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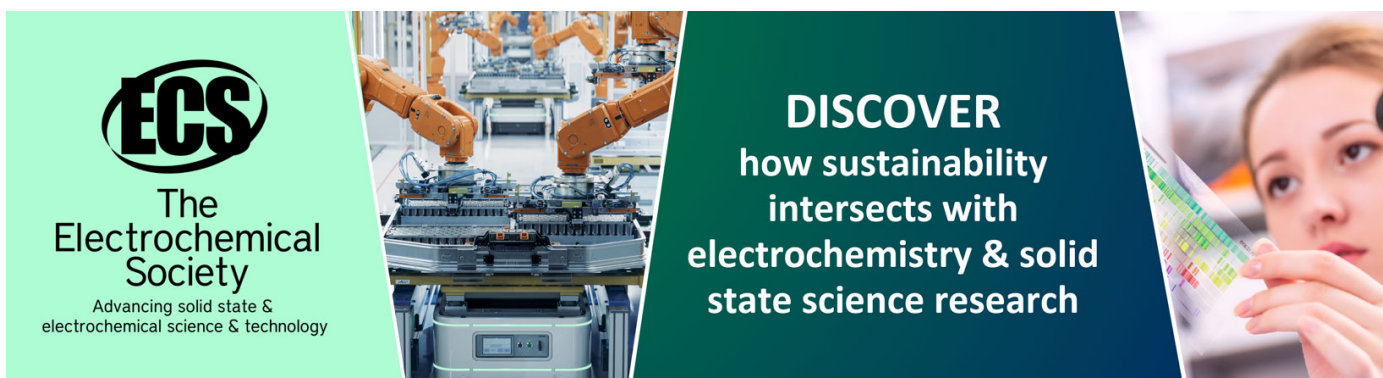
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Dosimetric investigation of proton therapy on CT-based patient data using Monte Carlo simulation

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Abstract. The aim of radiotherapy is to deliver high radiation dose to the tumor with low radiation dose to healthy tissues. Protons have Bragg peaks that give high radiation dose to the tumor but low exit dose or dose tail. Therefore, proton therapy is promising for treating deep-seated tumors and tumors locating close to organs at risk. Moreover, the physical characteristic of protons is suitable for treating cancer in pediatric patients. This work developed a computational platform for calculating proton dose distribution using the Monte Carlo (MC) technique and patient's anatomical data. The studied case is a pediatric patient with a primary brain tumor. PHITS will be used for MC simulation. Therefore, patient-specific CT-DICOM files were converted to the PHITS input. A MATLAB optimization program was developed to create a beam delivery control file for this study. The optimization program requires the proton beam data. All these data were calculated in this work using analytical formulas and the calculation accuracy was tested, before the beam delivery control file is used for MC simulation. This study will be useful for researchers aiming to investigate proton dose distribution in patients but do not have access to proton therapy machines.

1. Introduction

The aim of radiotherapy is to delivery high radiation dose to the tumor with low radiation dose to healthy tissue, resulting in the increased therapeutic ratio [1]. Conventional radiotherapy has limitation because photons have exit dose to healthy tissue behind the tumor which can cause side effects such as secondary malignancy. In contrast, protons have Bragg peaks with high radiation dose to the tumor but low exit dose or dose tail. Therefore, proton therapy is promising for treating deep-seated tumors and tumors locating close to organs at risk [2]. Compared to current radiotherapy technique such as intensity modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) using photons, proton therapy can decrease secondary malignancy risk [3]. In particular, the pencil beam scanning technique is considered to be advantageous for decreasing risks of developing secondary cancer after proton therapy compared to the passive scattering technique [4]. The physical characteristic of protons was shown to be suitable for treating cancer in pediatric patients [5], especially primary brain tumors such as high-grade glioma (HGG) that is aggressive and has high recurrent rates in pediatric patients [6].

This work is a part of the development of a computational approach for calculating proton dose distribution in patients treated with the pencil beam scanning method. The computational platform



consists of a MATLAB (MathWorks, Inc.) optimization program for generating a beam delivery control file and the Particle and Heavy Ion Transport Code System (PHITS) for Monte Carlo simulations to calculate proton dose distribution. The Monte Carlo simulation will use the beam configuration as described by the beam delivery control file and patient-specific CT data. The conversion of patient-specific CT-DICOM data to the Monte Carlo input and the calculation of monoenergetic proton beam data for the development of the optimization program will be described in this paper.

2. Material and method

The studied case is a pediatric patient with a primary brain tumor (HGG). The selected patient was originally treated by photon therapy at Radiation Therapy and Oncology Section, Radiology Division, Faculty of Medicine Ramathibodi Hospital, Mahidol University Bangkok Thailand. The CT-DICOM files of this patient were used for the calculation of the patient-specific proton dose distribution.

In the first step, the CT-DICOM files were converted to the PHITS input file using the DICOM2PHITS program, which is a part of PHITS. The conversion accuracy was tested against known values of electron densities in the Tissue Characterization Phantom (TCP) GammexTM 467. The TCP rods are displayed in figure 1(a). The verification process of the DICOM2PHITS program followed these steps:

- The TCP rods were scanned by a CT simulator (radiotherapy simulated exposure technique ; GE Optima 580, 120 kV, 255 mA, 1.25 mm slice thickness, 512 x 512 pixels).
- The TCP rod CT-DICOM files were sent to the DICOM2PHITS program for conversion to the Monte Carlo input file.
- The Monte Carlo input file was read by PHITS Version 2.76 for the simulation.
- The electron density value on the rod label was compared with the Monte Carlo output for each rod.
- Percentage differences between the calculated electron densities and the references should be less than 3%. However, if the percentage difference was more than 3% but less than 4%, it was considered acceptable. The selected tolerance was modified from [7].

A MATLAB optimization program was developed to create the beam delivery control file for the patient-specific Monte Carlo simulation. Apart from the patient's anatomical data, the optimization program required the depth dose distributions of monoenergetic protons, the proton range-energy relationship, the stopping power ratios to water for protons in different materials and the scattering characteristics of protons in different materials. All these data were calculated using analytical functions, as follow:

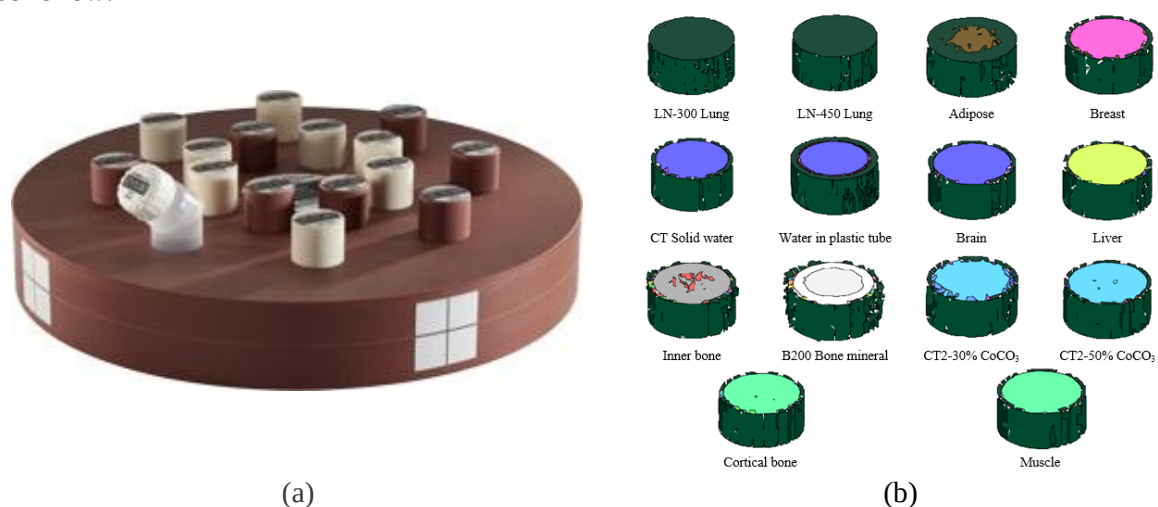


Figure 1. (a) Tissue characterization phantom GammexTM 467 and (b) the simulated TCP rods.

- Depth dose of monoenergetic proton [8]

$$D(z) = \Phi_0 \frac{e^{-\frac{2}{\sigma} \alpha^{\frac{1}{p}} \Gamma(1/p)}}{\sqrt{2\pi p \alpha^{1/p} (1+\beta R_0)}} \times \left[\frac{1}{\sigma} D_{-1/p}(-\zeta) + \left(\frac{\beta}{p} + \gamma \beta \right) D_{-1/p}(-\zeta) \right] \quad (1)$$

where Φ_0 is the primary fluence, $\Gamma(x)$ is the gamma function, β is the slope parameter of the fluence reduction relation and γ is the fraction of locally absorbed energy from nuclear interactions. The parameters α and p stem from the range-energy relationship, Eq. (2).

- Proton range-energy relationship [9]

$$R_0 = \alpha E_0^p \quad (2)$$

where α is 0.002579 that is approximately proportional to the square root of the effective atomic mass of the absorbing medium, E_0 is initial energy of protons and p is 1.736 for energies between 10 and 250 MeV (Geiger's rule). The α and p were fitted from Monte Carlo simulation.

- Stopping power ratio to water for protons in different material (Bragg's rule) [10, 11]

$$\left(\frac{S}{\rho} \right) = \sum W_i \left(\frac{S}{\rho} \right)_i \quad (3)$$

where w is the fraction by weight and $\left(\frac{S}{\rho} \right)_i$ is the mass stopping power of element i .

- In-patient scattering characteristics of proton in different materials [12]

$$\theta_0 = 14.1 \left[1 + \frac{1}{9} \log_{10} \left(\frac{t}{L_R} \right) \right] \left[\int_{-\infty}^t \left(\frac{1}{p\nu} \right)^2 \frac{dt'}{L_R} \right]^{1/2} \quad (4)$$

$$y_0(t') = 14.1 \left[1 + \frac{1}{9} \log_{10} \left(\frac{t'}{L_R} \right) \right] \left[\int_{-\infty}^{t'} \left(\frac{t'-z}{p\nu} \right)^2 \frac{\rho}{L_R} dz \right]^{1/2} \quad (5)$$

where θ_0 is the angular distribution of proton, y_0 is radial distribution of proton, t in grams per square centimetre is the areal density of the material, L_R in grams per square centimetre is the radiation length of the material, $p\nu$ in MeV is the product of momentum and the velocity of the protons at depth t' and ρ is the density of the material in grams per cubic centimeter.

The accuracy of these functions was tested by comparing the calculation results with literature data or Monte Carlo simulations of monoenergetic protons, before the delivery control file is used for simulating patient-specific proton dose distribution. The results of equations (1) and (2) were compared with the Monte Carlo simulations of monoenergetic protons of different energies, while the results of equation (3) were compared with the material data of PSTAR (Stopping Power and Range Tables for Protons) [11] and the material data implemented in PHITS, and the results of equations (4) and (5) were compared with available literature data [12]. In the final step, outside the scope of this paper, the patient-specific proton dose distribution from the PHITS Monte Carlo simulation and the dose distribution to be achieved according to the optimization program will be compared using the Gamma evaluation index of 3%, 3 mm (%dose difference and DTA (Distance to Agreement)), with the passing criterion of more than 95% (the similar criterion was used in Grevillot *et al.* [13]).

3. Result and discussion

To test the accuracy of the DICOM2PHITS program, the converted and referenced electron densities were compared for 14 different materials. The simulated rod images are displayed in figure 1(b). The electron densities were derived from the CT number with the conversion table that has been constructed with the best accuracy [14]. The conversion was accurate for 8 material rod values (differences were less than 3%), was moderately accurate for 4 material rod values (differences were more than 3% but less

than 4%) which may be caused by the broad ranges of CT numbers per material of the DICOM2PHITS database, and was insufficiently accurate for 2 material rod values representing lung equivalent materials LN-300 and LN-450 due to the low electron densities of these materials.

Regarding the proton beam data to be used in the MATLAB optimization program, the depth dose distributions of monoenergetic protons, the range-energy relationship and the stopping power ratios to water for protons in different materials were calculated based on equations (1)-(3). These results are in good consistency with the literature data or Monte Carlo simulations of monoenergetic proton beams. Some of the depth dose calculation results are displayed in figure 2. Investigations of in-patient scattering characteristics of protons and the Monte Carlo simulation of patient-specific proton dose distribution are works in progress.

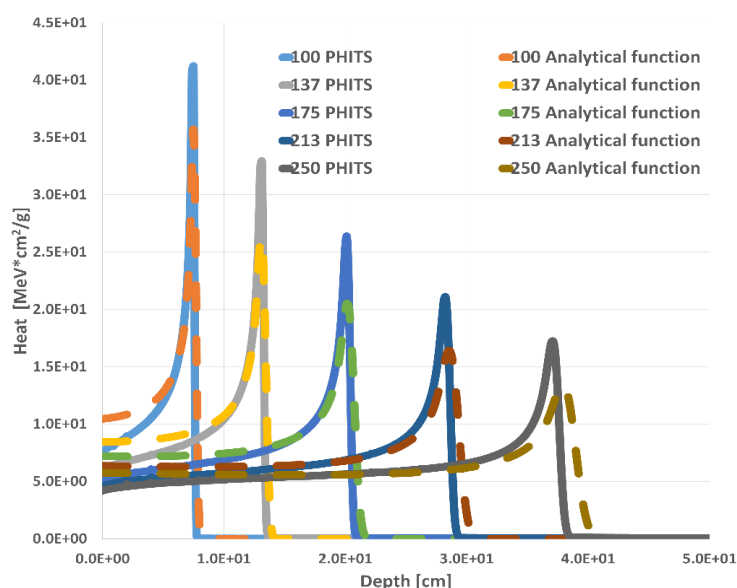


Figure 2. Proton depth dose comparison between PHITS simulation vs. analytical function in equation (1)

4. Conclusion

The paper describes the data preparation for the Monte Carlo simulation of patient-specific proton dose distribution. The described works include the conversion of CT-DICOM files to the input file of the Monte Carlo simulation and the generation of proton beam data to be used in a beam optimization program for creating a beam delivery control file for the Monte Carlo simulation. The DICOM2PHITS program used in this work was found to be suitable for conversion of CT-DICOM data to the Monte Carlo input file for most of the materials relevant to radiation therapy. The analytical functions used for calculating the proton beam data for the beam optimization program were found to be sufficiently accurate compared to literature data and Monte Carlo simulations of monoenergetic protons. This work is a part of a pilot project for development of a computational platform for dosimetric investigation of proton therapy using Monte Carlo simulation and patient CT data. The outcome of this project will be interesting for researchers aiming to investigate patient-specific proton dose distribution but do not have access to proton therapy machines and related equipment.

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