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Study on Microdosimetric Characteristics of 120 to 430 MeV/u Carbon Ion

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Abstract: Microdosimetric single event spectrum is a significant parameter in radiotherapy, which can be used to evaluate the radiation biological effect. In this paper, microscopic patterns of energy deposition are simulated with Monte Carlo code FLUKA at mixed radiation fields during carbon ions therapy. The results are compared with experimental measured results at 300 MeV/u carbon ion and good agreement has been found. Meanwhile, dose-weighted lineal energy spectra, frequency averaged lineal energy values and dose averaged lineal energy values of carbon ion with energy from 120 to 430 MeV/u were calculated, too. The frequency averaged lineal energy values are from 185 to 28.3 keV/μm while the dose averaged lineal energy values are from 272 to 64.1 keV/μm. These studies are useful for treatment plan in carbon ion radiotherapy.

Key words: microdosimetry; carbon ion; Monte Carlo; FLUKA; radiotherapy

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1 Introduction

With the Heavy Ion Medical Machine (HIMM) of the Institute of Modern Physics (IMP) coming online, more and more patients will be treated in next few years by carbon ion with energy from 80 to 430 MeV/u. Because of better physical and biological characteristics compared with photon, electron and proton, carbon ion has provided a better therapeutic effect for various tumors. While the essence of the radiotherapy for the tumor is that the biological structure (such as cells) of tumor is damaged by energetic ions, this damage depends crucially on the spatial distribution of energy deposition. For the purpose of investigating the radiation quality of carbon ions, a microdosimetric spectrum study has been carried out. Microdosimetric characteristics, which describe the energy deposition events in microscopic volumes, are used to explain and model differences of the radiation effect on biologic targets with same absorbed dose[1].

Tissue equivalent gas proportional counter(TEPC) is the dominating instrument used to measure imparted energy of single primary particle in volumes resembling microns of tissue and deduced quantities like lineal energy[2].

FLUKA is a general purpose tool for calculations of the particles transport and interactions with matter, which is jointly developed by the European Laboratory for Particle Physics (CERN) and the Italian National Institute for Nuclear Physics (INFN)[3−4]. Cell damage and biologic effect caused by ions can be described by Monte Carlo codes and coupled with models based on physical quantities[5], such as linear energy transfer(LET) and lineal energy y.

Several recent studies measured the lineal energy spectra with carbon ion with energy of 290, 300 and 400 MeV/u with TEPC, respectively[6−7]. Meanwhile, several studies mentioned that FLUKA can simulate the response of TEPC for photon and various ions from proton to iron ion[8−11]. However, there is not a systematic study about microdosimetric characteristics for carbon ion at therapeutic energies, and there are few domestic related researches. The aim of this paper is that using FLUKA Monte Carlo code to study the microdosimetric characters of carbon ion with energy from 120 to 43 MeV/u at different depth of the phantom, a recent microdosimetry measurement data for 300 MeV/u carbon ion was chose from published

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literatures for benchmarking the method that using FLUKA Monte Carlo code to simulate the TEPC's response function. After that the dose-weighted lineal energy spectra $yd(y)$, frequency averaged lineal energy values and dose averaged lineal energy values for carbon ions with the energy of 12, 150, 200, 250, 350, 400 and 430 MeV/u were calculated in the measurement set-up respectively.

2 Simulation model

In order to facilitate the comparison between simulation results and measurement one, the simulation model is consistent with the experimental condition chosen from published literature as much as possible[8]. This simulations and measurements are both based on a spherical TEPC(Model LET-1/2, Far West Technology, Inc, Goleta CA, USA), which consists of a 0.18 mm thick aluminum cap, a 3.7 mm thick A-150 plastic wall and an active cavity diameter of 12.7 mm, the active volume is filled with methane based tissue equivalent gas at the pressure of 120 mb, representing spherical tissue with the diameter of 2.7 m. The TEPC was placed at three depth corresponding to the plateau region, Bragg peak region, tail region of the Bragg curve in a standard water phantom(outer dimension 30 cm×30 cm×30 cm, including 2 cm thick PMMA side wall when carbon ion energy smaller than 350 MeV/u, and the dimension is 30 cm×30 cm×50 cm when carbon ion energy reaches 350 MeV/u or more). The simulation was performed using carbon beam spot with a Gaussian beam size of 3 mm(FWHM), The two dimensional structure of simulated model is shown in Fig. 1. The ranges of carbon ion with different energy in the phantom calculated with SRIM 2013[12] are listed in Table 1.

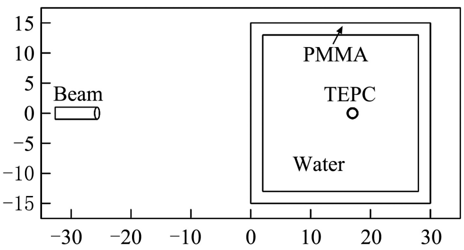

Fig. 1 Schematic view of the simulation model.
The length of the phantom augments is 50 cm in pace with the increasing of carbon ion energy. The position of the TEPC changes along with the Bragg peak region too.

Table 1 The ranges of carbon ion with energy from 120 to 430 MeV/u in phantom calculated with SRIM2013.

Energy/(MeV/u)	Range in the phantom(including 2 cm PMMA)/mm
120	35.5
150	52.8
200	87.5
250	128.1
300	172.2
350	231.1
400	287.3
430	320.1

Simulations were performed by FLUKA with the version 2011(released October 2014). The pre-defined default configuration 'HADROTHErapy' was chosen, this option uses per default delta-ray production and transportation cuts of 100 keV. In consideration of the 'wall effect', an onion-like structure was adopted to set different threshold of production and transportation for delta-ray as illustrated in Fig. 2. The thickness of different layer were motivated by the fact that in A-150 tissue equivalent plastic electrons of 100 and 10 keV have continuous slowing down approximation ranges of 126 and 2.2 μm, respectively[13]. 1 keV is the minimum threshold for the production and transportation of delta-ray that the FLUKA code can be set and run.

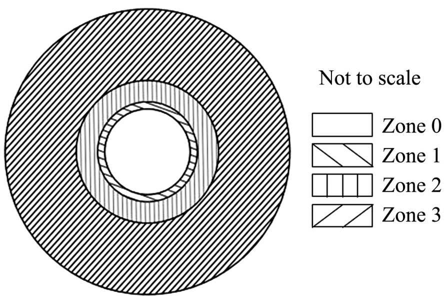

Fig. 2 Onion-like structure of the FLUKA model.
In the cavity(zone 0) and 3 μm thick layer (zone 1), the threshold was set as 1 keV; the adjacent layer of 197 μm (zone 2), the threshold was set to 10 keV; in the rest of the plastic wall(zone 3) and other space, the default threshold of 100 keV were set.

3 Data analysis

The simulated energy deposition in the TEPC was normalized to get imparted energy ε caused by one primary carbon ion, For the TEPC, the definition of lineal energy is given by $y=\varepsilon/l$, l is the averaged chord length of the volume.

The frequency averaged lineal energy y_F of the lineal energy spectra was calculated by integrating the lineal spectra from $\varepsilon_{\min}/l$:

$$y_{\mathrm{F}} = \int_{\varepsilon_{\min/l}}^{\infty} y f(y) \mathrm{d}y \ , \tag{1}$$

where $f(y)$ is the normalized lineal energy distribution, for the same reason, dose averaged lineal energy y_{D} was given by

$$y_{\mathrm{D}} = \int_{\varepsilon_{\min/l}}^{\infty} y \mathrm{d}(y) \mathrm{d}y = \frac{1}{y_{\mathrm{F}}} \int_{\varepsilon_{\min/l}}^{\infty} y^2 f(y) \mathrm{d}y \ , \tag{2}$$

where $\mathrm{d}(y)$ is the normalized dose lineal energy probability density. The energy threshold $\varepsilon_{\min}$ is used to restrain the electronic and background noise.

4 Results and Discussion

All simulations were performed by using monoenergetic carbon beam and with a Gaussian beam size of 3 mm(FWHM). Simulations were performed by using $10^5 \sim 10^6$ source particles. The statistical errors of simulated results are within 10%.

Fig. 3 shows simulated results and experimental data of the dose-weighted lineal energy spectra $y\mathrm{d}(y)$ of 300 MeV/u carbon ion at three depths in the beam axis of the water phantom. The three depths are corresponding to plateau region(25 mm), Bragg peak region(152 mm) and fragmentation tail region(250 mm), respectively.

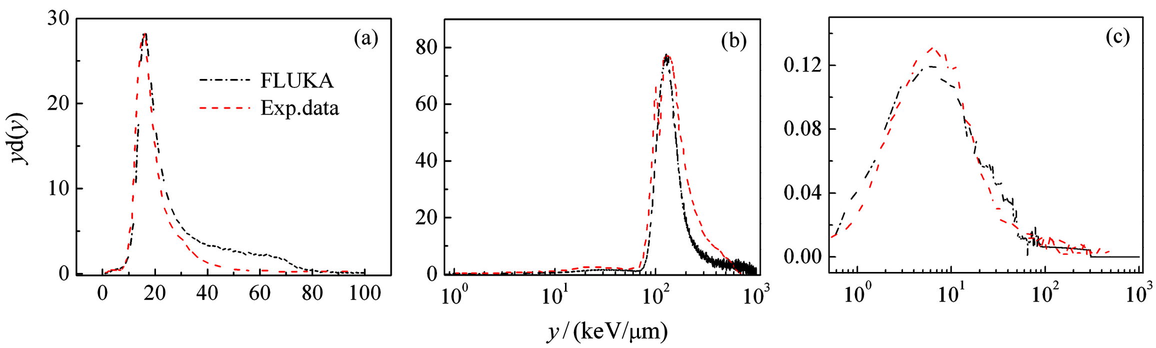

Fig. 3 (color online) Measurements and simulations of the dose-weighted lineal energy distribution versus lineal energy of a 300 MeV/u carbon ion beam at 25 mm(a), 152 mm(b) and 250 mm(c) in water phantom representing the plateau region, peak region and tail region.

The results of measurements and simulations are normalized to primary carbon ion. It's observable that general shape and features of the measured lineal energy spectra are reproduced by the Monte-Carlo simulations. A slightly shift of the peak of simulated data compared with the measured one is notable for Fig. 3(a), this might be explained by the beam which was impinging slightly off-centre on the TEPC when making measurement. The simulated values of dose averaged lineal energy y_{D} are within 5% of the measured values. For the frequency averaged lineal energy y_{F} values, the agreement is slightly worse, with a maximum deviation of 6.25%. The results are listed in Table 2. Measured lineal energy spectra have a considerably wider peak compare to simulate one.

According to the comparison of simulations with measurements at three depths which representing plateau region, peak region and tail region respectively in the water phantom with 300 MeV/u carbon ion, it indicated that the method by using FLUKA to calculate lineal energy spectra of carbon beam at different depths in phantom and describes the main features of the spectra reasonably well. We can draw the conclusion that the method is capable to simulate microscopic energy deposition patterns and we can do some prediction of microdosimetric characters at a wide energy range from 120 to 430 MeV/u for carbon ion.

Table 2 Measured and simulated frequency averaged lineal energy y_{F} values and dose averaged lineal energy y_{D}.

Carbon ion energy /(MeV/u)	Tissue diameter/(μm)	Depth in water/mm	Measurement/simulation(error) y_{F}/(keV/μm)	Measurement/simulation(error) y_{D}/(keV/μm)
300	2.7	25	14.4/13.5(6.25%)	17.3/18.1(4.62%)
		152	75.6/78.5(3.84%)	162/158(2.47%)
		250	3.90/3.78(3.08%)	13.8/14.12(2.32%)

With the measurement set-up, we also calculated the dose-weighted lineal energy spectra at Bragg peak, frequency averaged lineal energy values and dose averaged lineal energy values of carbon ion with energy from 120 to 430 MeV/u. Fig. 4 gives the dose-weighted lineal energy spectra at Bragg peak of carbon ion with energy from 120 to 430 MeV/u. With the increasing of the carbon ion energy, an obviously offset to the left of peak position in the $yd(y)$-y curve was observed.

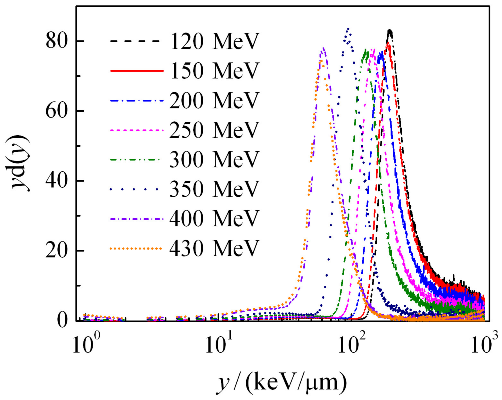

Fig. 4 (color online) Dose-weighted lineal energy distribution versus lineal energy at Bragg peak of a carbon ion with energy from 120 to 430 MeV/u.

Using a TEPC to estimate quality factors which are determined by LET has always been a desirable feature when applied to radiation protection dosimetry, while it has many published paper demonstrated that the dose averaged lineal energy y_D is a good approximation of LET for heavy ions[14−18]. To investigate this, the response function of TEPC was converted into lineal energy spectra and used to determine frequency averaged lineal energy y_F, and dose averaged lineal energy y_D. The results are shown in Table 3 and Fig. 5.

Table 3 Frequency averaged lineal energy values y_F and dose averaged lineal energy values y_D.

Carbon ion beam energies/(MeV/u)	y_F/(keV/μm)	y_D/(keV/μm)
120	185	272
150	161	258
200	135	224
250	105	190
300	78.5	158
350	56.1	115
400	36.8	78.5
430	28.3	64.1

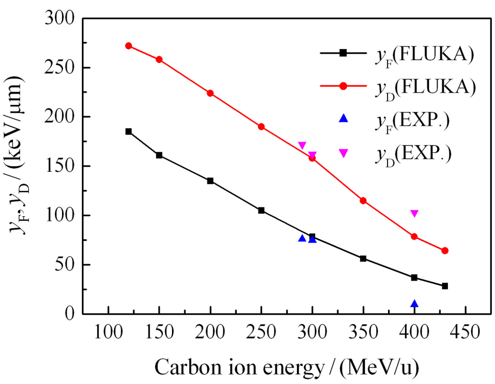

Fig. 5 (color online) Simulated and measured and for carbon ion from 120 to 430 MeV/u(lines are guide for eyes).

As shown in Fig. 5, frequency averaged lineal energy values y_F and dose averaged lineal energy values y_D are both decreased almost linearly with the increasing of incidence carbon ion energy. This is corresponding to the offset to the left of peak position in Fig. 4. The measured results for carbon ion with energy of 290, 300 and 400 MeV/u are also shown for comparison. Because this simulation set-up is based on the experiment of 300 MeV/u, therefore, it's a good agreement for dose averaged lineal energy values y_D, while a bigger deviation for frequency averaged lineal energy values y_F. However, the 400 MeV/u one is implement with a 6 cm SOBP carbon ion beam, as a consequence, it's reasonable for simulated y_F bigger than measurement one while smaller for y_D. It comes to a conclusion that those results are credible.

5 Conclusion

We have simulated the response of TEPC for carbon ion beam at several energies between 120 and 430 MeV/u, and the simulation results of 300 MeV/u carbon ion were compared with the measured one chosen from published literatures. The simulated frequency averaged and dose averaged lineal energy values agreed with the measured ones within 6.25% and 4.62% respectively. It demonstrated that the method by using FLUKA to simulate lineal energy spectra can describe the main features of the microdosimetry of carbon ion beam at different depths in phantom is credible. Some discrepancies between the simulated and experimental data were observed, these discrepancies need further survey but it can be partly explained by the environment that resulting lineal energy spectra are influenced by uncertainties in the physical set-up conditions in terms of beam characteristics and particle ranges in the given geometry.

In addition, we also calculated the dose-weighted lineal energy spectra at Bragg peak position, frequency averaged lineal energy values and dose averaged lineal energy values of carbon ion with energy from 120 to 430 MeV/u. Dose averaged lineal energy values y_D varies from 64 to 272 keV/μm, while frequency averaged lineal energy values y_F from 28.3 to 185 keV/μm, and frequency averaged lineal energy values y_F and dose averaged lineal energy values y_D are both decreased almost linearly with the increasing of incidence carbon ion energy. After be benchmarked with experiment in the future, those results may be the credible reference when making treatment plan in carbon ion radiotherapy.

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120～430 MeV/u 碳离子的微剂量学特性研究

庞成果[1,2]，苏有武[1]，徐俊奎[1,2]，李武元[1]，严维伟[1]，姚泽恩[2]

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摘要： 单粒子微剂量谱在放射治疗中是一个极其重要的参数，它可以用来评估辐射场的生物学效应。利用蒙特卡洛程序FLUKA模拟计算了由碳离子产生的混合辐射场能量沉积的微观模式。从已公开发表的文献中选取了实验测量300 MeV/u碳离子的线能能谱，并与相同物理条件下模拟计算得到的线能能谱相比较，结果吻合得很好。此外，还计算了120～430 MeV/u的碳离子的剂量平均线能能谱、频率平均线能和剂量平均线能。所得到的频率平均线能值为185～28.3 keV/μm而剂量平均线能值则为272～64.1 keV/μm。本文的结果对于制定碳离子放射治疗的治疗计划有着重要的意义。

关键词： 微剂量；碳离子；蒙特卡洛；FLUKA；放射治疗

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