MEASUREMENT OF THE STOCHASTIC RADIAL DOSE DISTRIBUTION FOR A 30-MeV PROTON BEAM USING A WALL-LESS TISSUE-EQUIVALENT PROPORTIONAL COUNTER

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The frequency distribution of the lineal energy, y , of a 30-MeV proton beam was measured as a function of the radial distance from the beam path, and the dosed mean of y , $\bar{y}_D$, was obtained to investigate the radial dependence of $\bar{y}_D$. A wall-less tissue-equivalent proportional counter, in a cylindrical volume with simulated diameters of 0.36, 0.72 and 1.44 μm was used for the measurement of y distributions, $yf(y)$. The measured values of $yf(y)$ summed in the radial direction agreed fairly well with the corresponding data taken from the microdosimetric calculations using the PHITS code. The $\bar{y}_D$ value of the 30-MeV proton beam presented its smallest value at $r = 0.0$ and gradually increased with radial distance, and the $\bar{y}_D$ values of heavy ions such as iron showed rapid decrease with radial distance. This experimental result demonstrated that the stochastic deposited energy distribution of high-energy protons in the microscopic region is rather constant in the core as well as in the penumbra region of the track structure.

INTRODUCTION

Radiation-induced biological effects are related to the track structure around charged particles and are strongly dependent on the type and energy of the radiation involved. Deposited energy in the subcellular region of a tissue causes damage to living cells through physical, chemical and biological processes. Measuring the deposited dose $D(r)$ as a function of radial distance r from the ion beam path provides information on the spatial distribution of deposited energy. Much data have been collected since 1960s for protons^(1–7), deuterons⁽³⁾ and the particles of helium^(4, 8, 9), carbon^(9, 10), nitrogen⁽¹¹⁾, oxygen^(9, 12, 13), neon^(11, 14), silicon⁽¹¹⁾, iron^(10, 15–17), nickel⁽¹⁸⁾, germanium^(19, 20), bromine⁽²¹⁾, iodine⁽¹²⁾ and uranium⁽¹⁹⁾ using tissue-equivalent proportional counters (TEPC) or tissue-equivalent ion chambers. Data on the stochastic depositions of energy such as the lineal energy distribution⁽²²⁾ $yf(y)$ are also of great importance for the verification of theoretical models applied to the evaluation of relative biological effectiveness (RBE) of radiation therapy^(23–27), and track structure models^(28–33) have been verified and improved on the basis of the data from radial dose distributions.

While much data on the deposited energy distributions at the microscopic scale have been reported for various ions and energies, there is a limited amount of data from measurements taken under homogeneous conditions using a wall-less TEPC^(1–7, 9, 10, 15, 19, 20, 34–37). Such a device can measure $yf(y)$ precisely for energetic ion beams in particular. The dose-mean of $yf(y)$, $\bar{y}_D$ is

an appropriate index for evaluating the beam quality in a microscopic region of interest. Toburen *et al.*^(19, 20) reported the dependence of $\bar{y}_D$ on radial distance in radial dose distributions taken for 5.9-MeV u^{-1} and 16.2-MeV u^{-1} Germanium ions. Their studies indicated that the values of $\bar{y}_D$ rapidly decrease with increasing radial distance and approach a constant due to secondary delta rays. For proton beams, Tsuda *et al.*⁽³⁷⁾ showed the unique characteristics of proton and ion beams with kinetic energies ranging from 20 to 160 MeV, whose values of linear energy transfer (LET) were less than $\sim 10 \text{ keV } \mu\text{m}^{-1}$. Under the broad beam irradiation condition, the obtained $\bar{y}_D$ values for the proton beams are larger than the LET values, and the $\bar{y}_D$ values of He, C and Si ions with kinetic energies of $>150 \text{ MeV } \text{u}^{-1}$ are less than those of LET. This is attributed to the discrete energy deposition of delta rays produced by high-energy protons.

To further investigate the microscopic energy deposition of high-energy protons in the radial direction, a wall-less TEPC^(10, 36, 37) has been used to measure stochastic radial dose distributions due to a narrow proton beam with kinetic energy of 30 MeV because there are little data for protons with energies of $>5 \text{ MeV}$. This paper reports the measured values of $yf(y)$ for a 30-MeV proton beam at different radial distances, the radially summed $yf(y)$, a comparison of the authors' experimental $yf(y)$ with that calculated by the particle and heavy ion transport code system, PHITS⁽³⁸⁾, and the dependence of $\bar{y}_D$ on radial distance.

MATERIALS AND METHODS

Experimental

The measurement of $yf(y)$ was performed with the 30-MeV proton beam produced from a K110 AVF cyclotron at Takasaki Ion Accelerators for Advanced Radiation Application (TIARA)⁽³⁹⁾ at the Japan Atomic Energy Agency. The cyclotron can accelerate protons and heavy ions up to 90 MeV and 27.5 MeV n^{-1} , respectively. Figure 1 shows the experimental set-up in the HB1 beam line at TIARA. The accelerated 30-MeV proton beam provided from the cyclotron was extracted into the air through an aluminium collimator with a hole 1 mm across.

The detection part of the wall-less TEPC^(10, 36, 37) was composed of a thin anode wire and a helical cathode wire, the sizes of each of which were 3 mm in diameter and 3 mm height. The inside of the wall-less TEPC was filled with a propane-based tissue-equivalent gas⁽²²⁾ (TE-gas), the volume percentage of the propane being 54.7 %, the carbon dioxide 39.7 % and the nitrogen 5.6 %. The pressures of the TE gas were set at 6.67×10^3 Pa (50 Torr), 1.33×10^4 Pa (100 Torr) and 2.67×10^4 Pa (200 Torr). The mean chord length of a cavity is $\pi d/4$ for the beam irradiation on the cylindrical detection part perpendicular to the central axis. The corresponding volumes are $0.36 \mu\text{m}$ at 50 Torr, $0.72 \mu\text{m}$ at 100 Torr and $1.44 \mu\text{m}$ at 200 Torr. The change of the gas pressure was set to be <1 % under each condition, because the stability of the gas pressure was directly related to the uncertainty of the simulated site size. The centres of the detection parts in the wall-less TEPC and the beam monitor were positioned in a straight line on the trajectory of the incident proton beam ($r = 0.0$). The vertical positions of the wall-less TEPC were changed to measure the $yf(y)$ values for different radial distances, r . The adjustment of height was performed using a lab jack with the precision of <0.5 mm.

Figure 1. Schematic and photograph of the experimental set-up.

A schematic of the measurement system is shown in Figure 2. For obtaining signals in a wide range, the signals from the wall-less TEPC were divided into three and fed into a digital storage oscilloscope (DSO) through a preamplifier and a linear amplifier. In order to reduce the pile up, the beam intensity was determined based on the count rates of the beam monitor 1, not on the beam current provided by the beam operator. The dead-time owing to the data processing in the hard-disc drive on the DSO was corrected using the recorded time stamp of each data.

The coincidence measurement between the wall-less TEPC and beam monitor 1 was performed by triggering the signal of the wall-less TEPC, because it had a lower detection efficiency than beam monitor 1, especially when the wall-less TEPC was positioned radially far from the beam path. The details of beam monitor 1 are reported elsewhere⁽¹⁰⁾. Beam monitor 1 consisted of 8×8 bundled plastic scintillation fibre arrays arranged laterally and vertically. The square cross section of each fibre was 1 mm^2 . The beam spread observed by the beam monitor 1 was estimated to be ~ 3 mm in diameter. The beam was likely to be dispersed by the Kapton film set on the exit of the collimator ($55 \mu\text{m}$ thick) and the beam window of the wall-less TEPC ($50 \mu\text{m}$ thick).

Beam monitor 2 was a 5-inch plastic scintillation detector used to obtain the total number of incident protons passing the wall-less TEPC and beam monitor 1. Using the total numbers of incident protons

Figure 2. Schematic of the measurement system.

measured by beam monitor 2, the normalizations of the radial doses and the $yf(y)$ were performed.

To remove the pile-up events recorded in beam monitor 1, the single events that were recorded at both/either the x and y axes positions were extracted from data, irrespective of the detected position in the sensitive area of the beam monitor 1. The obtained pulse-height distribution was then converted into y distributions based on the calibration data using a surface source of ^{244}Cm ($E_\alpha = 5.78$ MeV) installed inside the wall-less TEPC. A distance of 7 mm was kept between the centre of the source and the anode during the calibration, which was performed before and after each beam irradiation. The details of the experimental conditions have been reported elsewhere^(36, 37).

Dose-mean lineal energy

According to the definition of microdosimetry, the dose-mean lineal energy $\bar{y}_D$ was obtained from the $yf(y)$ distribution as follows⁽²²⁾:

$$\begin{aligned}\bar{y}_D &= \int_{y_{\min}}^{y_{\max}} y d(y) dy \\ &= \int_{y_{\min}}^{y_{\max}} y^2 f(y) dy / \int_{y_{\min}}^{y_{\max}} y f(y) dy,\end{aligned}\quad (1)$$

where $d(y)$ is the dose probability density of y , and $y_{\max}$ and $y_{\min}$ are the maximum and minimum values of y , respectively, which can be measured. Because the values of $y_{\min}$ were based on the noise levels under experimental conditions, the $\bar{y}_D$ obtained experimentally was restricted and differed from what would be obtained under ideal conditions (i.e. for $y_{\min} = 0$). Note that $\bar{y}_D$ is less sensitive to a change in $y_{\min}$ than $\bar{y}_F$ which is the frequency mean of y .

The frequency distribution measured at a radial distance r_i using a narrow beam is defined as $f_i(y)$. The ‘narrow’ beam diameter was less than ~ 3 mm at the sensitive volume of the wall-less TEPC. To compare the results with the calculation or with other measurements using a broad beam, the frequency distribution of y for a broad beam condition was obtained by summing the $f_i(y)$ values obtained at different radial distances r_i :

$$f(y) = \frac{\sum_{i=1}^n r_i R_i f_i(y) A_i}{\sum_{i=1}^n r_i R_i}, \quad (2)$$

where R_i is the relative probability of a single event per incident proton occurring in the detection part of the wall-less TEPC and A_i is the relative area at a radial distance, r_i . The ‘broad’ beam diameter is ~ 10 cm, which is large enough to cover the radial distance range of the measurement in this study. The value of R_i was determined as the ratio of the number of protons

detected in the wall-less TEPC and beam monitor 1 to total number of incident protons on beam monitor 2.

RESULTS AND DISCUSSION

Lineal energy distributions

Figure 3 shows the measured $yf_i(y)$ values under TE gas pressures of 50, 100 and 200 Torr. The area under each dataset was normalised by the total count of

Figure 3. Lineal energy distributions measured in 0.36 μm at 50 Torr, 0.72 μm at 100 Torr and 1.44 μm at 200 Torr diameter simulated tissue volumes as a function of the radial distance from a 30-MeV proton beam.

Figure 4. Stopping power of protons⁽⁴⁰⁾ and electrons⁽⁴¹⁾ in human tissue and water.

beam monitor 2 at each radial distance. The uncertainties represent one standard deviation based on the statistical counts for each bin. At each pressure, the shape of the distribution at $r = 0.0 \mu\text{m}$ seems not to be so different than other distributions measured far from the beam path, although the count is much higher than those obtained at other radial distances. This is because the 30-MeV proton beam has similar stopping power (dE/dx) to the produced delta rays, whereas the dE/dx values of heavy ions are sufficiently large to show distinct peaks from delta rays in the pulse-height distributions⁽³⁷⁾. The values of dE/dx of protons and electrons in human soft tissue (muscle) and water, which were calculated using the SRIM code⁽⁴⁰⁾ and the ESTAR code⁽⁴¹⁾, respectively, are presented in Figure 4. It is noted that the difference of the values of dE/dx between the soft tissue and water is not significant in this energy range and that the value of dE/dx for 30-MeV protons in soft tissue is $\sim 2 \text{ keV } \mu\text{m}^{-1}$. The broad peaks of the primary 30-MeV protons are seen around $1 \text{ keV } \mu\text{m}^{-1}$ in each distribution at $r = 0.0 \mu\text{m}$ under all pressure conditions. The counts obtained away from the beam path are much smaller than those at $r = 0.0 \mu\text{m}$ and decrease by increasing the radial distance.

Radial dose distributions

Measured radial doses are shown in Figure 5, along with the calculations performed using the models of Katz *et al.*^(28, 29), Chunxiang⁽³⁰⁾, Chatterjee⁽³¹⁾ and Kiefer⁽³²⁾ and the Monte Carlo simulation-based model by RITRACKS⁽³³⁾. The uncertainties of radial distance are within the size of the symbols. The relative measured radial doses agree with the calculation fairly well, although among the calculation models, slight differences can be found.

Comparison of $yf(y)$ with Monte Carlo simulation

Radially summed $yf(y)$ values are presented in Figure 6. Experimental data were obtained according

Figure 5. Radially summed lineal energy distributions for 30-MeV proton beam along with the distributions calculated by PHITS. The areas under the distributions are normalised to unity.

to Equation (2) by summing the measured $yf_i(y)$ from 0.0 to the maximal radial distances under pressures of 50, 100 and 200 Torr. The areas under the distributions were normalised to unity. The calculation of $yf(y)$ using the microdosimetric calculation procedure⁽⁴²⁾, incorporated into the PHITS code⁽³⁸⁾, was ideally performed from $r = 0.0$ to infinity in the homogeneous condition filled with water. The statistical uncertainties for the PHITS calculation are too small to be observed. Beyond $10 \text{ keV } \mu\text{m}^{-1}$, the measured data are larger than the calculation. The reason can be explained by the additional energy deposition from the delta rays produced in the structural materials such as the cathode wire, as reported in (43). However, the experimentally obtained $yf(y)$ agree with the calculation fairly well. This result implies that the range of the radial distance determined in the measurement, $> 1.8 \mu\text{m}$, is large enough to obtain the $yf(y)$ under an infinite condition in water.

Comparison of $\bar{y}_D$ for protons with for heavy ions

Figure 7 shows the evaluated $\bar{y}_D$ values at various radial distances for 30-MeV protons along with those for 5.9 MeV u^{-1} uranium^(19, 20), 16.2 MeV u^{-1} germanium⁽¹⁹⁾ and 600 MeV u^{-1} iron⁽¹⁵⁾. The uncertainties of the radial distances cannot be seen in Figure 7, because the $\bar{y}_D$ values are smaller than symbol sizes. In comparison with the $\bar{y}_D$ values of the 30-MeV protons with those for other ions in radial distance far from the beam path, the $\bar{y}_D$ of the 30-MeV protons is consistent with other results. The reasons are that the maximum energy of delta rays is proportional to the kinetic energy per nucleon and the dE/dx of electrons in the energy range from 1 keV to 1 MeV decrease with kinetic energy, as shown in Figure 4.

Figure 6. Radial dose distributions for a 30-MeV proton beam (relative comparison).

For the heavy ions, $\bar{y}_D$ decrease with radial distance rapidly and almost remain constant in radial distance far from the beam path, owing to the relatively small energy deposition of delta rays. Moreover, the values of $\bar{y}_D$ at $r = 0.0$ are the largest because the dE/dx of the incident heavy ions are much greater than that of the delta rays. On the other hand, for the 30-MeV proton beam, the value of $\bar{y}_D$ at $r = 0.0 \mu\text{m}$ is the smallest and $\bar{y}_D$ increases gradually with radial

Figure 7. The radial dose-mean lineal energy ($\bar{y}_D$) measured in $0.36 \mu\text{m}$ (square), $0.72 \mu\text{m}$ (circle) and $1.44 \mu\text{m}$ (triangle) diameter simulated tissue volumes as a function of the radial distance from a 30-MeV proton beam and other heavier ions^(15, 19, 20). Lines are in place to guide the eye.

Figure 8. Calculated $yf(y)$ for protons with incident energy of 1 and 30 MeV in simulated tissue volume of $0.72 \mu\text{m}$.

distance. This dependence of $\bar{y}_D$ on radial distance, the opposite of that observed in heavy ions, can be explained by the fact that the dE/dx of the 30-MeV protons is almost equivalent to those of the delta rays, as shown in Figure 6. Because the value of dE/dx includes all the contributions of delta rays, the energy deposition of the 30-MeV proton at $r = 0.0 \mu\text{m}$ is reduced from that of the delta rays.

For further discussion, Figure 8 shows the $yf(y)$ calculated using the microdosimetric function⁽⁴²⁾ of the PHITS code for protons with incident energy of 1 and 30 MeV in simulated tissue volume of $0.72 \mu\text{m}$. For the $yf(y)$ for 30 MeV, already shown in Figure 6, only one broad peak can be seen, because the contribution of the primary protons and the delta rays are overlapped. On the other hand, for 1-MeV protons, one

can see two peaks: one is for the primary protons around $\sim 30 \text{ keV } \mu\text{m}^{-1}$ and the other for delta rays is found in the range of $y < \sim 4 \text{ keV } \mu\text{m}^{-1}$. It is revealed that the $\bar{y}_D$ values for high-energy protons increase with radial distance and remain almost constant, and the dependence of $\bar{y}_D$ on radial distance for low-energy protons is similar to those of heavy ions. Hence, the stochastic deposit energy distributions of high-energy protons is rather constant in the microscopic region both in the core and the penumbra region of the track structure compared with heavy ions, though the radial dose decreases with radial distance.

CONCLUSIONS

Radial distributions of lineal energy for a 30-MeV proton beam have been obtained using a wall-less TEPC. The obtained radial dose distributions agreed with predictions by theories and models fairly well. The radially summed $y(y)$ were found to agree with the results calculated by the microdosimetric function of PHITS. It was found that for high-energy protons, the values of $\bar{y}_D$ increase gradually with radial distance due to the relatively small dE/dx of the incident proton beam, and the stochastic deposit energy distributions in the microscopic region are rather constant both in the core and in the penumbra region of the track structure. Stochastic and spatial data of the deposited energy in the microscopic region will be useful for precise modelling of radial dose as well as clinical application for the estimation of RBE.

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