SECONDARY PARTICLE DOSE AND RBE MEASUREMENTS USING HIGH-ENERGY PROTON BEAMS

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Abstract

High- and intermediate-energy protons are not able to directly form a track in a CR-39 etch detector (TED). Such detectors, however, can be used for the detection and dosimetry of the beams of these particles through the registration of secondary charged particles with sufficiently high values of linear energy transfer (LET). The studied were realized in a clinical proton beam of the NCC Korea, with primary energy of 72 to 220 MeV (1.1 to 0.4 KeV/ μm). The contribution of the secondary particle dose and the value of RBE both increase with decreasing proton energy. A strong agreement between experimentally obtained results and the predicted total cross sections was verified by the Alice code. Stimulation of the secondary particle dose by the Geant4 code also predicted results in agreement by experimental results. It is clear that higher cross sectional values lead to an increased production of secondary particles. This secondary particle dose is highly important for applications such as radiotherapy, radiobiology, and radiation protection.

INTRODUCTION

The concept of radiation protection is based on a connection between the radiation quality and quantity, often referred to as linear energy transfer (LET). There are several techniques used for LET spectra measurements. In order to create particle tracks, a solid-state nuclear track detector (SSNTD) was exposed to nuclear radiation (neutrons or charged particles), etched, and examined microscopically [1]. Heavier, high-energy, charged particles, particularly protons are now being used in radiotherapy. When energy levels are sufficiently high, secondary particles with high LET are produced through nuclear interactions, which may change therapeutic beam characteristics [2]. Dosimetry measurements are understood and transformed into biological efficiency by means of a biological weighting function. The goal of the current experiments was to study qualitative and quantitative changes in the secondary particle microdosimetry with the aforementioned proton energy.

EXPERIMENTAL PROCEDURES

Material and Methods

Irradiation was performed at the National Cancer Center (NCC) in Korea. CR-39 plates of 20 × 20 × 0.75 mm were used throughout this study. The samples were irradiated by various proton energies using a Cyclotron with a beam current of 5nA over time periods ranging between 1–3 min. CR-39 track detectors (available from Intercast Europe SpA via Natta 10/a 43100, Parma, Italy) were used. Two corners of each detector were irradiated. One corner was irradiated with ^{252}Cf fission fragments and the other corner was irradiated with ^{241}Am alpha particles at the Sungkyunkwan University. The task was completed to check the exact etching conditions and to determine the bulk etching rate [3].

LET Spectrometer Base on Chemically Etched CR-39 TED

After irradiation, each piece of the CR-39 detector was etched in a 70°C 6N NaOH solution, as this is the most popular and commonly recommended etchant [4]. The etching time was 15 h, which corresponded to the removal of an approximately 20-μm-thick layer on each side of the detector. After etching, the CR-39 samples were cleaned in running water for 30 min and dried. The value of V was calculated by combining at least 2 of the previously mentioned track parameters. Final optimization was presented through comparison of the removed layer recalculated from V-values and directly measured through fission fragment track diameters. The resulting V-spectra were corrected for by using the critical detection angle. Anisotropy can be obtained easily by the Alice code [5]. By taking into account the anisotropy the critical and solid angles are easily corrected to determine the V-spectra. V-distributions were then transformed into LET spectra using calibration curves [6] with the heavy charged particles. This calibration curve, based on irradiation with 12C to 56Fe ions and LET in water ranging from 7.9–200 keV/μm, was based on extrapolated data extended to the much higher values of LET. The etched tracks were observed using an optical microscope. The microscope image was viewed with a high-quality camera connected to a PC-based image analyzer. With a magnification of 1000 pixels, the single field-of-view area considered was approximately 4.71×10^{-4} cm^2. The image analyzer displays images on a monitor and tracks appear as dark spots on a clear white background.

Integral Dosimetry and Microdosimetry Characteristics and RBE Calculated from LET Spectra

Dose characteristics and clinical radiobiological effectiveness for the particles having LET values higher than 10 keV/μm can be obtained from the LET spectra by the following:

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$$D_{LET} = \int (\frac{dN}{dL}) LdL; \quad (1)$$

$$H_{LET} = \int \left(\frac{dN}{dL}\right) LQ(L)dL; \quad (2)$$

$$R_{LET} = \int \left(\frac{dN}{dL}\right) Lr(L)dL; \quad (3)$$

dN/dL represents the number of tracks in an LET interval; L is the value of the LET; and QF (L) is the quality factor corresponding to the value of L; and r (L) is the biological weighted function [7].

Range and LET were calculated by the SRIM code [8]. By knowing the LET, the total absorbed dose at any point (D_{point}) is easily calculated. By calculating D_{LET} and R_{LET} from Eqs. (1) and (3), it is possible to determine the amount of RBE for the total beam by using this formula $1 + (R_{LET}–D_{LET})/D_{point}$.

The radiation quality is characterized by the methods and procedures of microdosimetry. A tissue equivalent proportional counter (TEPC) is the basic experimental microdosimetry instrument. When employing the TEPC at high dose rates or in the presence of very intense low-LET components in a radiation field, values obtained should be crosschecked with those provided by other methods. For this purpose, the microdosimetry method based on a chemically track-etched detector (TED) was developed.

RESULT AND DISCUSSION

The LET spectrometer has the potential to study both the dose D (L) and the dose equivalent H (L) distributions in terms of the LET. In order to determine H (L), we used the recommendations and quality factors from the International Commission on Radiological Protection (ICRP) from 2004 [9]. To determine the LET values in the range of 17 < LET < 710 keV/µm in tissue, only the spectra for V-values between 0.7 and 1.7 were collected. The lower limit represents significant background contributions and upper limits indicate the presence of highly significant track overlapping. Figure 1 for proton energy of 220 MeV shows the three factors of L*D (L), L*H (L) and L*N (L) peaks are a descending function of the LET, that the spectra peak in the region is around 150 keV/µm, and that they are all ascending functions of the LET from 16 to 550 keV/µm. The average value of the LET, with respect to energy delivery, can be estimated at approximately 279 keV/µm for the dose and to approximately 316 keV/µm in the case of the dose equivalent with ICRP 92 quality factors. The calibration curve and statistical uncertainties, which are associated with the number of tracks, contribute to the overall uncertainty.

For the CR-39 samples exposed to different beam energies, the integral characteristics of the absorbed dose D and the equivalent absorbed dose H, obtained from Eqs. (1) and (2).

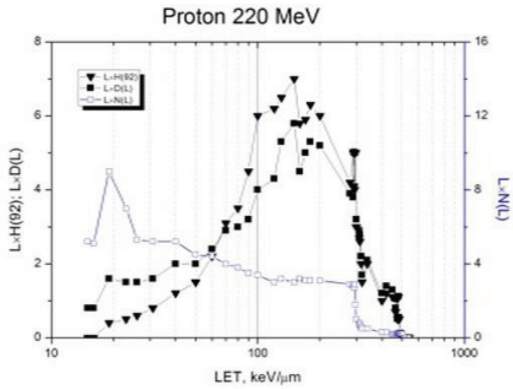

Figure 1: Event number LN(L), dose LD(L), and dose equivalent LH92(L) distributions in terms of LET for Ep = 220 MeV.

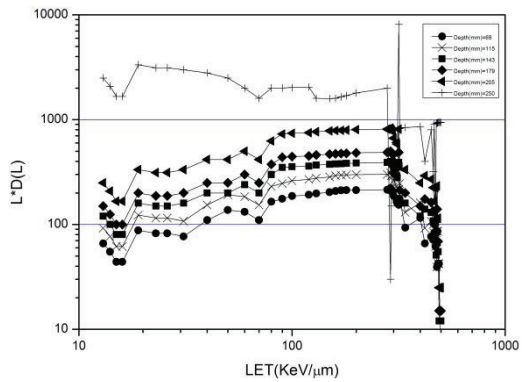

Figure 2: The distributions absorbed doses for various depths in CR-39 as L*D(L) for a primary proton energy of 220 MeV.

The absorbed dose D and the dose equivalent H for different proton energies of 72, 150, and 220 MeV were measured. The results reported in our previous work with 9.6 to 30 MeV protons [10] and the published results reported by others with 70 to 180 MeV protons [11] are presented in Table 1. As shown in Table 1, the absorbed dose, the dose equivalent, and the total reaction cross-sections decrease as the proton energy increases. These findings appear to be minimally incongruent with previously published results, which might be related to a systematic uncertainty. It is highly important that the prediction of possible nuclear reactions and the calculation of their reaction cross-sections with the Alice code clearly explain variations in the absorbed dose and the dose equivalent with the incident proton beams. In addition, Table 1 contains the calculated ratios of the secondary particle dose to the primary proton dose using the GEANT4 code. This was found to be different from experimentally measured values but in higher proton energies as the discrepancy is not large as in the case of low proton energies.

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Table 1: Absorbed dose D and dose equivalent H for different proton energies ranging from 30 to 220 MeV along with the prediction of the total cross-sections for the constitutive CR-39 material obtained using the Alice code and calculation of secondary particle dose by GEANT4

Energy (MeV)	Total cross section (mb) for $^{1}P+^{16}O$	Total cross section (mb) for $^{1}P+^{12}C$	Absorbed dose	Dose equivalent	The dose ratio of secondary to primary particles(experimentally)	Total secondary dose ratio by Geant4 %
9.6	708.1	574.0	296	4270	29.6%	-
16.6	559.4	523.6	185	2421	18.5%	-
30.0	470.3	384.7	75	1311	7.5%	5.10
72	**313.5**	**251.4**	**74.2**	**607**	**5.4%**	**5.10**
130	238.7	189.1	49.3	400	4.3%	3.43
150	**223.7**	**176.7**	**43.7**	**337**	**4.1%**	**3.08**
180	205.1	162.0	28.7	292	2.9%	3.14
220	**187.6**	**124.2**	**27.1**	**256**	**2.7%**	**3.1**

The biological weighted function r(L) was established to determine a single parameter that could estimate the quality of radiation used in therapy. This function was improved with the goal of reproducing RBE ratios for beams with different radiation qualities and is based on the microdosimetry approach described previously [7]. Distributions of the absorbed dose, D(L), in LET at various CR-39 depths for a 220MeV proton beam are shown in Fig 2. Basic parameters of RBE are obtained from Eqs. (1) and (3) for the 220 MeV proton beam and are found in Table 2. It is clear from Table 2 that the RBE value increases with decreasing proton energy.

Table 2: REB calculation based on the microdosimetry method for 220MeV proton beams.

Depth in CR-39(mm)	69	115	143	179	205	250
E_{mean} (MeV)	180	150	130	100	72	Bragg
D_{point} (mGy)	225	179	147	98	75.3	3.1
D_{LET}(mGy)	3.4	4.1	5.5	6.8	7.4	2.7
D_{LET}/D_{point} %	1.51	2.29	3.74	7.09	9.8	87.09
R_{LET}(mGy)	6.052	6.84	8.52	9.25	10.28	3.86
RBE	1.011	1.015	0.020	1.025	1.038	1.37

CONCLUSION

The LET spectrometer was used to determine dosimetric characteristics and LET spectra in high-energy proton beams. Our results suggested a non-negligible contribution of high-LET secondary particles to the dose characteristics in the high-energy proton. To the extent that proton radiobiology and proton radiotherapy studies are concerned, the dose due to secondary high-LET charged particles changes not only the quantity but also the quality characteristics of the beam. While the secondary charged particles contribute only a few percent to the absorbed dose at the beam entrance, the absorbed dose may increase substantially at greater depths. Due to the increased fraction of high LET particles, the radiobiological characteristics of the beam may also change with the depth. This effect may be of lesser significance than assumed through the values of quality factors, but it may be responsible for the increased effectiveness of high-energy protons in radiotherapy [7].

In regards to radiation protection, the contribution of secondary high-LET charged particles modifies radiation quality factors. While the quality factor for ionization losses is approximately 1.0, secondary high-LET particles may exceed a quality factor of 10. Calculations revealed that this phenomenon might modify the average quality factor in the human body by a factor of more than 2 [12].

REFERENCES

[1] R. L. Fleisher et al., *Nuclear Tracks in Solid,* University of California Press, Berkeley,USA, (1975).
[2] A. G. Molokanov et al., Radiat. Prot. Dosim. 99 (2002) 433.
[3] S. A. Durrani and R. K. Bull (1987) *Solid State Nuclear Track Detection,* Pergamon Press, Oxford, UK (1987).
[4] M. Ghergherehchi M et al., Iran. J. Radiat. Res. 6 (2008) 113.
[5] M. Blann, *Recent Progress and Current Status of Preequilibrium Reaction Theories and computer Code Alice*. UCRL-JC-109052(1992).
[6] F. Spurny et al., Radiat. Meas. 40 (2005) 343.
[7] A. Wambersie and H. G. Menzel., Radiat. Prot. Dosim. 70(1997) 517.
[8] J. Ziegler et al., The Stopping and Range of Ions in Matter. in: Ziegler JF (Ed.) Pergamon, New York, See also www.SRIM.org (1986).
[9] ICRP 92 (2004) *Recommendations of the international commission on radiological protection: Relative biological effectiveness (RBE), Quality factor (Q), and radiation Weighting factor (WR)*. ICRP Publication, 92(2004) 9.
[10] M. Ghergherehchi et al., J. Korean. Phys. Soc. 58 (2011) 1082.
[11] F. Spurn'y et al., Radiat. Meas. 34 (2001) 527.
[12] V. E Dudkin et al., Health. Phy. 23 (1972) 663.