

## A First step toward for Prompt Gamma Ray imaging technique during Antiproton Therapy using Boron particle

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In this study, we propose a tumor monitoring technique using prompt gamma rays emitted from the reaction between an antiproton and a boron particle, and verify the improvement of the therapeutic effectiveness of the antiproton boron fusion therapy compared with proton and antiproton beam without boron. The tumor monitoring system during the antiproton therapy was simulated using the Monte Carlo simulation code. We acquired the percentage depth dose of the antiproton beam from a water phantom with and without three boron uptake regions (BURs; region A, B, and C). The obtained results were compared with the performance of a conventional proton beam. The tomographic image of the BURs was reconstructed using prompt gamma ray events which sorted from the single photon emission tomography during the treatment. In addition, quantitative methods were adopted to show the accuracy of the reconstructed image. The tomographic image using 719 keV prompt gamma ray showed that the BUR was successfully identified from the simulation results. Moreover, the maximum peak of antiproton beam with boron is almost three times greater than that of proton beam. We confirmed the feasibility of tumor monitoring during the antiproton therapy as well as the superior therapeutic effect of the antiproton boron fusion therapy.

### I. INTRODUCTION

The antiproton, the stable antiparticle of the proton, has the same physical characteristics of the proton, but carries a negative charge and different magnetic moment [1]. Antiprotons are generated by accelerating protons which accelerated to 26 GeV/c in a proton synchrotron to strike a fixed target; the collision produces a small quantity of antiprotons (less than 1%) [1]. Consequently, some researchers concluded that they could be applied in radiation therapy [1,2]. The biologically effective dose ratio has showed that the antiproton is four times more effective than the conventional proton for cell irradiation [3-5]. Tumor monitoring using the prompt gamma ray presents several advantages. First, the region accuracy of the irradiation can be evaluated during the treatment. In case of inaccuracy, the therapy can be stopped immediately. Second, as the status of the tumor under treatment can be confirmed, the accuracy of the treatment level can be analyzed, and the prognosis estimated. Third, the radiation treatment planning for the next therapy can be easily corrected through the reflection based on the prognosis from the previous prompt gamma ray imaging.

Briefly, the purpose of this study is to verify the effectiveness of the antiproton boron fusion therapy and the acquisition of the tumor image by using the prompt gamma ray emission during the treatment.

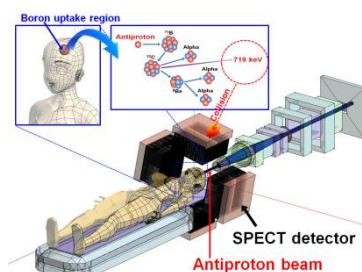


Fig.1. The water phantom, including three boron uptake regions (BURs; red regions), is located at the center of the four head single photon emission computed tomography system. The antiproton beam reacts with the boron particles at the BURs. The emission of the 719 keV prompt gamma ray is illustrated in the inset..

## II. METHODS AND RESULTS

We used the Monte Carlo N-particle extended (MCNPX, Ver. 2.6.0, Los Alamos National Laboratory, Los Alamos, NM, USA) simulation code to prove the correctness of the concept at the basis of the proposed monitoring technique [6].

The cylindrical water phantom (density = 1 g/cm<sup>3</sup>) had a diameter of 160.0 mm and a height of 100.0 mm [8]. The three different-sized BURs were placed at different locations, and denoted as region A (diameter = 20.0 mm, x = 15.0 mm, y = -13.2 mm), region B (diameter = 15.0 mm, x = -18.9 mm, y = -6.4 mm), and region C (diameter = 10.0 mm, x = 3.9 mm, y = 19.6 mm). The height of the three BURs was 20.0 mm. The boron concentration was 780 µg/g; this value was derived from a previous BNCT study on the clinical use of boron concentration.

For the operation of the MCNPX, the concept of boron concentration should be defined as the density. When the boron particles were stacked at the tumor, the tumor volume had an average density of 2.0 g/cm<sup>3</sup>. This value is sufficiently differs in relation to the conditions (e.g., patient, metabolism, etc.), and it is not an absolute standard.

As the 719 keV prompt gamma ray is a single photon, a four head SPECT system was used to acquire the tomographic image of the identified tumor region. Typically, conventional SPECT is used to detect low energy photons (< 500 keV). As 719 keV is relatively high photon energy, the design of a collimator and high-density detector material had to be considered. In our simulation, to simulate the SPECT system, we used a tungsten (density = 17.3 g/cm<sup>3</sup>) parallel collimator with a thickness of 2.5 mm and lutetium yttrium oxyorthosilicate (LYSO, density = 7.3 g/cm<sup>3</sup>) detector material with a thickness of 30 mm. The flux of the antiproton source was set at  $2.56 \times 10^{10}$  n/cm<sup>2</sup>-s, which sufficiently covered the BURs. Fig. 1 shows a diagram of the simulation setup, including the SPECT system, the phantom, and the antiproton therapy system. The schematic in the inset illustrates the atomic reaction occurring between antiproton and boron.

The energy spectrum of the prompt gamma ray emitted during the reaction between antiproton and boron was deduced using the F8 tally function (energy deposition tally) of the MCNPX code [6]. Furthermore, the percentage depth dose (PDD) of the antiproton was extracted from the water phantom, including the BURs, using the F6 tally function (absorbed dose tally) of the MCNPX code [6]. The acquisition of the tomographic image to monitor the tumor during the treatment required a SPECT scan with a low projection number.

The events of the 719 keV prompt gamma ray for imaging were collected using a 10% energy window. The receiver operating characteristic (ROC) curve was used to analyze the accuracy of the reconstructed image.

## III. CONCLUSION

The treatment of a tumor using an antiproton beam with boron particles has clearly positive effects. First, the proton maximum dose level can be increased by the antiproton boron fusion reaction, and a more critical dose can be transferred to the tumor than that delivered in conventional antiproton therapy or proton therapy. Second, tumor monitoring using the prompt gamma rays produced by the reaction between the antiprotons and the boron is possible during the treatment, and can provide the guidance for a more accurate radiation therapy. In future work, further simulation studies including a clinical factors will be performed.

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