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Neutron beam characterization and dose calculation of accelerator-based boron neutron capture therapy with Monte Carlo simulations

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1. Introduction

Boron neutron capture therapy (BNCT) is binary radiation treatment modality. It treats tumor cell selectively using ^{10}B compound and neutron beam. The ^{10}B nuclei which have high thermal neutron capture cross-section, release α particle and ^{7}Li ion in ^{10}B(n, α)^{7}Li reaction. These products have high linear energy transfer characteristics and their ranges are around single cell diameter (~10 μm). Therefore, BNCT can selectively treat the tumor cell by the targeted boron drug delivery [1]. In the South Korea, accelerator-based BNCT (A-BNCT) facility is under construction aiming to make epithermal neutron source. A-BNCT has advantages over reactor based BNCT, i.e. comfortable accessibility, cheap maintenance costs, simple operation and neutron beam characteristics [2].

The primary object of this study was to characterize the neutron beam from the facility and calculate the therapeutic dose of A-BNCT. We used Monte Carlo simulations with DICOM CT images.

2. Methods and Results

2.1 Target and moderator design

The target and moderator assembly (Figure 1) were fully designed and revised from the previous study by Pohang Accelerator Laboratory, PAL. The target is changed from previous study to the 20 mm thick bulk beryllium target and supporting material copper. The copper is used for the heat exchanger due to its high thermal conductivity. The various materials of moderator, beam shaper, collimator and shielding are also marked on the Figure 1.

2.2 Monte Carlo Simulations

Monte Carlo simulations were done using Geant4 version 10.3 [3]. The entire assembly geometry was imported to Geant4 geometry. We used the reference physics list named “QGSP_BIC_AllHP” which uses evaluated nuclear data sets from TENDL-2014 and ENDF/B-VII.1 for the precise simulations of neutron and proton.

The incident proton beam to the beryllium target was assumed as uniform field (13 x 13 cm^{2}) and mono-energy (10 MeV). Before the dose calculation, the phase-space file was made to reduce computing time for the other repetitive patient dose calculations. The neutrons and gamma which passed through the moderator and filter were collected to make a phase-space file recording the position, direction, energy and particle name of each radiation. Then, this phase-space file was used to irradiate DICOM CT images.

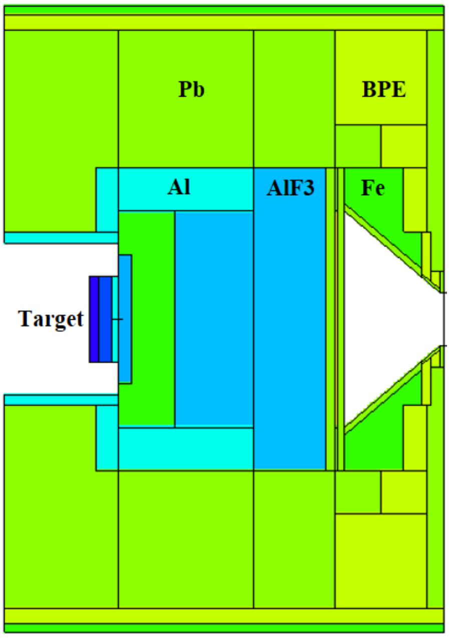

Fig. 1. The target and moderator assembly (designed by PAL).

2.3 Dose calculation of A-BNCT dosimetry

The dose calculation of the A-BNCT is distinct from the conventional radiation therapy. The dose was separated into four components, (a) boron dose – from α, ^{7}Li particle, (b) nitrogen dose, (c) fast neutron dose, (d) gamma dose to correct the different biological effectiveness of each dose components in the tissue [4]. The boron dose is produced by ^{10}B(n, α)^{7}Li reaction, nitrogen dose is produced by ^{14}N(n, p)^{14}C reaction, fast neutron dose is from ^{1}H(n, n’)^{1}H reaction and gamma dose is from photons created inside the patient body and incident photons. These four dose components are classified and collected in the Monte Carlo simulations. The weight factors, CBE (Compound Biological Effectiveness) for the boron dose and RBE (Relative Biological Effectiveness) for the others were used from the previous study [5].

The anonymized patient’s DICOM CT images were modified to have spherical tumor (4 cm in diameter) in 5 cm depth. The boron concentration of tumor and normal tissue was defined as 15, 60 ppm, respectively.

3. Results

3.1 Neutron beam characteristics

Figure 2 shows the neutron and gamma beam spectrum at the beam exit. The neutron beams are moderated passing through the moderator. Over 85% of neutrons are in the epithermal range at the beam exit. Figure 3 shows the radial flux at the aperture whose final radius is 6 cm. The flux also steeply decreased after 6 cm apart.

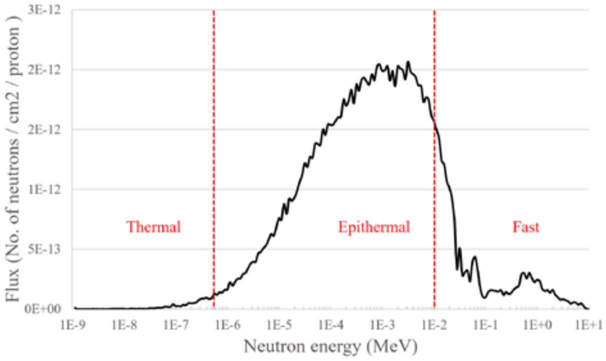

Fig. 2. The neutron energy spectrum.

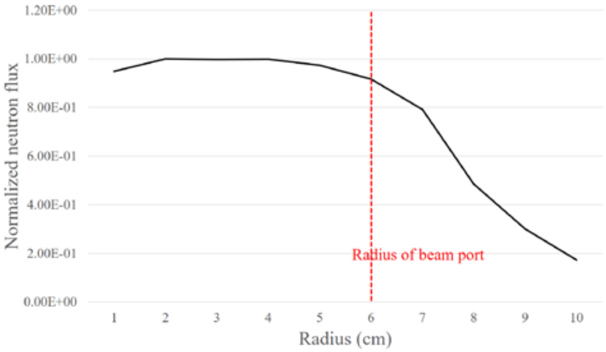

Fig. 3. The radial flux of neutron beam.

3.2 Dose along the beam axis

Figure 4 shows the depth dose (weighted) along the beam axis. At the depth of tumor, the boron dose steeply increased and gradually decreased until tumor ends showing the therapeutic effect to the tumor region. At the shallow depth, however, the fast neutron and gamma dose dominates the total depth dose. This could be reduced by optimizing the moderator and collimator design.

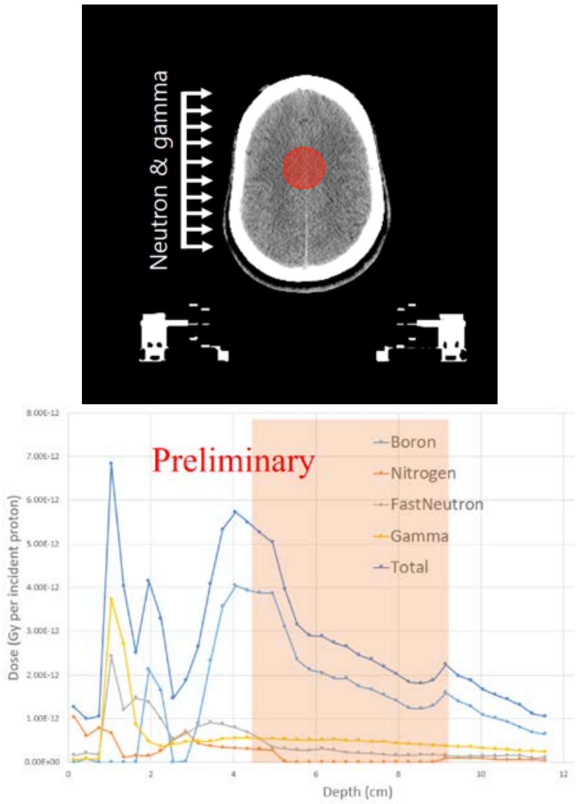

Fig. 4. DICOM CT image, the red circle is tumor region (top), the weighted depth dose along the beam axis (bottom).

4. Conclusions

In this study, the beam characteristics and dose were calculated with Monte Carlo simulation. There are improvement points remaining in assembly design to reduce shallow depth dose, however, the calculated dose components of A-BNCT from this study is the first step of getting better therapeutic effects. These data could be used for not only in the treatment planning system but also in the clinical research area in the near future.

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