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Prompt Gamma Ray Imaging during Proton Boron Fusion Therapy: A Monte Carlo study

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1. Introduction

Many approaches to develop an effective radiotherapy technique have been investigated based on physical and medical theory [1-3]. One of the latest effective radiation therapy techniques called proton boron fusion therapy (PBFT) is based on the proton boron fusion reaction and has been proposed and verified for radiotherapy in a feasibility study [4,5]. As shown in Figure 1, a proton captures ^{11}B, resulting in an excited state of ^{12}C, which divided into a 3.76 MeV alpha particle and ^{8}Be. Then, ^{8}Be decays immediately into two 2.46 MeV alpha particles and a 719 keV prompt gamma ray [4,5].

Monitoring the therapeutic region is one of the most important factors to perform successful radiotherapy. Several studies have estimated the distribution of the boron uptake region (BUR) during the treatment [4]. Moreover, a real-time monitoring technique using 478 keV prompt gamma rays has been reported [5].

Our proposed prompt gamma ray imaging method during PBFT is analogous to the boron neutron captur therapy (BNCT) imaging technique. If the detection conditions for 719 keV prompt gamma rays are optimized, tumor region monitoring can be realized during PBFT using a single photon emission computed tomography (SPECT) scanner. This image reconstruction technique is based on the image itself using the prompt gamma rays generated in the BUR. Thus, the purpose of this study was to verify the effectiveness of tumor region monitoring method using 719 keV prompt gamma rays during PBFT and to confirm the therapeutic effect of PBFT.

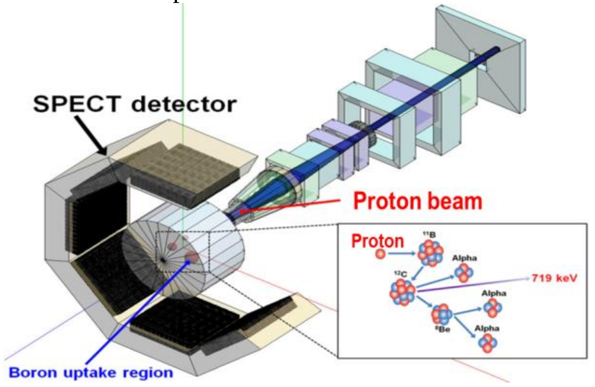

Figure 1. Diagram of the principle of the proton boron fusion therapy (PBFT) and single photon emission computed tomography (SPECT) system using a Monte Carlo simulation tool. The water phantom included boron uptake regions (BUR) surrounded by a four head SPECT that detected and reconstructed the 719 keV prompt gamma ray events from BURs in the virtual phantom.

2. Methods and Results

PBFT therapeutic conditions were simulated using the Monte Carlo n-particle extended (MCNPX, Ver. 2.6.0, National Laboratory, Los Alamos NM, USA) simulation code, as illustrated in Fig.1 [3,4].

2.1 System description

The four heads of the SPECT detectors included LYSO (density = 7.2 g/cm^3) detector material, which has high stopping power and high light output with fast decay time. A scintillator block of 400 × 200 × 30 mm^3 was comprised of an 80 × 40 crystal array based on position sensitive photomultiplier tube size (H8500, Hamamatsu Photonics, Hamamatsu City, Japan). The center of the detector was located 10 cm from the coordinate center. The spherical virtual water phantom (diameter = 18 cm, density = 1 g/cm^3) contained four BURs. The four BURs had spherical patterns with different diameters (1, 2, 2.5, and 3 cm, density = 2.08 g/cm^3), and they were placed at different locations (A: (0, 0, 3), B: (−3, 0, 0), C: (0, 0, −3), and D: (3, 0, 0)). A distance between the proton source and the center of the water phantom was 15.4 cm. A tungsten parallel collimator (density = 17.3 g/cm^3, thickness = 0.25 cm, and height = 8 cm) was designed to attach to the LYSO block.

2.2 Energy spectrum and percentage depth dose

Energy spectrum was acquired using the F8 tally (energy distribution tally) function in MCNPX, which generates the energy distribution of pulses created in the detector to confirm the emission of prompt gamma rays generated by the proton boron reactions [3]. The Gaussian energy broadening value for the LYSO in the MCNPX code was referred from a previous study [4]. The energy window range was set to 20% of the 719 keV prompt gamma ray peaks to acquire the effective events needed for image reconstruction.

The percentage depth dose (PDD) of the proton beam was deduced using F6 tally (absorbed dose tally) in MCNPX [2,4]. The water phantom was divided into 100 frames of 0.1 cm in the z-direction with/without a BUR for measuring PDD. The center of the BUR was used as adapted to the proton's maximum dose level point from water without the BUR.

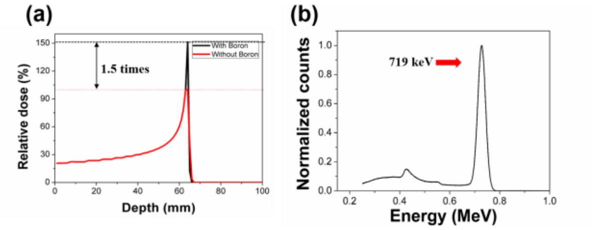

Figure 2. (a) Percentage depth dose (PDD) of the proton beam from the water phantom with and without boron uptake regions (BURs). The red line indicates the PDD of the proton beam without boron, whereas black line indicates the PDD of the proton beam with BURs. (b) Energy spectrum of prompt gamma ray caused by reaction between protons and boron; the 719 keV prompt gamma ray is clearly observed.

2.3 Imaging capability and reconstructed image evaluation

The phantom images were reconstructed using the maximum likelihood expectation maximization (MLEM) reconstruction algorithm at iteration number 1, 5, and 10. Projection data at each rotation angle were used to reconstruct the image. The raw data from the 64 projections with a rotating angle frame of 11.25° was acquired, and a 20% energy window was applied to the 719 keV peak.

After acquiring the PBFT-SPECT images, the image profile was measured according to the function of iteration number. In addition, contrast was acquired on the region of interest (ROI) for each BURs.

The distance between two BURs and full width at half maximum (FWHM) of the line profile was measured according to the iteration numbers to quantitatively evaluate the reconstructed image.

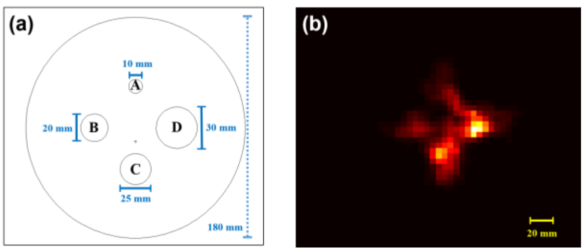

Figure 3. (a) Original pattern of the virtual water phantom including the four boron uptake regions (BURs). This diagram presents the diameter of each BUR and the water phantom. (b) Reconstructed prompt gamma ray image using the maximum likelihood expectation maximization algorithm and 64 projections. Pixel size on the reconstructed image was 5 mm.

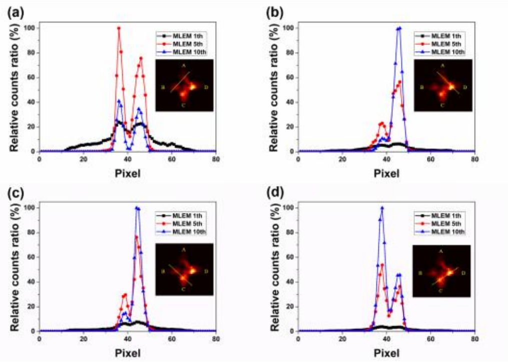

Figure 4. Image profile including two boron uptake regions (BURs). The graph of the relative counts ratio of A and B regions is shown in (a) based on the iteration number (1, 5 and 10), and the image profile shows the relative counts ratio of each line including the two different BURs in (b - d) for iteration numbers 1, 5, and 10.

3. Conclusions

This study was performed to confirm the feasibility of a SPECT tumor monitoring technique during PBFT. The optimal image conditions for acquiring prompt gamma ray images were investigated through a quantitative image evaluation of prompt gamma rays according to the iteration number for MLEM reconstruction technique, we evaluated the FWHM and distance between two BURs on each image profile for each iteration up to ten, as well as contrast for each BUR within the ROI. Although further verification is essential to confirm the feasibility of clinical application using this method, this study shows the basic concept of the tumor monitoring technique for further studies. In addition, this method has various advantages compared with conventional techniques, such as high therapeutic effectiveness and tumor monitoring during treatment. The PBFT-SPECT system provided precise guidance as a promising tumor monitoring technique for more accurate particle therapy.

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