dimensional gamma-ray image.

However, the 478 keV gamma-rays must be measured in a very high neutron flux field, because we have to use a very intense neutron source. Especially, capture gamma-rays of 2.22 MeV produced by the ^{1}H(n,γ)^{2}H reaction and annihilation gamma-rays of 511 keV to be detected just adjacent to 478 keV gamma-rays become a very large and critical background. Also, actual medical conditions, i.e., protocol, irradiation site and so on, must be considered. Taking into account the above situation, we set four design criteria as follows:

(1) The spatial resolution should be about several mm in the obtained SPECT image from the viewpoint of medical treatment.
(2) It is necessary to complete a measurement in about 60 min, because the treatment time of BNCT is normally less than 1 h.
(3) The number of counts per unit detector should be more than 1000 counts so that the statistical accuracy can be kept to be less than several percent.
(4) The energy resolution, full width at half maximum (FWHM), should be less than 33 keV (511–478 keV) so as to measure annihilation gamma-rays and 478 keV prompt gamma-rays separately.

Finally, we decided to employ a CdTe device as an elemental gamma-ray measuring device after precise investigation.[1]

Practically, at first, by theoretical calculations the necessary efficiency of the elemental CdTe detector was fixed. The size of the CdTe crystal was then determined meeting the spatial resolution requirement and keeping the necessary efficiency.[2,3] Consequently, we confirmed that the thickness of more than 30 mm was necessary in case of assuming that the incident surface was 2 × 1.5 mm.[4]

Next, the expected performance was confirmed through test measurements with an actually produced CdTe crystal. It was found from the measurement that 478 keV and annihilation (511 keV) gamma-rays could be measured separately, although it has been pointed out to be a critical problem so far.[5,6]

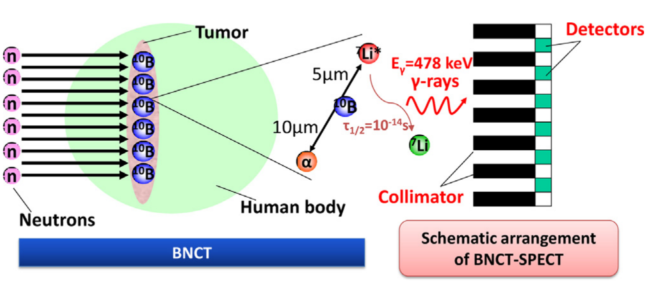

Fig. 1 – Principle of BNCT-SPECT.

2. Aim

The purpose of this study is to design the measuring device arrangement of array-type CdTe detector for BNCT-SPECT. In this study, we investigate the design feasibility of the BNCT-SPECT system considering the detector assembly, irradiation room and even arrangement of CdTe crystals. At first, we design a suitable collimator which would be a very important part of the array-type CdTe detector. As the design target, we set the number of counts being greater than 1000 for 60 min at 478 keV peak and, supplementarily, set signal to noise (S/N) ratio being greater than unity. As mentioned later in Fig. 6, the S/N ratio is not acceptable. To improve the S/N ratio at the photopeak of 478 keV, anti-coincidence measurement is examined by using an array-type CdTe detector.

3. Materials and methods

We designed a collimator for an array-type CdTe detector so that a sufficient number of counts (>1000) could be obtained within 1 h with an acceptable S/N ratio in a real BNCT scene. Fig. 2 shows a schematic drawing of the collimator. The CdTe detector size was assumed to be achievable maximum dimensions (2 mm × 2.5 mm × 40 mm) at present in Japan. The collimator hole diameter was determined to be 2 mm considering the CdTe detector size and the spatial resolution. The