Biological dose calculation on dual-layered dual energy computed tomography images for carbon ion therapy

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1. Introduction

Carbon ion radiotherapy (CIRT) is a type of charged particle therapy and is currently being applied clinically in 5 countries and 12 centers around the world. In addition, treatment centers are being built in more countries and clinical applications are scheduled.

What makes CIRT different from conventional photon radiotherapy is biological effectiveness. When carbon ions and photons of the same dose are irradiated, the biological effect of carbon is greater, and its relative size is expressed as relative biological effectiveness (RBE). The value obtained by multiplying the physical dose (PD) by the RBE is called the biological dose (BD), and carbon ion treatment planning (TP) is performed based on BD. Therefore, calculating the RBE of carbon ions is very important to the TP of carbon ions, and RBE modeling for predicting RBE has been studied and is still being developed [1].

In this study, biological doses for dual-layered dual energy computed tomography (DECT) images were calculated using the original local effect model (LEM) among the RBE calculation models of carbon ion using the Monte Carlo toolkit, TOPAS [2].

2. Materials and Methods

2.1 Dual-layered dual-energy Computed Tomography (DECT)

The DECT acquisition equipment used in this study is Philips IQon Spectral CT, which is a dual-layer method using one x-ray source and a dual-layer detector [3]. Using this equipment, effective atomic number (EAN) images and electron density (ED) images of the patient were acquired. Material decomposition for each pixel was performed on the CT slice by using the acquired two images. [4, 5].

2.2. Local effect model (LEM)

RBE refers to the ratio of the dose at which the radiation of interest produces a biological effect equal to the reference radiation (photon), and is expressed as an equation as follows.

$$\mathrm{RBE} = \frac{Dose_{ref}}{Dose_{ion}} \Big|_{\mathrm{isoeffect}} \quad (1)$$

According to the above equation, the RBE value varies depending on how the endpoint, the reference radiation, and the radiation of interest are defined.

The RBE model used in this study is the local effect model (LEM), and the original model proposed in 1997 was used [6]. The LEM is a model that determines the entire biological effect of a cell by combining biological effects occurring in a local area of a cell. In calculation, biological effects occurring along the track structure are integrated and calculated, and the expression for this is shown in (2).

$$\mathrm{S(D)} = e^{\overline{-N(D)}} \quad (2)$$
$$\overline{N(D)} = \int \frac{-lnS(d(x,y,z))}{V} dV \quad (3)$$

S(D) is the survival fraction of the cell, N(D) is the average number of lesions of the cell nucleus, V is the volume of the cell nucleus, and d(x,y,z) is the local dose. S(D), which means the cell survival fraction, follows a linear-quadratic (LQ) model, and finally, RBE is calculated using S(D) of photon and ion.

2.3. Biological dose calculation

Dose calculation for DECT images was performed using the Monte Carlo simulation code, TOPAS. To this end, the result of material decomposition performed in 2.1 (material composition information and physical density information for each pixel) was imported into the code. This process was done through an in-house material converter. In addition, in order to compare the dose calculation results using DECT, dose calculation based on Single Energy Computed Tomography (SECT) of the same patient area was performed, and SECT images were imported through the stoichiometric method embedded in the code [7].

Dose was calculated for three cases.

Case 1 : monoenergetic carbon ion beam is irradiated from the lateral direction of the image.

Case 2 : monoenergetic carbon ion beam is irradiated from the perpendicular direction

Case 3 : scanned from the anterior direction using the modeled beam scanning system

For monoenergetic beam, 290 MeV/u, and for 2D beam scanning, 100 MeV/u were used. In case 1, 2, an integrated depth dose (IDD) was used, and in case 3, a 2D dose distribution was obtained. Each case number coincides with the beam number and the whole geometries are shown in Fig. 1.

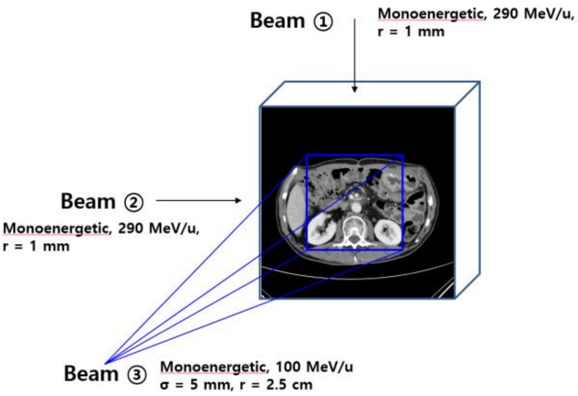

Fig. 1. Beam irradiation geometry

For RBE calculation, LQ model parameters α and β values for each voxel were obtained. Considering the effect of secondary fragments, the α and β values for each pixel were obtained using the low dose approximation [8]. Finally, the biological dose was obtained by multiplying the physical dose for each voxel by the acquired RBE.

Before obtaining α and β for each voxel through the extension of the TOPAS code, a monoenergetic 290 MeV/u ion beam was irradiated to the water phantom as a preliminary result to obtain the RBE_{10} distribution in the depth direction.

3. Preliminary Result

As the calculation of the physical dose, the IDD obtained in Case 1 and 2 is shown in Fig. 2 and Fig. 3. In Cases 1 and 2, the Bragg peak position of monoenergetic ion in DECT was -1.6 / +1.7 mm from the SECT, and the dose difference at the peak was -3.8 / +3.7% respectively.

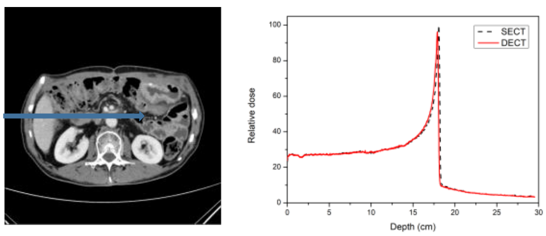

Fig. 2. IDD curve of lateral beam

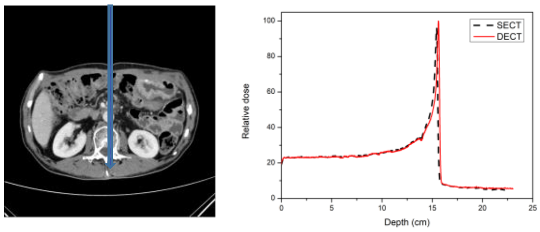

Fig. 3. IDD curve of beam perpendicular to the coronal plane

In the case of RBE calculation, depth direction RBE_{10} curve was obtained when monoenergetic ions were irradiated on the water phantom as a preliminary result. The depth-RBE curve is shown in fig 4, and $RBE_{10.mix}$ is the result of combining the effects of secondary fragments.

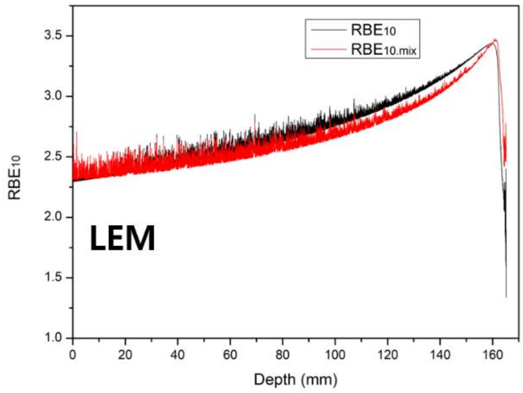

Fig. 4. Depth-RBE curve in water phantom

4. Ongoing and Further studies

Currently, we are developing TOPAS extensions to obtain α and β for each voxel. When this is completed, the DECT / SECT-based biological dose of the patient image will be calculated, and the differences will be compared and analyzed.

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REFERENCES

[1] P. Karger and P. Peschke, “RBE and related modeling in carbon-ion therapy”, Physics in Medicine and Biology, 63, 01TR02, 2018.

[2] J. Perl, J. Shin, J. Schumann, B. Faddegon, H. Paganetti, “TOPAS: an innovative proton Monte Carlo platform for research and clinical applications, Physics in Medicine and Biology, 39, 6818-6837, 2012.

[3] Hyun Woo Goo, Jin Mo Goo, “Dual-Energy CT: New Horizon in Medical Imaging”, Korean Journal of Radiology, 18, 4, 555-569, 2017

[4] G. Landry, et al., "Simulation study on potential accuracy gains from dual energy CT tissue segmentation for low-energy brachytherapy Monte Carlo dose calculations, Physics in Medicine and Biology, 56, 6257-6278, 2011

[5] Hünemohr, et al., "Tissue decomposition from dual energy CT data for MC based dose calculation in particle therapy", Medical Physics, 41, 6, 2014

[6] M. Scholz et al., "Computation of cell survival in heavy ion beams for therapy", Radiat Environ Biophys, 36, 59-66, 1997

[7] W. Schneider, T. Bortfeld and W. Schlegel, "Correlation between CT numbers and tissue parameters needed for Monte Carlo simulations of clinical dose distributions, 45, 459-478, 2000

[8] M. Krammer, M. Scholz, "Rapid calculation of biological effects in ion radiotherapy", 41, 1959-1970, 2006