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Experimental measurement of the correlation between CT number and heavy ion range*

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Abstract: For precision delivery of the Bragg peak of a heavy-ion beam to a target volume in ion beam therapy, it is necessary to know the tissue stopping power. A general approach to solve this problem in ion beam therapy is to convert X-ray CT (computed tomography) numbers into water-equivalent path length (WEPL) coefficients using a CT-WEPL calibration curve for all voxels traversed by the beam. This work aims at establishing a CT-WEPL coefficient calibration curve for the heavy ion therapy project at IMP, so as to compute the range of carbon ion beams in tissues easily according to the patient CT data. Several tissue-equivalent materials were applied to measure their WEPL coefficients using a high-energy carbon ion beam in this work. A CT-WEPL calibration curve was obtained through fitting the measured data, which can be used directly for dose optimization and facilitates the design of patient treatment plans significantly at IMP.

Key words: heavy ion therapy, CT number, WEPL, CT-WEPL calibration curve

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1 Introduction

The use of heavy-ion beams such as carbon ion beams in cancer therapy has attracted growing interest worldwide because of their high dose localization in the end of the range (Bragg peak) and increased relative biological effectiveness (RBE) across the Bragg peak region. Following the pioneering work of the Lawrence Berkeley Laboratory in the US, the National Institute of Radiological Sciences in Japan and the Gesellschaft für Schwerionenforschung (GSI) in Germany began cancer radiotherapy using heavy ions. The Institute of Modern Physics (IMP), the Chinese Academy of Sciences, China, has launched superficially-placed tumor treatment using carbon ions with a maximum energy of 100 MeV/u in the earlier therapy terminal at HIRFL-SSC since November, 2006. Three years later, IMP started to treat deep-seated tumors with high-energy carbon ions in the therapy terminal at HIRFL-CSR.

Because of their physical characteristics, heavy ions have definite ranges in matter. In order to precisely deliver the Bragg peak of a heavy ion beam to a target volume, it is necessary to know the tissue stopping power (or relative stopping power) distribution along the beam path. Proton computed tomography (CT) [1] and heavy-ion CT [2, 3] seem to be promising techniques for obtaining two-dimensional stopping power distribution. Both of them, however, are under development at present. Since Chen et al [4] and Mustafa [5] published their calibration tables, converting patient X-ray CT numbers to water-equivalent path length (WEPL) coefficients, which equal the relative stopping power of water, has become possible. At GSI, the current CT-WEPL coefficient calibration curve is derived by measuring the WEPL of tissue equivalent materials [6–8]. Systematical investigation of the relationship between CT

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numbers and WEPL coefficients at the Paul Scherrer Institute in Switzerland indicates that stoichiometric calibration is more accurate than the tissue substitute calibration [9, 10]. Because of the intrinsic differences among CT scanners, different CT scanners can produce various CT number distributions for the same materials [11–13]. Many factors may influence the measured CT numbers of a CT scanner, such as the setting parameters of the CT scanner itself (tube voltage, filter, etc.), sample geometry and size, and so on. Thus, there is no general calibration curve between CT number and WEPL coefficient based on experiments. For instance, the water equivalent path length of a therapeutic carbon beam in a CT image obtained from a patient was computed according to the CT-WEPL calibration curves established previously by Jäkel et al. [6], Minohara et al. [14], and Jacob et al. [15] and the results are 316.64, 306.11 and 318.88 mm, respectively. Clearly, there are obvious differences among the results, and even the deviation is larger than 10 mm. Because the correlation between CT number and WEPL coefficient influences dose optimization and resulting dose distribution directly, a special CT-WEPL coefficient calibration curve should be established for specific CT scanners.

This work aims at establishing a CT-WEPL coefficient calibration curve for the treatment planning system (TPS) of cancer radiotherapy with carbon ions at IMP. Several tissue equivalent materials were used to measure their WEPLs in the terminal for deep-seated tumor treatment with heavy ions at the HIRFL-CSR. Based on these data, a CT-WEPL coefficient calibration curve and its corresponding mathematic equation were obtained. This formalism derived from this work can be incorporated into the TPS directly and facilitates the design of patient treatment plans significantly at IMP.

2 Materials and methods

2.1 Sample preparation

In this study, tissue equivalent solutions such as alcohol, peanut oil, water, and saturated brine, were selected as tissue substitutes, mainly because their compositions are close that of a human body. Fresh tissues including the liver, kidney, lung and fat of a pig were selected. Polystyrene boxes with an inner wall spacing of 30.4 mm were used as sample containers. All the tissues were put directly into the containers. During storage and transportation, these sample containers were kept upright to prevent any displacement of the tissues inside the containers.

The duration time from the preparation of the fresh tissue samples to the end of the experiment was kept to within 24 h. These fresh samples were stored in a refrigerator at 4 ℃ except when CT scanning and the measurement of WEPLs in the therapy terminal. The tissue equivalent solutions in the containers were kept at room temperature, about 25 ℃.

2.2 CT scan

The Somatom Sensation Open CT scanner (Siemens, Germany) installed at IMP was used for CT number measurements. All the samples positioned on the couch with the inbuilt laser system were scanned one by one. The scan direction, which was the same as the ion-beam's incident direction, was perpendicular to the bigger surface of the containers. The samples were scanned at a tube voltage of 120 kVp (kV peak) and a resolution of 1.2 mm.

2.3 WEPL measurement

A 200 MeV/u carbon-ion beam was delivered by the CSR for this study. Uniform irradiation fields for the carbon ion beam at the iso-center of the therapy terminal were generated by a pair of dipole magnets equipped in the beam delivery system under the operation mode of continuous raster scanning. The experimental setup is shown in Fig. 1. A square irradiation field of 1 cm×1 cm for the carbon ion beam was shaped by a manual multi-leaf collimator. The percentage depth dose distributions were measured in a water tank (MP3, PTW, Germany) with two parallel ionization chambers (PTW, Germany). The reference ionization chamber was taken down from the MP3 water tank and positioned upstream of the samples. All of these instruments were set up on the patient couch with laser pointers installed in the treatment room. The orientation of the containers was kept at the same condition as that of the CT number measurements. The measuring ionization chamber in the water tank was moved along the ion-beam direction with a resolution of 0.1 mm. For saving beam time, only the Bragg peak regions for these samples were measured. The WEPL coefficient (k) of the materials under measurement is defined as:

$$k = 1 + \frac{\Delta S}{d}, \tag{1}$$

where ΔS is the difference between the peak positions of the carbon ion beam in the water tank without and with the sample and d is the thickness of the sample under measurement.

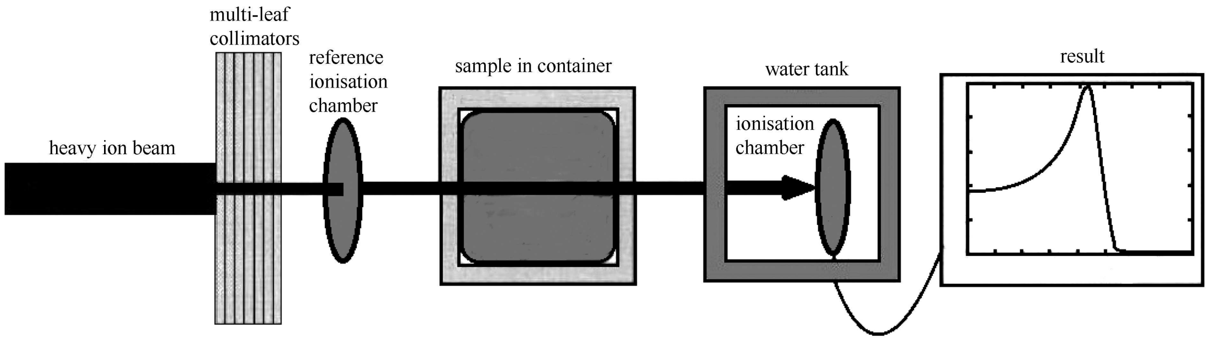

Fig. 1. Schematic diagram of the experimental setup.

3 Result

The CT number distributions were measured along the beam path layer by layer for the various materials. There was a significant change of the CT numbers presented on both sides of the inner walls, probably caused by the existence of transition zones with spacing of about 1 mm between the sample and the inner walls of the container. The transition zones were indeed short compared with the relative homogeneous region of the sample in the middle part. Therefore, the measured CT numbers at the transition zones were excluded in the following calculation for the CT number of the samples. The mean value of the central region of 50×50 pixels (approximately 1 cm×1 cm) for all the layers of the sample under measurement was calculated as the sample's CT number. The CT numbers for all the samples obtained in this way are listed in Table 1 together with the standard deviations coming from the data analysis.

Table 1. The measured CT numbers for various materials.

sample	CT number	sample	CT number
saturated brine	319±18	peanut oil	−126±3
liver	81±14	alcohol	−223±3
kidney	44±11	lung	−532±75
water	−3±8	air	−1001±2
fat	−85±7		

Figure 2 shows the percentage depth-dose distributions of the carbon ion beam passing through the different samples. Material specific shifts of the Bragg peaks according to the corresponding stopping powers can be observed clearly. Additionally, there is an obvious extended Bragg peak for the lung tissue, mainly because of its inhomogeneous compositions leading to differences in the ion range within the irradiation field. Each peak location in depth was read out from the data presented in Fig. 2 and then the different materials' WEPLs were computed using Eq. (1). The resultant WEPLs for all the samples under measurement are shown in Table 2.

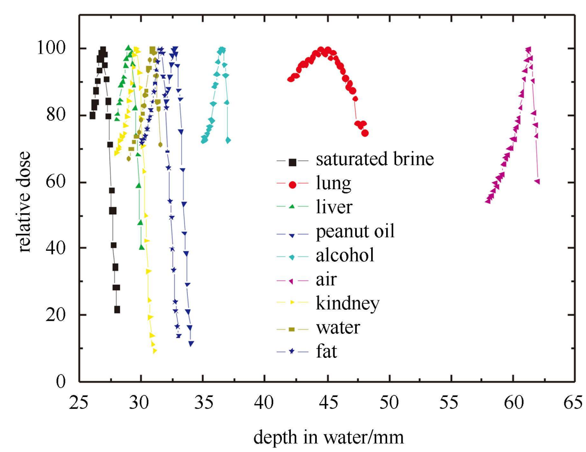

Fig. 2. Pecentage depth-dose distributions (around Bragg peak regions) of the carbon ion beam passing through the materials under measurement in water.

Table 2. Bragg peak positions in depth and WEPL coefficients for different materials.

tissue	Bragg peak/mm	k	tissue	Bragg peak/mm	k
saturated brine	26.8	1.13	Peanut oil	32.7	0.94
liver	29.0	1.06	Alcohol	36.5	0.82
kidney	29.5	1.05	Lung	44.6	0.55
water	30.9	1.00	Air	61.2	0.003
fat	31.5	0.98			

A segmented linear fitting of the WEPLs as a function of CT number to the data listed in Table 2 for the different samples results in the following formalism (Eq. (2)) for the low- and high-density regions, and the correlation coefficients are 0.9985 and 0.9585, respectively.

$$k=\begin{cases}1.054\times10^{-3}\mathrm{CT}+1.073\,, & CT<-75\\ 3.580\times10^{-4}\mathrm{CT}+1.021\,, & CT\geqslant-75\end{cases}. \qquad (2)$$

4 Discussion

Many factors may affect the accuracy of this study. Because the moving step of the measuring ionization chamber was 0.1 mm, the measurement of the Bragg peak locations of the carbon ion beam in depth could only reach this precision in this study. The error caused by this factor could be controlled within 0.4%. The divergence of the orientation of the sample containers from the beam direction caused by positioning error was expected to be less than one degree, leading to only an error of 0.02% in the range measurement. Additionally, the irradiation and the CT scanner were kept under the same conditions during experiment. So the total error of the measured WEPL coefficients is thought to be less than 0.4%.

The WEPL data measured by Jäkel et al. [6] and Rietzel et al. [8] are also displayed in Fig. 3. Phantom materials, which were designed to closely imitate the elemental composition of real tissues, were used in the work of Jäkel et al. The fitting curve obtained in this study has good agreement with their measured data. Two different CT scanners were applied in the work of Rietzel et al. Some differences could be observed between the measured results using Scanner 1 and Scanner 2. Nevertheless, all the data measured by Rietzel et al are in good agreement with the calibration curve derived from this work.

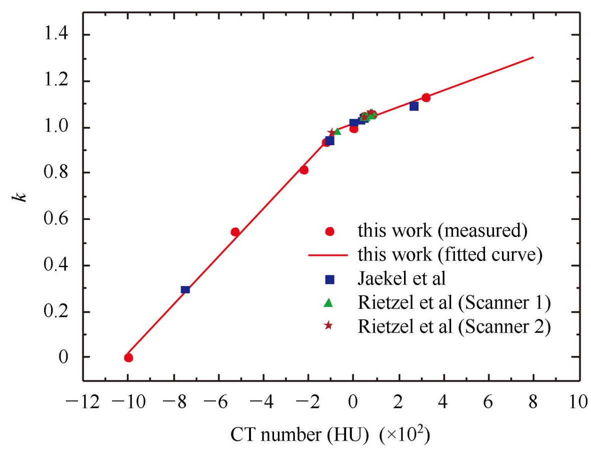

Fig. 3. The CT-WEPL coefficient (k) calibration curve derived from the measured data in this work. The circles represent the data obtained in this work. The squares, triangles and pentagons represent the data measured by Jäkel et al. and Rietzel et al. with two different CT scanners, respectively.

In conclusion, a CT-WEPL calibration curve was definitely obtained in this work for the CT scanner at IMP. It can be used directly for dose optimization and facilitates the design of patient treatment plans significantly for the heavy ion therapy project at IMP.

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