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Original research article

Design of spread-out Bragg peaks in hadron therapy with oxygen ions

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ABSTRACT

Aim: Design of a numerical method for creating spread-out Bragg peak (SOBP) and evaluation of the best parameter in Bortfeld Model to this aim in oxygen ion therapy.
Background: In radiotherapy, oxygen ions have more biological benefits than light beams. Oxygen ions have a higher linear energy transfer (LET) and larger relative biological effectiveness (RBE) than lighter ones.
Materials and methods: For the design of the spread-out Bragg peak (SOBP) for oxygen beam, we designed a numerical method using the Geant4 Monte Carlo simulation code, along with matrix computations.
Results: The profiles of the Bragg Peak have been calculated for each section in the target area by the Geant4 tool. Then, in order to produce SOBP smoothly, a set of weighting factors for the intensity of oxygen ion radiation in each energy was extracted through a numerically designed method. This method was tested for producing SOBP at various widths and at different depths of a phantom. Also, weighting factors of intensity for producing a flat SOBP with oxygen ions were also obtained using the Bortfeld model in order to determine the best parameters. Then, the results of the Bortfeld model were compared with the outcomes of the method that was developed in this study.
Conclusions: The results showed that while the SOBP designed by the Bortfeld model has a homogeneity of 92–97%, the SOBP designed by the numerical method in the present study is above 99%, which in some cases even closed to 100%.

1. Background

High energy ionizing radiation, through delivering dose to matter, and creating Bragg peaks in a particular area in the target, is an appropriate option for radiation therapy. The radiation dose in the entrance area is low, while the maximum dose in the target area is delivered. Compared to light ions, oxygen is classified as a beam with a high linear energy transfer (LET). A beam with a high LET has a larger RBE than low LET such as photons and protons.[1] In addition, the dose of the oxygen beam at the end of the Bragg peak leads to a large slope

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that prevents the absorption of unwanted doses to sensitive organs.

Obviously, because of Bragg peaks thinness, a monochromatic ionizing ray is not suitable for cancer treatment. Therefore, we need to extend Bragg peak to produce a smooth dose in the tumor area, which is possible by preparing an ion beam array with appropriate energy distribution. The problem of the production of an SOBP through a weighted unit of monochromatic proton beams has been investigated by various researchers, in particular by Bortfeld and Schlegel,[2] Bortfeld,[3] Pedroni et al.,[4] Hérault et al.,[5] Hérault et al.,[6] Kooy et al.,[7] and Jette and Chen.[8] In these studies, the SOBP design was investigated in a variety of ways, such as analytical methods, Monte Carlo methods and, based on the results, were mainly compared with empirical findings. However all of these studies were performed for proton irradiation.

With the development of hadron therapy with ions other than proton therapy, it is necessary to design methods for modulating the intensity of ions such as helium, carbon, oxygen, or other ions that are involved in the Hadron therapy at the research stage. Most carbon studies, e.g. Sakama et al.[9] and Suit et al.[10] examined filters for smoothing SOBP in passive scattering proton beams method. For the pencil beam scanning method, these studies have not been actively pursued until now, and only few studies have addressed this issue until now. For example, the SOBP design for carbon monoxide irradiation in the Hadron Therapy has been studied in Kim et al.[11] But no specific study has been done on heavy ions such as oxygen.

For proton, there is a variety of algorithms for modulating the intensity of ion beams to produce a smooth SOBP in previous research. Bortfeld and Schlegel[2] reported a simple way of determining the weights of primary energies to the creation of SOBP for proton beams. Jette and Chen[8] improved the results obtained by Bortfeld by introducing corrections to this method. The smoothness of the SOBP obtained by this method (i.e. the *Bortfeld model*) is strongly dependent on the parameter p which refers to the power of energy in the power-low energy-range relation in Eq. (1) presented below. Since the value of this parameter, depends on the type of ion, ion energy, and also the width of the SOBP, it is difficult to guess the p value for designing the treatment. Hence, finding more suitable methods for producing a smooth SOBP is necessary.

2. Aim

In this study, due to the irradiation of oxygen ions, a numerical method was proposed based on Monte Carlo and Matrix Computations (that we call the MCMC method) to generate weighting factors. This method can be used for the other ions, too. In this process, we first find the profiles of the Bragg peaks at various depths of a phantom using the Monte Carlo calculations (in this study, by the Geant4 tool), then using an algorithm of matrix computation, we calculate the weights for the intensity of each monochromatic ion beam. Here, the MCMC method has been used for 5 different SOBPs with different depths and widths. In each case, the SOBP's homogeneity ratio has been calculated and compared with the results of the Bortfeld model.

3. Materials and methods

3.1. Simulation by Geant4 code

The Geant4 computing code is a package used for the Monte Carlo simulations of interacting particles with materials.[12] The system designed in the Geart4 Monte Carlo code is as shown in Fig. 1. The world is an air cube with dimensions of $2 \times 2 \times 4$ m and a cylindrical phantom with a radius of 0.5 m and a height of 1.8 m is in the world's volume so that the cylinder axis of the phantom is in the direction of the z-axis. The phantom is made from water. According to the energy of the oxygen ions, the length of the phantom was chosen in such a way that all the major ions in the phantom interior were stopped.

Due to SOBP production, the dose in each point overlaps with different depth-dose distributions that have been generated from different incident energies. So, for example, for producing an SOBP with a width of 3 cm at a depth of 3.5 to 6.5 cm in the phantom, the required ion energies will be from 140 MeV/u to 195 MeV/u for oxygen ions. This band of energy is divided into 22 sections (i.e. 23 monochromatic oxygen beams, with a difference of 2.5 MeV/u between two consecutive beams). The diameter of pencil beam is chosen 0.4 cm without divergence. The pencil beam of the oxygen ions, along with z-axis, hits the phantom and enters it.

To calculate the absorbed dose at different points of the phantom, we can use the cube scoring mesh. To evaluate the depth-dose distribution along the axial direction of the main beam, we used a cubic mesh and calculated the dose on the main axis of the incident beam at intervals of 0.1 mm.

Fig. 2 shows the distribution of the normalized dose along the z-axis for 23 different beams with the lowest energy (E = 140 MeV/u) that make a Bragg peak at x = 3.5 cm and the Bragg peak of the beam with maximum energy (E = 195 MeV/u) is at x = 6.5 cm (by this Bragg peak suite, we want to create a smooth SOBP, called SOBP1). Also, the second set of Bragg peaks, shown in Fig. 2, is from x = 11 cm to x = 14 cm (we also intend to create a flat SOBP from this set, called SOBP2).

The sum of these two sets of 23 dose profiles is also shown in Fig. 3. It is clear that these diagrams have not a desired smoothness of SOBP and it is strongly necessary to consider suitable weights for the intensity of each incident beam so that

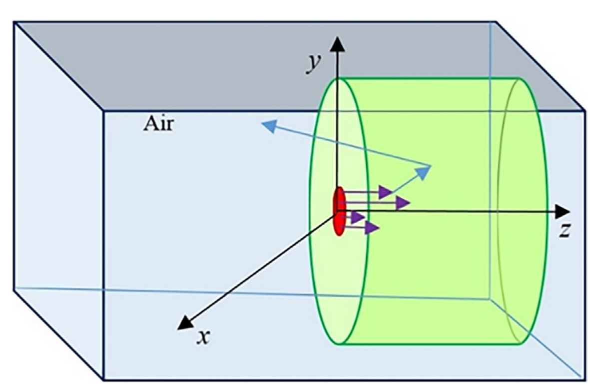

Fig. 1 – The geometry of system in the Monte Carlo simulation.