Experimental Evaluation of Proton Dose Calculations in Phantoms Simulating a Clinical Heterogeneity in Patients

Ryosuke Kohno[a], Yoshihisa Takada[b], Takeji Sakae[c], Toshiyuki Terunuma[d], Keiji Matsumoto[b], Akihiro Nohtomi[b] and Hiroyuki Matsuda[b]

[a]Division of medical physics, National Institute of Radiological Sciences (NIRS), Chiba, 263-8555, Japan, [b]Institute of Applied Physics, University of Tsukuba, Tsukuba, 305-8573, Japan, [c]Institute of Clinical Medicine, University of Tsukuba, Tsukuba, 305-8575, Japan, [d]Proton Medical research Center (PMRC), University of Tsukuba, Tsukuba, 305-8575, Japan
e-mail: r_kohno@nirs.go.jp

ABSTRACT

In a treatment planning for actual patients with a complex internal structure, we often expect that proton beams, which pass through both a bolus and the heterogeneity in body, will form complex dose distributions. Therefore, the accuracy of the calculated dose distributions has to be verified for such a complex object. Then dose distributions formed by proton beams passing through both the bolus and phantoms simulating a clinical heterogeneity in patients were measured using a silicon semiconductor detector. The calculated results by the range-modulated pencil beam algorithm (RMPBA) produced large errors compared with the measured dose distributions since dose calculation using the RMPBA could not predict accurately the edge-scattering effect both in the bolus and in clinical heterogeneous phantoms. On the other hand, in spite of this troublesome heterogeneity, calculated results by the simplified Monte Carlo (SMC) method reproduced the experimental ones well. It is obvious that the dose-calculations by the SMC method will be more useful for application to the treatment planning for proton therapy.

Key words: Proton dose distribution, simplified Monte Carlo method, pencil beam algorithm, heterogeneity

1. INTRODUCTION

A proton dose calculation method using the broad beam algorithm[1] has been widely used for treatment planning because of its simplicity and short calculation time. However, the calculation results often do not agree well with the measurement results for a target with large heterogeneities since it does not take into account the effect of ray mixing by multiple scattering effects of protons in material. To improve the accuracy of dose calculation for proton treatment planning, we have developed a dose calculation method based on the pencil beam algorithm (PBA)[1] and the range-modulated pencil beam algorithm (RMPBA)[2]. Dose calculation based on the pencil beam algorithm is current stream for proton treatment planning. However, the PBA and RMPBA do not model edge-scattering correctly, thus these calculation method methods produces errors in the boundary region of thick heterogeneous material whose edge is parallel to the beam's central axis[3]. On the other hand, since Monte Carlo methods take into account all physical interactions between particles and materials, they can accurately simulate the edge-scattering effect on proton. A simplified Monte Carlo (SMC)[3] dose calculation method has been developed to improve the situation. The accuracy of dose calculations by the method has been already evaluated for proton beams traversing geometrical phantoms[3]. However, in a treatment planning for actual patients with a complex internal structure like lung cancers or skull base tumors, the accuracy of the calculations may deteriorate due to rather complex dose distributions formed by proton beams passing through both the bolus and the heterogeneity in body. Therefore, the accuracy of the calculated dose distributions has to be verified further for such a complex object. In this paper, we investigate the accuracy of the calculated dose distributions by the RMPBA and the SMC by comparing the results with measurements for a phantom simulating a patient.

2. MATERIALS AND METHODS

2.1. Dose calculation methods

Dose distribution of the pencil beam in the RMPBA is separated into a central-axis term and an off-axis term. The central-axis term is a measured depth-dose curve in water of the range-modulated broad beam. The off-axis term is a two-dimensional Gaussian distribution whose standard deviation is a lateral beam spread which is a function of depth in water. The dose $F(x,y,z;(x_0,y_0))$ generated by a single range-modulated pencil beam with an entrance position, (x_0,y_0), is

given by

$$F(x,y,z;(x_0,y_0)) = \phi(x_0,y_0)RMDD(z)\frac{1}{2\pi\sigma(z;(x_0,y_0))^2}\exp(-\frac{(x_0-x)^2+(y_0-y)^2}{2\sigma(z;(x_0,y_0))^2}), \quad (1)$$

where $\phi(x_0,y_0)$ is the measured intensity profile of the modulated broad beam at the entrance position of the bolus, RMDD(z) the depth-dose distribution of the range-modulated broad beam, $\sigma(z;(x_0,y_0))$ the pencil beam spread. We can obtain the dose distribution in water by generating many pencil beams and by summing the dose distributions over (x_0,y_0). In the SMC method, a water-equivalent model of heterogeneous materials is used as well as in the RMPBA. Namely, each voxel of calculation volume is considered to be equivalent to water having the same range loss. The SMC method uses a measured depth-dose distribution of a broad beam in water to calculate energy loss at a given depth. The Highland formula is used for calculation of the rms value of multiple Coulomb scattering in each voxel. The crucial point is the use of the measured depth-dose curve for calculation of energy losses in materials, which simplifies the calculation yet preserving accuracy of calculation and serves to reduce calculation time.

2.2. Experiment

Measurements were carried out using a horizontal beam line at the old Proton Medical Research Center, University of Tsukuba. Approximately 250 MeV mono-energetic protons are supplied from the High Energy Accelerator Research Organization (KEK) 500MeV booster synchrotron through a carbon energy degrader and a momentum-analyzing system of the medical beam line. The incident protons were scattered by a 3-mm-thick lead plate (referred to as the first scatterer) to obtain a laterally uniform spatial distribution at a distant position. A binary range shifter of 253 mm thickness and a ridge-filter of 40 mm "spread–out Bragg peak (SOBP)" width were placed between the first scatterer and a patient couch on which we mounted devices for measurement of dose distribution. The residual range of the proton beam traversing them was 70 mm in water. To verify the accuracy of the calculated dose distributions for a complex object, we prepared heterogeneous phantoms (200×200×10 mm), which were made of Tough Water phantoms (TW) and Tough Lung phantoms (TL) and a bolus for the phantoms. The water equivalent thickness of a slab (10 mm in thickness) of TW and TL are 10.2 and 3.4 mm, respectively. These phantoms were arranged to simulate a lung cancer as shown in Fig. 1. We measured lateral (x)-dose distributions formed by proton beams passing through both the bolus and heterogeneous phantoms at intervals of one phantom thickness (10 mm) by scanning a silicon semiconductor detector (SSD) from z=12 to 132 mm.

3. RESULTS AND DISCUSSION

Comparison was made among measurements, the RMPBA and the SMC method. Figure 2 shows the iso-dose distribution measured by the SSD, that calculated by the RMPBA and that by the SMC method, respectively. The iso-dose curves are drawn for every 10% increase of the maximum relative dose. The experimental result by the SSD is obtained by interpolating the experimental lateral-dose distributions taken in 10 mm steps in the depth direction. The white region shows that with a relative dose of more than 90%, and the black region shows that with a relative dose less than 10%. The calculated results by the RMPBA produced large errors around x=0 from z=72 to z=132 mm compared with the measured dose distributions since dose calculation using the RMPBA could not predict accurately the edge-scattering effect around boundary at x=0 both in the bolus and in heterogeneous phantoms. In particular, predicted relative dose, 20%, at (x,z)=(5,132) by the RMPBA is 15% lower than the measured one, 35%. Moreover, edge-scattered protons which is the cause of the overdose also affect doses in the critical organ deeper than z=132 mm. Namely, this means that dose calculation by the pencil beam algorithm for such complex case could produce large errors which might result in a harmful effect in the critical organ. On the other hand, the SMC reproduced the measurements well. Thus, considering a possible harmful aftereffect due to hot spots formed by the edge-scattered protons and a possible under-dose region due to cold spots, it is obvious that the dose-calculations by the SMC will be more useful for application to the treatment planning for proton therapy.

4. CONCLUSION

The proton dose distributions determined by the SMC method agreed well with the experimental results, though those determined using the RMPBA could not predict the edge-scattering effect at all. In conclusion, care should be taken to apply the RMPBA to dose calculations for complex objects with large heterogeneities and the SMC method will be useful for more accurate dose prediction for such complex objects.

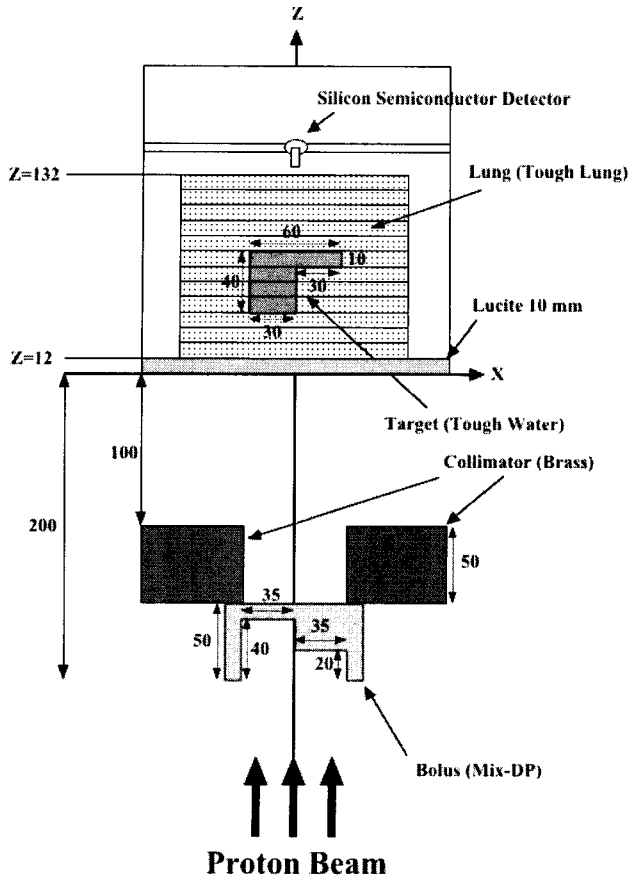

Fig. 1. Experimental arrangement for measurements of dose distributions in phantoms simulating a clinical heterogeneity in patients (plan view).

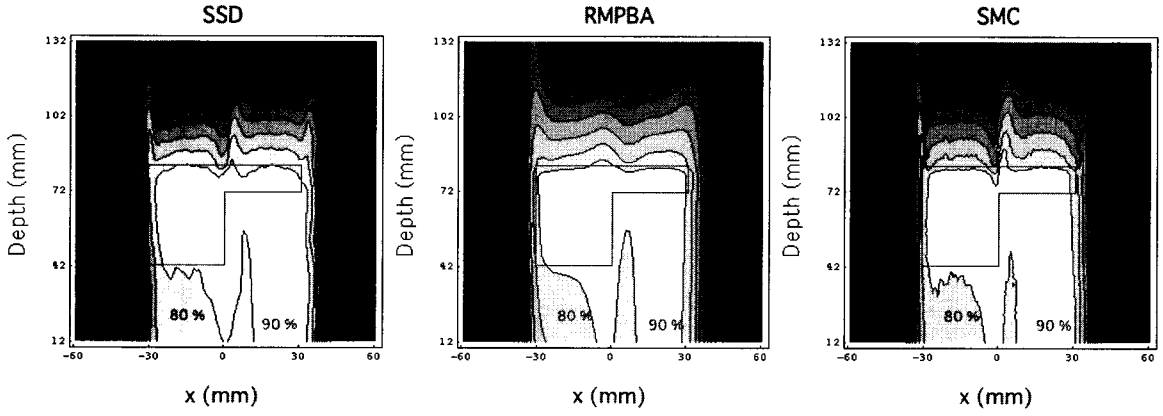

Fig. 2. Comparison of the iso-dose determined by the SSD (left) and by calculations using the RMPBA (middle) and the SMC method (right).

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