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Calibration Procedure for Beam Monitors in Scanned Carbon Beam Therapy at HIRFL

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Abstract: As an important step of the application of spot scanning technique to heavy ion therapy, an experimental calibration procedure of online beam monitors based on standard of absorbed dose to water has recently been developed for scanned pencil-like carbon ion beam in the deep-seated tumor therapy terminal at the Heavy Ion Research Facility in Lanzhou (HIRFL). In this work, creating homogeneous irradiation field with steerable spot beam was tested using a 207 MeV/u pencil-like carbon ion beam. Then the verification of energy dependence of the calibration factors (CFs) and the influence of scanning step on the CF were also shown, as a part of the heavy ion clinic dosimetry researches. The results showd that the monitor CF presented energy dependence and performed stable response with deviation of 1.8% for the variation of scan steps. In this paper, the suitability and effectiveness of beam monitor calibration procedure for dynamic particle beam delivery were verified and the further research points to improve the calibration procedure were suggested.

Key words: spot scanning; monitor calibration; energy dependence; scan step

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1　Introduction

Due to the favorite characteristics of heavy ion beam such as inverted depth-dose distribution (Bragg peak) and high relative biological effectiveness (RBE), heavy-ion cancer therapy has attracted growing interest all over the world. In order to make optimal use of these characteristics and to achieve accurate treatment, it is significant to deliver a high dose to a tumor selectively while preventing undesired exposure of surrounding normal tissue and organ at risk (OAR)[1-3]. Many research groups joined in this field with their heavy ion accelerators (cyclotrons or synchrotrons) in America, Japan, Germany, China and other countries[4-7]. In China, basic researches of heavy-ion radiotherapy were started in 1995 at the Institute of Modern Physics (IMP), Chinese Academy of

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Sciences (CAS), and fruitful achievements have been obtained in terms of radiation physics, radiobiology and therapeutic technique[8-22]. Ionization chambers are recommended for use as reference monitors in all clinical ion beams since the IAEA published the code of practice TRS-398 (IAEA 2000) and recommended procedures for ion chamber reference dosimetry for all types of external beams[23-26]. Also the monitor calibration procedure has been widely adopted to evaluate absorbed dose to water, which is one of the basic check processes before caring out the clinic tumor irradiation.

In conventional radiation therapy with high-energy photon or electron beams, the monitor calibration may be very simple: The method usually applied is to perform a measurement of absorbed dose under reference conditions that dominated by a certain number of monitor units which resulted from the beam monitor. Similarly, the dose verification of treatment plan can be done simply at a single point in the treatment field. After the year 2000, even this calibration method was transferred to most of the proton and ion therapy facilities according the IAEA protocol for the measurement of absorbed dose to water. The calibration of the beam monitor for passively scattered carbon ion (proton) beam is very similar to that of X-ray beam. A dose measurement is performed in the center of a reference spread of Bragg peak (SOBP) with 10 cm× 10 cm field size (or largest available field size) and a predefined modulation width as recommended for reference conditions by the TRS-398 (IAEA 2000). The monitor calibration coefficient for this reference field is defined as the ratio of the measured dose to the respective number of monitor units (MUs). The number of MUs required for a specified prescribed dose is then obtained by dividing the prescribed dose by this calibration coefficient[27]. The procedure is in principle the same at the therapy terminals of Heavy Ion Research Facility in Lanzhou (HIRFL), China, where ^{12}C ions are applied using a passive beam delivery technique[28].

Pencil beam scanning offers better conformation of dose without collimators and compensators and possibly lowers neutron contamination compared to passive beam scattering techniques. But monitor calibration procedure of dynamic scanning system become more complicated than that of passive beam delivery system. The dose that cover the target volume can be shaped in all three dimensions for scanned ion beam while the dose can be varied from spot to spot allowing to compensate for the pre-irradiation of proximal subvolume and dose contributions from fragments[29]. The SOBP changes for each scan spot in every treatment field, which deliver dose with optimized and inhomogeneous beam intensity pattern. Besides, for scanned beams, the treatment planning system has to specify the number of ions for each scan point and each energy. Therefore, the monitor calibration coefficient is provided in units of ions/MU rather than dose/MU. Consequently the monitor calibration procedure recommendations of TRS-398 regarding reference conditions are no longer appropriate.

Recently an active spot-scanning beam delivery system has been developed in the deep-seated tumor therapy terminal at HIRFL based on the newly-built Cooling Storage Ring (CSR). Pencil carbon ion beams were steered laterally by horizontal and vertical scanning magnets in accordance with a predefined grid of scan spot to deliver the dose to a target volume in combination with longitudinally active energy variation by the CSR. The beam is kept stable at each scan point until a preset number of particles is applied and then moves quickly to the next scan point without switching the beam off. The scanning is controlled by the online beam monitoring system. A nitrogen filled parallel plate ionization chamber is installed at the active spot scanning system as main online monitor, which will control the absolute number of carbon ions to be applied at a certain energy at a certain scan spot. Apparently it is also necessary to calibrate the online monitor for each energy in terms of particle numbers. In the field of ion dosimetry the approaches of direct measurement of particle number are basically limited and direct measurement of particle number is hardly achieved through ionization chamber. Fortunately followed the procedure founded by Hartmann[30], the measurement of particle number can be translated by comparing the monitor readout with the absorbed dose measured in a phantom under certain reference conditions when using dynamic beam delivery system.

In this paper, our monitor calibration procedure for dynamic particle beam delivery system was outlined and its suitability and effectiveness was verified by dose measurements in the plateau region.

2 Experiments

2.1 Calibration method

The calibration factor (CF) at energy E, C(E), defined as the particles (N) per MU, is given by

$$C(E)=\frac{N}{\mathrm{MU}}=\frac{D_{\mathrm{meas}}}{S_E(x)MU}\Delta x\Delta y\ , \qquad (1)$$

where D_{meas} is the accumulative absorbed dose measured in the mono-energetic homogeneous fields, $S_E(x)$ is the mass stopping power of carbon ions with an initial energy E at the depth of measurement x. Δx and Δy are the spacing between the scan points in the x and y directions.

The absorbed dose is determined by (1) the readout of the dosimeter M which corrected for incomplete saturations and density effects, (2) the CF for the chamber in terms of absorbed dose to water in a ^{60}Co field N_{w}, and (3) a irradiation beam quality factor k_{Q} as following,

$$D_{\mathrm{meas}}(P_{\mathrm{eff}})=Mk_{\mathrm{Q}}N_{\mathrm{w}}\ , \qquad (2)$$

where, P_{eff} denotes the effective point of measurement in the carbon ion beam and k_{Q} accounts for the differences in beam quality relative to the calibration beam quality. During the calibration, the MU was set to the same at each scanning point in the homogeneous calibration field, and the dose measurement was conducted in the entrance region in air by ionization chamber located in the center of the field.

2.2 Irradiation field for calibration

In order to verify the generation capability of uniform irradiation field for monitor calibration a mono-energetic circle field of 60 mm in diameters was generated with the 207 MeV/u pencil-like carbon beam. The homogeneous calibration fields were generated by the dynamic beam delivery system in the treatment terminal at HIRFL using a Gaussian shaped beam spot of 22.8 mm full width at half maximum (FWHM), which were checked with a ionization chamber (IC) array of 729 detectors with a small sensitive volume each (PTW 2D-ARRAY, Freiburg, Germany). The pencil beams, produced by the HIRFL synchrotron, were magnetically deflected stepwisely in vertical and horizontal directions to "paint" the field by two pairs of bending dipole magnets in accordance with a predefined grid of scan spot, typically spaced 3 mm in both directions. The MU is the same at each scan point.

During the calibration, a small thimble chamber (Farmer chamber, type 30013, PTW-Freiburg, Freiburg, Germany) as the dose detector was placed in the center of the homogeneous fields. The total water equivalent path length before the sensitive volume of the chamber including the thickness of the beam delivery device and monitor systems amounts to 6.8 mm.

2.3 Energy dependence of calibration factors

The therapeutic online monitors at HIRFL-CSR were calibrated in units of particles per MU for all the available energies while the particle numbers were determined based on the measurement of absorbed dose to water in mono-energetic circle fields of 60 mm in diameters since the direct measurement of particle fluence cannot be performed. The calibration measurement of the beam intensity monitors was performed at six different energies E ranging from 172 MeV/u to 207 MeV/u with an interval of 7 MeV/u, which corresponds to the Bragg peak positions in water of 67.09 mm to 92.27 mm with an average interval of 4.9 mm.

2.4　Influence of scan steps

The influence of various scan steps on CF with carbon ions was first studied in the deep-seated tumor therapy terminal at HIRFL-CSR in this work. The measurement was taken in plateau regions with two types of calibration fields (circular and rectangular) using a 207 MeV/u Gaussian carbon ion beam. ϕ 60 mm fields were scanned with beam spot spacings of 3, 4, 5, 6 and 7 mm, respectively, and the beam spot spacings of rectangular fields of 60 mm side length were set to 3, 4, 5 and 6 mm, respectively. The MU was set to the same at each scanning point among each calibration field.

3　Results

3.1　Calibration field

In-air spot lateral profile in the x direction of the xy-plane were checked in the plateau region ($z = 6.8$ mm) with a small parallel plate ionization chamber (Markus chamber, type 23343, PTW-Freiburg, Freiburg, Germany), which has a cylindrical sensitive volume of 5.3 mm in diameter and 2 mm in height, for the 207 MeV/u pencil-like carbon beam.

As shown in Fig. 1, the parameterized Gaussian shape and the measured relative values were in great agreement, with a FWHM of 22.8 mm. The Gaussian shaped beam spot is the key of the calibration field, because the mono-energetic calibration field delivering a homogeneous dose is the prerequisite for the application of Eq. (2). For this purpose, the PTW 2D-ARRAY with 729 small chambers was used for the dose homogeneity measurement. The measured data acquired from the x direction of the ϕ60 mm field are plotted in Fig. 2, representing the lateral profile of the calibration field. This mono-energetic field of ϕ60 mm was close to the entrance region at a depth of 6.8 mm in the water. The homogeneity of the calibration field for each energy is generally required to be better than 5%. The calculated beam profile based on the beam spot with initial angular and radial spreads, shown in Fig. 2, has good agreement with

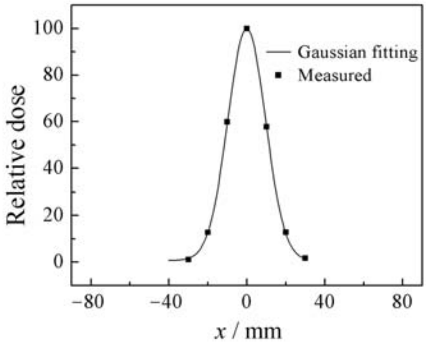

Fig. 1　In-air beam spot lateral profile in the x direction measured in the plateau region ($z = 6.8$ mm) for the 207 MeV/u pencil-like carbon beam (squares). Solid line represents the calculated beam profile based on the beam with initial angular and radial spreads (the initial Gaussian beam spot with lateral spread).

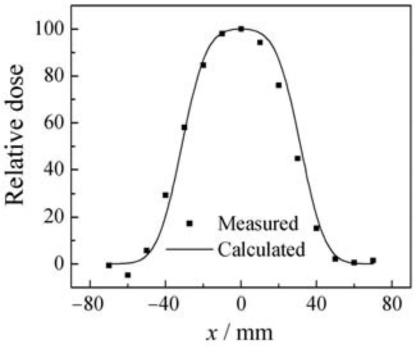

Fig. 2　The lateral profile of the calibration field in the x direction measured in the plateau region for the 207 MeV/u pencil carbon beam (squares). Solid line represents the calculated beam profile based on the beam spot with initial angular and radial spreads (the initial Gaussian spot with lateral spread).

the measured data.

3.2 Energy dependence

In Fig. 3, the monitor CFs measured using the six different energies are displayed. The measurement at each energy was repeated eight times and the reproducibility of the results was within 11%. The solid line shown in Fig. 3 is the linear fitting of the energy dependence of the monitor CF $C(E)$.

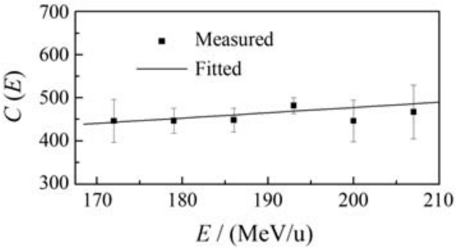

Fig. 3 The energy dependence of the monitor CF $C(E)$ for the six different energies of the carbon ion beams.

3.3 Influence of scan steps

The monitor CFs under the conditions of various scan steps are shown in Fig. 4. The results indicate that the response of the beam monitor to carbon ions basically was almost the same although the scan step increased significantly. For both the rectangular and circular calibration fields, the average CFs were 447.8 and 376 with tiny deviations of 1.8% and 1.3% respectively when the scan step varied from 3 mm to 6 mm. However for the rectangular field with the scan step of 7 mm, the CF went up to 493.6. Probably, the fact that the low dose envelope of pencil beam extended outside of the field a lot may account for such an increase in the case of 7 mm step scanning.

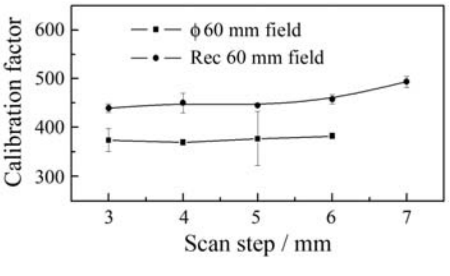

Fig. 4 The monitor CFs under conditions of various scan steps for circular and rectangular calibration fields.

4 Discussion

The calibration procedure presented in this paper provides a unique and simple method for particle monitor calibration in the dynamic beam scanning delivery at HIRFL-CSR, which is valid for various energies and possible SOBPs applied to patients.

This study was carried out based on a pencil-like carbon ion beam that provided by the HIRFL-CSR synchrotron. The details of the pencil beam such as the depth-dose distribution and the beam lateral spreads were the basic data for heavy ion dosimetry research. The beam lateral spreads were due to the multiple scattering when the beam passed through the beam exit vacuum window and the devices necessary for beam monitoring and shaping such as beam monitors and ridge filter. Physically, the beam lateral spreads could be described with different types of the mathematical model. However previous experiments have already shown that the lateral spreads of particle beam were approximately symmetric and could be described with a 2D Gaussian model[3, 5, 23] as follows:

$$P(x, y)=\frac{1}{2\pi\sigma_1\sigma_2}\times \exp\left\{-\frac{1}{2}\left[\left(\frac{x-\mu_1}{\sigma_1}\right)^2+\left(\frac{y-\mu_2}{\sigma_2}\right)^2\right]\right\}. \qquad (3)$$

As shown in Fig. 1, the measured beam-profile data in the x direction were in good agreement with the fitting according to Eq. (3). In addition, the calculated field profile based on the beam spot with initial angular and radial spreads had good agreement with the measured points as shown in Fig. 2. Therefore, the capability of creating uniform irradiation fields by the spot-scanning system was verified through laterally superposing single Gaussian-shaped beams.

Due to the energy dependence of stopping power and the w value, which introduce uncertainties in the radiation quality factor k_Q in Eq. (1), the monitor CF also presented energy dependence[11] as shown in Fig. 3. Although the scan step increased significantly in the case of either the round or the rectangular calibration field, the response of the beam monitor to the carbon ions was almost the same, indicating that the CF was not affected by the variation of scan steps if the lateral spread of the pencil beam could keep stable (Fig. 4). The two points above are reflected clearly in this work. The independence of CF on scan step shows that the reference conditions for calibration in terms of scan step are steady.

It should be noticed that although there was no scan-step dependence of calibration factor, the CF derived from the rectangular field was larger than that from the round one. This is because there were 441 scan points in the rectangular field with 60 mm side length, but only 353 points in the round calibration field instead. The more 88 pencil-like carbon ion beams contributed to an increase in dose in the center of the rectangular field, leading to the increase of the CF. On the other hand, the disparity of the CFs obtained in both the fields suggests that the calibration fields shaped by the spot scanning system in this work were not large enough for the calibration task. So it is essential that a calibration field should be homogeneous and large enough to eliminate the influence of the low dose envelope of a mono-energetic pencil beam on monitor calibration[31]. In other words, the distance between the detector's center and the boundary of a calibration field should be larger than the radius of the low dose envelope of a pencil beam.

Besides energy and calibration field size, LET, beam spot size, the measurement device and environment also influence the beam monitor calibration[32]. LET affects the dose measurement through incomplete saturation of ionization chamber. The smaller the LET, the smaller the correction. Saturation correction may vary for some ionization chambers between only 1% at 25 keV/μm and up to 10% at 1 000 keV/μm[33]. The measurement position has an impact on the accurate dose determination as well. Less uncertainty are introduced by positioning the measuring chamber in the plateau region rather than in the SOBP region, as we did in this work.

To investigate the effects of field size and beam scattering on the monitor calibration, two types of experiments should be made in the near future: (1) calibration in various fields using a certain single pencil-like beam; (2) calibration in a certain calibration field with various single pencil beams. Furthermore, to compensate for the field-size dependence of dose measurement in spot scanning beam delivery an accurate beam model, which includes the low dose envelope of single pencil beams, should be developed urgently.

5 Conclusion

A beam monitor calibration procedure for dynamic particle beam delivery was outlined and its suitability and effectiveness were verified by dose measurements in the plateau region. The method of beam monitor calibration presented in this paper will be improved through stressing the necessity to include recommendations for dynamic beam monitor calibrations in the TRS-398. The CF, reflecting the response of the beam monitor to incident particles, maintain a steady status along with the increase of scan step and the beam monitoring system shows its steadiness and reliability for the carbon ion therapy at HIRFL-CSR.

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面向 HIRFL-CSR 主动式点扫描技术的剂量标定方法研究

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摘要：基于 HIRFL-CSR 肿瘤重离子治疗终端主动式束流配送系统发展了面向三维点扫描适形调强治疗技术的在线监测器点扫描剂量标定方法。为了验证点扫描剂量标定方法的稳定性和可靠性，利用 HIRFL-CSR 提供的 C 离子束考察了在线监测器剂量标定因子的能量依赖以及不同扫描步长的影响。结果表明：在线监测器剂量标定因子存在能量依赖；不同扫描步长对剂量标定因子影响较小(偏差小于 1.8%)。证明了点扫描剂量标定方法的稳定性和可靠性。鉴于在三维点扫描适形调强治疗技术中影响在线监测器点扫描剂量标定因子的因素较多，建议今后续继续研究点扫描剂量标定因子影响因素，修正和完善点扫描剂量标定方法。

关键词：三维点扫描治疗方法；在线监测器剂量标定；标定因子；能量依赖；重离子临床剂量学

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