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Development of a new ridge filter with honeycomb geometry for a pencil beam scanning system in particle radiotherapy

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ABSTRACT

A ridge filter (RGF), a beam energy modulation device, is usually used for particle radiotherapy with a pencil beam scanning system. The conventional RGF has a one-dimensional (1D) periodic laterally stepped structure in orthogonal plane with a central beam direction. The energy of a beam passing through the different thicknesses of the stepped RGF is modulated. Although the lateral pencil beam size is required to cover the several stepped RGF units to modulate its energy as designed, the current trend is to decrease lateral beam size to improve the scanning system. As a result, the beam size becomes smaller than the size of the individual RGF unit. The aim of this study was to develop a new RGF with two-dimensional (2D) honeycomb geometry to simultaneously achieve both a decrease in lateral beam size and the desired energy modulation.

The conventional 1D-RGF and the 2D-RGF with honeycomb geometry were both designed so that the Bragg peak size of a 79 MeV/u carbon ion pencil beam in water was 1 mm RMS in the beam direction. To validate the design of the 2D-RGF, we calculated depth dose distributions in water using a simplified Monte Carlo method. In the calculations, we decreased the lateral pencil beam size at the entrance of the RGF and investigated the threshold of lateral beam size with which the pencil beam can reproduce the desired Bragg peak size for each type of RGF. In addition, we calculated lateral dose distributions in air downstream from the RGF and evaluated the inhomogeneity of the lateral dose distributions.

Using the 2D-RGF, the threshold of lateral beam size with which the pencil beam can reproduce the desired Bragg peak size was smaller than that using the 1D-RGF. Moreover, the distance from the RGF at which the lateral dose distribution becomes uniform was shorter using the 2D-RGF than that using the 1D-RGF. These results indicate that when the periodic length of both RGFs is the same, the 2D-RGF allows use of a pencil beam with smaller lateral beam size and a shorter distance from the RGF to the target, resulting in improvement in the conformity of dose distribution in a tumor.

1. Introduction

Thanks to its characteristic depth-dose distribution with a Bragg peak, particle beam radiotherapy provides high dose deposition within a tumor and is an effective tool for cancer therapy. The National Institute of Radiological Sciences (NIRS) in Japan has performed carbon-ion particle radiotherapy since 1994 using the Heavy-Ion Medical Accelerator in Chiba (HIMAC) [1]. To maximize the advantages of carbon-ion beams, the NIRS introduced a three-dimensional (3D) pencil beam scanning system in 2011 [2]. This irradiation system achieves conformal dose distribution to the tumor by scanning a pencil beam laterally with a pair of scanning magnets and longitudinally with changing the accelerated beam energy. In therapeutic irradiation, since the Bragg peak size is narrow, slight displacement of the beam path can induce inhomogeneities in depth-dose distribution. The narrow Bragg peak increases treatment time for the irradiation of an entire target volume. To achieve conformal dose distribution with a shorter irradiation time, an energy modulation device called a ridge filter (RGF) [3] is usually used. Use of the RGF increases the Bragg peak size and suppress the inhomogeneities of dose distribution due to beam position displacement. This also decreases irradiation time.

The RGF is a one-dimensional (1D) periodic laterally stepped structure (Fig. 1). The energy loss of the particles depends on the beam's incident position on the RGF. Designing each step thickness and width, we can control the energy modulation of the beam and the broaden the Bragg peak size. To obtain the designed Bragg peak size using the RGF, the lateral part of the pencil beam must be wide enough to pass through the multiple stepped units. In addition, to

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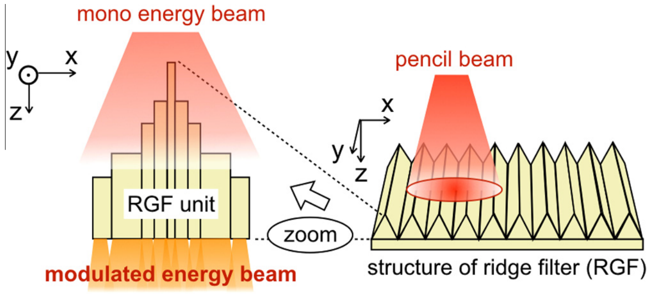

Fig. 1. Schematic of a conventional 1D-RGF structure. The *z*-direction corresponds to the beam direction. A RGF unit has fine stepped structure in a lateral direction.

obtain a laterally-homogeneous conformal dose distribution by scanning the beam, sufficient distance from the RGF is required to decrease the dose inhomogeneities induced by the particles scattered by the different thicknesses of the RGF steps [4].

However, the current trends are decrease of the lateral beam size, which is equivalent to an individual unit of the RGF, and shortening of the distance from the filter to the patient to improve the conformity of dose distribution in the tumor. The pencil beam with such a small beam size cannot reproduce the designed Bragg peak size with the conventional 1D-RGF. The aim of this study is the development of a new RGF to achieve the desired dose distribution using a smaller pencil beam and shorter RGF-to-target distance.

2. Materials & methods

We have designed a new RGF with two-dimensional (2D) honeycomb geometry as shown in Fig. 2. Extending the conventional 1D structure to the 2D structure, the number of RGF units laterally covered by the same size of pencil beam increases. In addition, the honeycomb geometry is the most efficient to pack the most RGF unit into the area covered by the pencil beam. We designed the new 2D-RGF with honeycomb geometry so that the Bragg peak size of a 79 MeV/u carbon ion-beam in water was 1 mm RMS in the beam direction. We first designed the number of beams with different energies required to produce the desired Bragg peak size and the weight of each beam. The number of beams defines the number of steps of a RGF unit and the weight of each beam defines the width of each step. We also designed the 1D-RGF with the same periodic length of the 2D-RGF for comparison. We assumed that the RGFs are made from polymethylmethacrylate (PMMA).

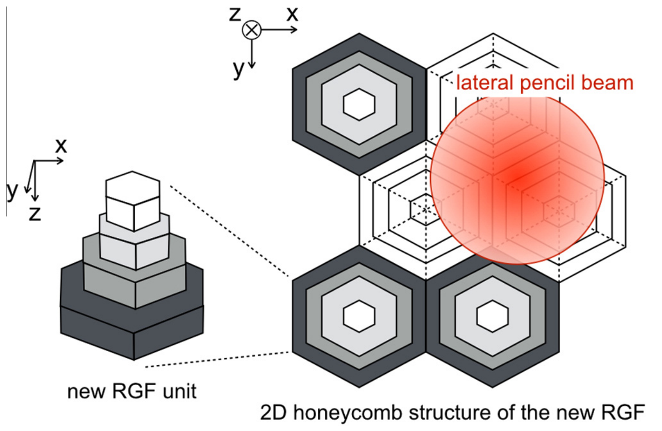

Fig. 2. Schematic of a new 2D-RGF with honeycomb geometry. The *z*-direction corresponds to the beam direction.

To validate the design of the RGFs, we calculated and compared dose distributions produced by the beam passing through the 1D-RGF to those of the beam passing through the 2D-RGF using the simplified Monte Carlo (SMC) method [5,6]. The SMC method calculates a dose distribution by tracking individual particles. The SMC starts tracking a particle at the entrance to the RGFs. We define the initial lateral beam size and the RMS value of initial angular distribution. When the particles pass a material, the SMC converts the range loss in the material to that in water. The SMC uses a measured depth dose distribution in water and dose deposit in the material is defined by the measured dose distribution and the calculated range loss in water. Scattering projection angles are given by random numbers according to a normal distribution with a standard deviation calculated by the Highland formula [7]. We used actual radiation lengths depending on a material for the calculation of scattering angles.

For the calculation using the conventional 1D- and new 2D-RGF, we investigated and compared the minimum beam size which can reproduce the desired Bragg peak size. First, we defined different beam sizes upstream of the RGF and calculated depth dose distribution using individual pencil beams in water. The calculated dose distributions with each of the beam sizes were compared with the designed one and the difference was evaluated by the chi-squared index defined below:

$$\chi^2 = \sum_z \frac{\{Calc.(z) - Dsgn.(z)\}^2}{Dsgn.(z)} \tag{1}$$

where *Calc.(z)* and *Dsgn.(z)* is the calculated and designed dose value at the depth of *z* mm in water, respectively. The large chi-square means a large difference of depth dose distribution between the design and the calculation. For the one condition of the initial beam size, we varied the center position of the incident pencil beam within the RGF unit to evaluate the dependence of the depth dose distribution on the incident beam position.

We also calculated lateral dose distributions in air downstream from the RGF to evaluate the relationship between the distance from the RGF and the lateral inhomogeneities of dose distribution induced by the RGF. The lateral inhomogeneities are defined as:

$$inhomogeneity = \frac{1}{f_{ave}} \sqrt{\sum_x \sum_y \frac{\{f(x,y) - f_{ave}\}^2}{n}} \tag{2}$$

where $f(x, y)$ is the fluence value at the lateral position of (x, y) and f_{ave} is the averaged value in the evaluated irradiation field. The n is the number of evaluated points. The inhomogeneity is equivalent to the rms value of the uniform irradiation field. When the inhomogeneity is less than the statistical error of the SMC calculation, the lateral distribution is regarded as uniform.

3. Results & discussions

Fig. 3 shows the previously designed and the two calculated depth dose distributions in water. One of the calculations used the conventional 1D-RGF and another used the new 2D-RGF with honeycomb geometry. We assumed that the lateral beam size defined as RMS value was 0.3 × the periodic length of the RGF. In Fig. 3(a), we found that the calculated distributions with the conventional 1D-RGF depended on the incident center position of pencil beam. The difference of calculated dose distribution from the designed one due to this dependence induces dose inhomogeneity in a tumor. In contrast, the calculated distribution with the 2D-RGF did not depend on the incident center position of pencil beam and reproduced the designed distribution well.

Fig. 4 shows the calculated relationship between the ratio of periodic length of the RGF to the lateral beam size and the

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