ABSORBED DOSE IN ION BEAMS: COMPARISON OF IONISATION-AND FLUENCE-BASED MEASUREMENTS

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Abstract
A direct comparison measurement of fluorescent nuclear track detectors (FNTDs) and a thimble ionisation chamber is presented. Irradiations were performed using monoenergetic protons (142.66 MeV, \(\phi = 3 \times 10^6 1/\text{cm}^2\)) and carbon ions (270.55 MeV/u, \(\phi = 3 \times 10^6 1/\text{cm}^2\)). It was found that absorbed dose to water values as determined by fluence measurements using FNTDs are, in case of protons, in good agreement (2.4 \%) with ionisation chamber measurements, if slower protons and Helium secondaries were accounted for by an effective stopping power. For carbon, however, a significant discrepancy of 4.5 \% was seen, which could not be explained by fragmentation, uncertainties or experimental design. The results rather suggest a W-value of 32.10 eV ± 2.6 \%. Additionally, the abundance of secondary protons expected from Monte-Carlo transport simulation was not observed.

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INTRODUCTION

Fluorescent nuclear track detectors (FNTDs) based on Al₂O₃:C,Mg single crystals and laser-scanning confocal fluorescence microscopy [1] allow for high-accuracy fluence determination. FNTDs exhibit excellent particle detection efficiency and can register all types of primary and secondary ions present in clinical beams (exemplary shown in Fig. 1, inserts) [2]. Potential applications of the FNTD technique are seen where employment of ionisation chambers is challenging, such as in laser-accelerated protons, dosimetry in magnetic fields or in vivo dosimetry. However, using FNTDs, discrepancies of ~8% to ionisation-based measurements were observed in the authors’ studies. At the time, the findings were not conclusive owing to shortcomings in the experimental designs. In this contribution, a direct comparison study of FNTDs and a thimble ionisation chamber is presented to investigate this discrepancy in more detail.

MATERIALS AND METHODS

Fluorescent nuclear track detectors

Al₂O₃:C,Mg single crystals grown by Landauer Inc., Stillwater, OK, USA, were used as FNTDs. (4x8x0.5 mm³ in size). Al₂O₃:C,Mg contains Fe²⁺ (2Mg) colour centres, which undergo radiochromic transformation under ionizing radiation yielding intra-centre fluorescence at 750±50 nm when stimulated at 620±50 nm. Since transformed centres are optically, thermally and temporally stable, this enables optical imaging of energy deposition and hence charged particle tracks in three dimensions [3]. Further, it has been shown that the fluorescence amplitude of the particle tracks is related to the linear energy transfer (LET) of the particles enabling particle discrimination on a wide range of LET [4]. However, the performance of FNTDs for particle spectroscopy in clinical applications with the read-out protocol used within this study has still to be specified in more detail [5].

Zeiss LSM 710 ConfoCor 3

The Zeiss LSM 710 ConfoCor 3 inverted laser scanning confocal microscope was used for detector read-out with the configuration described in Ref. [6] [633 nm for excitation, 655 nm for emission]. Potentials of the FNTD technique are seen where employment of ionisation chambers is challenging, such as in laser-accelerated protons, dosimetry in magnetic fields or in vivo dosimetry. However, using FNTDs, discrepancies of ~8% to ionisation-based measurements were observed in the authors’ studies. At the time, the findings were not conclusive owing to shortcomings in the experimental designs. In this contribution, a direct comparison study of FNTDs and a thimble ionisation chamber is presented to investigate this discrepancy in more detail.

ImageJ processing software

ImageJ ([7], [8]) was used together with the ‘Mosaic’ background subtractor [9] and particle tracker [10] plug-ins for subtracting the fluorescence background and finding the particle track positions [2]. Further data processing was done in R (version 2.14.2) [11].

Fluence-based dose approximation

The absorbed dose to water for the beam quality $Q$ (e.g. p or ¹²C), $D_{w,Q}$, can be determined by the particle fluence, $\phi$, and the mass stopping-power of water $\frac{\sigma_{w,Q}}{\rho_w}$ through

$$D_{w,Q} = \phi \cdot \frac{\sigma_{w,Q}}{\rho_w}$$

In case of mixed particle fields, dose contributions from different particle species $T$ and kinetic energies $E$ have to be considered:

$$D_{w,Q} = \frac{1}{\rho_w} \cdot \sum_T \int_E \frac{dE}{\phi(E) \cdot \sigma_{w,Q}(E,T)} \cdot \frac{\sigma_{w,Q}}{\rho_w}$$

Fluence assessment using FNTDs

Within this study, the approach described in Ref. [2] was used to determine $\phi$, i.e. by

$$\phi = \frac{N}{A}$$

where $N$ is the number of particles counted and $A$ the analysed area. In case of ions traversing the FNTD under a polar angle $\theta \neq 0^\circ$ (e.g. non-perpendicular irradiation or misalignment of the FNTD under the microscope), $A$ is not the planar area $A_{\perp}$. This effect has been accounted for by multiplying $A$ with a correction factor, $k_A$.

$$A_{\perp} = k_A \cdot A = \cos \theta \cdot A$$

with $\theta$ derived from the 3-d track structure information obtained within the FNTD. With respect to the carbon ion irradiations, particles were discriminated concerning the relative fluorescence amplitude of their tracks into primary particles and secondary lighter fragments in general. In case of proton irradiations, no particle discrimination was applied (Figure 1, inserts). Since FNTDs have a track detection efficiency of ≥ 99.83% [2] and uncertainties of $A$ have been proven to be negligible, the fluence uncertainty is dominated by (Poisson) counting statistics:

$$\sigma_{FNTD} = \frac{\sqrt{\phi}}{\phi} = \frac{1}{\sqrt{\phi A_{\perp}}}.$$
7 mm RW-3 in front and 10 mm RW-3 for backscatter). For the FNTD, 4.7 mm instead of 7 mm RW-3 were placed in front to obtain a compatible experimental setup considering the effective point of measurement of the cylindrical ionisation chamber as given in Ref. [14]. For further calculations, a water-equivalent pathlength (WEPL) of 1.025 ± 0.011 was used for RW-3 [15].

Particle energy and spectra
Monte-Carlo (MC) transport simulations yielded information on the absorbed dose to water and particle fluences as a function of energy for primary and secondary particles. The FLUKA code ([16], [17]), version 2011 v2.17 was used. Scoring was done for a water volume (1x1x0.003 cm³) behind 7.7 mm of water. To study the potential influence of the phantom and the detector material, additional simulations were done where the water surrounding the target volume was replaced by RW-3 of corresponding thickness and the target volume by Al₂O₃, respectively.

EXPERIMENTS

Irradiations
Irradiations were performed at the Heidelberg Ion-Beam Therapy Center (HIT) with a field size of 10x10 cm². The phantoms were located at the iso-centre and irradiated with protons (142.66 MeV) and carbon ions (270.55 MeV/u) at a nominal fluence of 3x10⁶ 1/cm². No ripple filter to broaden the Bragg-Peak was used. The beam application monitor system (BAMS) at HIT, featuring three ionisation chamber monitors, is calibrated in terms of particle fluence by a Farmer-type air-filled ionisation chamber on a daily basis allowing for a tolerance of ±1%. To increase significance in this study, 18 additional measurements with the Farmer chamber placed in the RW-3 phantom were performed (carbon ions) and used to fine-tune the monitor chambers. Since this effect is independent of ion type, the adjustment was applied to the proton data as well. In total, four FNTDs (three FNTDs) were irradiated with carbon ions (protons).

FNTD read-out
All FNTDs were read-out 20 µm below the detector surface. “Z-stacks” of five images separated by ∆z = 1 µm (1H) and 5 µm (12C) covering an area of 1.02 mm² were acquired. In order to improve the signal-to-noise ratio, a median intensity projection of the z-stacks was calculated where applicable [2].

Irradiation-field homogeneity
Physical beam records from the accelerator log system were forward-calculated and analyzed regarding deviations from the nominal particle fluence. Additionally, cross sections of the irradiated FNTDs in horizontal and vertical direction were acquired yielding a good approximation of the spatial fluence distribution.

Table 1: Monte-Carlo transport simulation results on CSDA energy, dose to water, and effective stopping power at 7.7 mm water-equivalent thicknesses (WET). Following WET were considered for the calculation of the particle energy at the detector surface (Eprim) using the CSDA by the “libamtrack” library [18]: (1) 2.89 mm, which includes all traversed materials between the high-energy beam line and the iso-centre, (2) 4.82 mm (4.7 mm RW-3). Stopping-powers for protons were taken from Ref. [12] and scaled for carbon ions using the effective ion charge.

| Primary | Eprim(CSDA) [keV/µm] | Eprim(MC) [keV/µm] | Dwater [Gy·cm²] | Φout [keV/µm] | SSCC | Δs / sCSDA |
|---------|----------------------|---------------------|-----------------|--------------|------|-------------|
| Proton  | 138.29               | 138.33±0.13         | 9.678x10⁻²±0.11 | 1.004        | 0.6038 | +4.8 %      |
| Carbon  | 261.88               | 262.00±0.13         | 2.202x10⁻²±0.11 | 1.183        | 13.69  | +0.3 %      |
Table 2: MC transport simulation results on relative fluences and doses for a water volume at WET of 7.7 mm.

| Primary   | Quantity | Low E | High E | He | Li | Be | B | C | Low E | High E |
|-----------|----------|-------|--------|----|----|----|---|---|-------|--------|
| Proton    | Fluence  | 1.2 % | 98.8 % | <1 %| <0.2 %| -  | - | - | -     | -      |
|           | Dose     | 4.0 % | 95.1 % | 0.7 %| 0.1 %| -  | - | - | -     | -      |
| Carbon    | Fluence  | 14.8 %| -      | 2.4 %| 0.3 %| 0.2 %| 0.4 %| 0.1 %| 81.8 %| -      |
|           | Dose     | 1.7 % | -      | 0.6 %| 0.1 %| 0.1 %| 0.3 %| 0.2 %| 97.1 %| -      |

* Additional 0.1 % relative dose from oxygen (O).

RESULTS

The mean of the 18 Farmer chamber measurements performed in the carbon ion beam yielded an adjustment of $\sigma_{FC} = 1.19 \% \pm 0.01$ pp (percentage point, SE) for the monitor system, i.e. the “corrected theoretical dose ($D_{FC}$ (Theory, cor.))” (Figure 1).

Protons

For protons, a deviation of $\Delta_{p} = 6.89 \%$ between the mean fluence-based dose to water value of 2.61 mGy ± 0.83 % as obtained with FNTDs (Figure 1, left, blue line) and the ionisation-based value of 2.80 mGy ± 0.41 % (black line) was found assuming a monoenergetic proton beam with energy $E_{beam} = 138.3$ MeV by a continuous-slowing-down approximation (CSDA) (Table 1). However, as indicated by the simulations, this is only true for $\Phi_{Mon}(E_{beam}) = 98.8 \%$ of the protons detected, the remaining $\Phi_{Mon}(E < E_{beam}) = 1.2 \%$ of lower-energy protons deposit a significant relative dose (4.0 %, Table 2), even in the entrance channel. Additionally, fragments like helium or lithium are very rare but still have a considerable contribution to dose due to their high stopping power. Taking these contributions into account by an effective stopping power (Table 1), the discrepancy $\Delta_{p}$ decreases to 2.4 %.

Carbon ions

In case of carbon ions, both the primaries’ fluence $\Phi_{Mon}$ and the fluence of the secondary fragments could be assessed owing to their very different signatures (Figure 1, right insert). The mean dose value based on $\Phi_{Mon}$ of 61.45 mGy ± 0.71 % (Figure 1, right, blue line) was 7.4 % lower than that determined by the ionisation chamber of 66.35 mGy ± 0.41 % (green line). According to the transport simulations in Table 2, primary carbon ions account for 97.1 % of the dose, whereas protons (helium) with a relative fluence of 14.8 % (2.4 %) contribute 1.7 % (0.6 %), the influence of heavier fragments is minor. The effective stopping power is therefore very similar to the one from the CSDA approach (Table 1), and taking the energy distribution and secondaries (Table 2) into account reduces the discrepancy $\Delta_{c}$ by only 2.9 pp leaving 4.5 %.

Field homogeneity

Forward calculations of the physical beam records have shown that the uniformity of the irradiation fields was within ± 0.8 % for all carbon and proton irradiations. Although the sensitive area of the ionisation chamber is 1.08 cm² larger than the area of the FNTD, a deviation of 7.4 % between ionisation- and fluence-based dose measurements would mean that the fluence outside of the area covered by both FNTD and ionisation chamber would have been on average 9.6 % higher, which is far beyond the routinely checked constrains of this clinically used system. Further, no significant measured fluence gradients were observed over the length and width of the FNTD.

Influence of phantom and FNTD

Small (0.5 % in dose) influence of the RW-3 phantom on the dose to water was seen in the MC simulations in case of the proton beam, mainly due to an increased production of helium. No similar effect has been seen for the carbon ion beam. The Al$_2$O$_3$ of the FNTD did not change the spectrum significantly within the 20 µm in front of the measurement plane.

DISCUSSION

Given the uncertainties $\sigma_{FRS}$ as reported in the TRS-398 (2% in $D_{FC,0}$ for p and 3 % for $^{12}$C), for the FNTD (Poisson error, area correction factor), and from experimental design (e.g. inhomogeneous irradiation, machine stability and beam direction), it is believed that the dose assessment of the fluence-based approach agrees with the ionisation-based data in the case of protons. In case of carbon ions, however, the difference is still significant. It is also puzzling that in the carbon beam, the authors detect a relative secondary fluence of approximately $\Phi_{BAMS}$ He, Li = 3.3 % instead of 17.5 % as predicted by the simulation. If one used these values for dose assessment, the $\Delta_{c}$ would have been 7.0 % instead of 4.5 %. Even using a more detailed geometrical model of the BAMS including 1 m of air gap to the isocentre did not reduce $\Delta_{BAMS}$ He, Li to < 17.0 %.

CONCLUSION AND OUTLOOK

FNTDs are able to yield correct dose estimation for protons. The assumption of a monoenergetic beam, even in the entrance channel, is invalid since slower protons and secondaries contribute significantly and an effective stopping power has to be employed. These corrections account for the discrepancies seen in the authors’ previous experiments. Since the FNTD fluorescent track amplitude depends on the particle species and energy [4]-[5], the effective stopping power might be estimated from the intensity histogram of the particle tracks. For carbon ions, however, secondary particles did not fully account for the discrepancies found. Considering the detection efficiency of FNTD technology, it seems unlikely that a significant portion of tracks were not registered. This might stimulate discussions on the accuracy of the $k_{Q,0}$ factor for carbon beams [19]. Since the stopping power in this energy range is known quite accurately (1-2 %), one might question the currently used constant $W_{\text{air}}$-value of 34.50±0.52 eV (1.5 %) [14]. The presented findings would imply a $W_{\text{air}}$-value of 32.10±0.83 eV (2.6 %). This uncertainty includes all conceivable sources of errors including $\sigma_{FNTD}$, $\sigma_{FC}$, and $\sigma_{FRS}$ (except for the uncertainties given for long-term stability of user dosimeter, establishment of reference conditions, dosimeter reading relative to beam monitor and beam quality correction). More
conclusive results are expected from absolute dose to water measurements in a carbon ion beam with a water calorimeter, which would allow to directly calibrate ionisation chambers in units of absorbed dose to water without applying radiation-field-dependent correction factors.

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