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Tomographic image of prompt gamma ray from boron neutron capture therapy: A Monte Carlo simulation study

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1. Introduction

Boron neutron capture therapy (BNCT) is an accurate radiation therapy technique based on the high cross-section of the $^{10}B(n, \alpha)^{7}Li$ reaction. After a thermal neutron (<1 eV) is captured by the boron, in 94% of the neutron captures, a 1.47 MeV ^{7}Li ion and 0.84 MeV alpha particle, which has a high linear energy transfer (LET), are emitted from the reaction point. In addition, it decays immediately through a 478 keV prompt gamma ray. The resulting neutron captures in ^{10}B are used for radiation therapy. The occurrence point of the characteristic 478 keV prompt gamma rays agrees with the neutron capture point. If these prompt gamma rays are detected by external instruments such as a gamma camera or single photon emission computed tomography (SPECT), the therapy region can be monitored during the treatment using images. A feasibility study and analysis of a reconstructed image using many projections (128) were conducted. The optimization of the detection system and a detailed neutron generator simulation were beyond the scope of this study.

2. Materials and Methods

The ordered subset expectation maximization (OSEM) algorithm was used to reconstruct 3D BNCT−SPECT image. And dose delivery quantity of boron region and the accuracy of reconstructed image were verified. In case of simulation, the pixelated SPECT detector, collimator and phantom were simulated using Monte Carlo n−particle (MCNPX) simulation tool. In addition, the geometric specifications of the phantom and SPECT detector were chosen for the evaluation of reconstructed image. In the simulation, there were three major portions for BNCT−SPECT system. First, a thermal neutron source (<1 eV) was used to react with the boron uptake region in the phantom. The distance between the source and the center of the phantom was set at 20 cm using the parallel collimator. At the center of the phantom, the neutron flux passed through the entire cross−sectional area of the phantom. In the preliminary simulation, about 10 thousand deposit events for the 478 keV gamma rays were collected from an NPS of 2 billion over approximately 18 hours. To effectively utilize the simulation time, a value of 60 million was chosen for the NPS of each neutron source in the MCNPX simulation for one projection. Then, in order to simulate the parts of a brain tumor, the phantom for BNCT−SPECT included bone, skin, brain, and boron uptake regions. Each geometric pattern had a spherical pattern, and three different boron uptake regions were located in the middle of the brain material. The density of all the boron regions was 2.08 g/cm3, and their diameters were 6 cm, 4 cm, and 2 cm. The brain material was 18 cm in diameter and had a density of 1 g/cm3. The densities of the bone and skin materials were set at 1.92 g/cm3 and 0.93 g/cm3, respectively, and these two materials were 0.2 cm thick spherical shells with outer diameters of 18.4 cm and 18.8 cm, respectively. The bone under the skin surrounding the brain material included three boron uptake regions. The center coordinates of these three boron regions were A: (−5, 0, 0), B: (0, 5, 0), and C: (5, 0, 0). CsI(Tl) scintillator was chosen as the material for the detector, which has a density of 4.51 g/cm3, one pixel of the 67 × 67 CsI(Tl) scintillator was 0.6 cm × 0.6 cm × 3 cm in size. Sorting the necessary photon events for image reconstruction was possible using the P−trac data. In order to reconstruct the BNCT−SPECT image, the prompt gamma rays had to be collected at the detector area with the energy and position data. The data from 128 projections for each sorting process were used to achieve image reconstruction. The OSEM reconstruction algorithm was used to obtain a tomographic image with eight subsets and five iterations, because too many iterations caused severe degradation of the source signal, and too few subsets induced a long reconstruction time. Thus, the preliminary research data showed that the most suitable conditions were eight subsets and five iterations to reconstruct and evaluate an image. A diagram of the whole system of SPECT is shown in Fig 1.

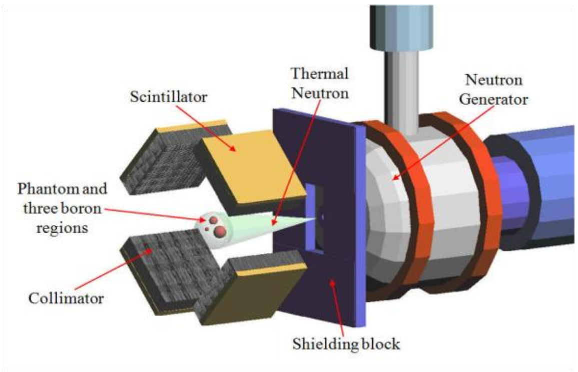

Figure 1. Diagram of BNCT SPECT system for simulation. Four heads detection system with neutron generator and shielding block, three boron uptake regions (red sphere) in brain phantom and thermal neutron emission (green cone).

3. Results and Discussion

In the case of the reconstructed images, even though 97 × 97 pixels were applied to the image, the image quality was improved by the application of 10 times matrix interpolation between pixels. The SPECT reconstructed image of a 478 keV prompt gamma ray is shown in Fig. 2.

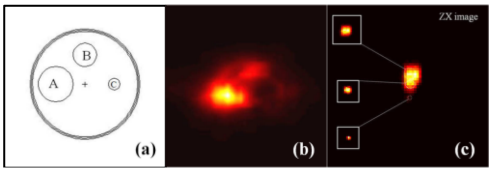

Figure 2. Original pattern image of brain phantom, including three boron uptake regions (a), image reconstructed using OSEM algorithm (b), and ZX plane image (c).

ROC curve analysis method was used to evaluate the geometric accuracy of a reconstructed image. To determine the true signal from a pixel, a tolerance value was applied to compare the signal intensity of each pixel. The tolerance value was set using plus or minus N−value (0−10%) at average value of signal intensity. The area under the curve (AUC) was calculated as the gross area under each ROC curve. The three calculated AUC values were 0.738 (A region), 0.623 (B region), and 0.817 (C region). The AUC value of C region was higher than the values for the other regions.

4. Conclusion

The possibility of extracting a 3D BNCT–SPECT image was confirmed using the Monte Carlo simulation and OSEM algorithm. The quality of the prompt gamma ray SPECT image obtained from BNCT was evaluated quantitatively using three different boron uptake regions and was shown to depend on the location and size relations. The prospects for obtaining an actual BNCT–SPECT image were also estimated from the quality of the simulated image and the simulation conditions. When multi tumor regions should be treated using the BNCT method, a reasonable model to determine how many useful images can be obtained from SPECT can be provided to the BNCT facilities based on the preceding imaging research. However, because the scope of this research was limited to checking the feasibility of 3D BNCT–SPECT image reconstruction using multiple projections, along with an evaluation of the image, some simulation conditions were taken from previous studies. In the future, a simulation will be conducted that includes optimized conditions for an actual BNCT facility, along with an imaging process for motion correction in BNCT.

Although an excessively long simulation time was required to obtain enough events for image reconstruction, the feasibility of acquiring a 3D BNCT−SPECT image using multiple projections was confirmed using a Monte Carlo simulation, and a quantitative image analysis was conducted.

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