Systematic Measurement of Lineal Energy Distributions for Proton, He and Si Ion Beams Over a Wide Energy Range Using a Wall-less Tissue Equivalent Proportional Counter

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Heavy ion/Lineal energy/Tissue equivalent proportional counter/LET.

The frequency distributions of the lineal energy, $y$, of 160 MeV proton, 150 MeV/u helium, and 490 MeV/u silicon ion beams were measured using a wall-less tissue equivalent proportional counter (TEPC) with a site size of 0.72 $\mu$m. The measured frequency distributions of $y$ as well as the dose-mean values, $y_D$, agree with the corresponding data calculated using the microdosimetric function of the particle and heavy ion transport code system PHITS. The values of $y_D$ increase in the range of LET below $\sim$10 keV $\mu$m$^{-1}$ because of discrete energy deposition by delta rays, while the relation is reversed above $\sim$10 keV $\mu$m$^{-1}$ as the amount of energy escaping via delta rays increases. These results indicate that care should be taken with the difference between $\gamma_D$ and LET when estimating the ionization density that usually relates to relative biological effectiveness (RBE) of energetic heavy ions.

INTRODUCTION

The biological effects of energetic heavy ion beams have attracted attention, particularly in particle beam therapies and space activity. Energetic heavy ion beams can reach organs or tissues inside the human body and deposit energy. It is generally recognized that biological effects such as oncogenesis and cell death are related to energy deposited locally to irradiated cells. Energetic heavy ions produce secondary particles by means of ionization and fragmentation along their path through the human body. The spatial characteristics of energy deposition by heavy ions in tissue are thus different according to the kinds of heavy ions and their energies.1,2)

Dose estimation for patients in operations with such particle beam therapies is based on the biological dose, which is the absorbed dose multiplied by its relative biological effectiveness (RBE). RBEs are generally evaluated as a function of the linear energy transfer (LET). The LET, however, is defined as the mean energy loss of the primary charged particles per unit length, and it can present information on neither the spatial distribution of energy deposition nor the stochastic effects by secondary electrons (delta rays).

A recently developed biological dose calculation method3) using a microdosimetric kinetic model (MKM)4,5) enables one to obtain RBE based on lineal energy, $y$, which is defined as energy deposition per average chord length in a region.6) The MKM is used for the cell survival response calculation and will be integrated into the treatment planning system for a scanned carbon beam therapy.7) The physical part of the method is based on a calculation model to obtain the $y$ distribution in water, which is then incorporated as a microdosimetric function8) in the particle and heavy ion transport code system PHITS.9,10) The model has been verified using measured $y$ distribution data obtained using 600 MeV/u iron11) and 290 MeV/u carbon12) ion beams. Both data sets were measured using wall-less tissue equivalent counters, hereafter referred to as wall-less TEPCs.6,13)

To establish a more reliable biological dose calculation model, however, systematic verification of the microdosimetric function should be performed using various heavy ion beams over a wide energy range, since multiple secondary particles are produced by energetic heavy ion beams through ionization and nuclear reactions.

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With these conditions in mind, measurements of the frequency distribution of \( y, y_f(y) \), were performed using selected energetic heavy ions that differed in terms of atomic number and LET in wide range from 0.52 keV \( \mu \)m\(^{-1} \) to 260 keV \( \mu \)m\(^{-1} \), for further improvement of the physical model used in the biological dose calculation method.\(^8\) The systematically measured data using a recently developed wall-less TEPC\(^1\) were compared with values calculated using the microdosemetric function of PHITS. The differences between the dose-mean lineal energy and the LET are also discussed.

**EXPERIMENTAL**

Measurements of the \( y_f(y) \) for energetic heavy ion beams were performed in the HIMAC-BIO beam line at the Heavy Ion Medical Accelerator in Chiba (HIMAC)\(^1\) of the National Institute of Radiological Science (NIRS), Japan, using a wall-less TEPC.\(^1\) The features of the wall-less TEPC with nearly wall-less detection part are shown in Fig. 1. The wall-less TEPC has a cylindrical detection part consisting of a thin spiral wire (cathode) and a thin central wire (anode). The electric field in the detection part is sustained by filed tubes that made of copper and set on the both side of the detection part. The applied potentials were \(-800\) volt to a cathode, an anode to \(0\) V (GND) and \(-665\) volt to the filed tubes, respectively. The diameter and height of the detection part are both \(3\) mm. The detection part was positioned at the center of container filled with a propane-based tissue-equivalent gas, TE-gas,\(^6\) at a pressure of \(13.3\) kPa (100 Torr), whose pressure is equivalent to a \(0.72\) \(\mu\)m site size in tissue. A \(14\) cm diameter beam window made of a \(50\) \(\mu\)m thick polyamide film was positioned for use in inserting the heavy ion beams into the container of the wall-less TEPC. The

**Table 1.** Ion beam species used in the measurement.

<table>
<thead>
<tr>
<th>Ions</th>
<th>( H^+ )</th>
<th>( He^{2+} )</th>
<th>( Si^{14+} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic mass</td>
<td>1</td>
<td>4</td>
<td>28</td>
</tr>
<tr>
<td>Effective charge</td>
<td>1</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>( E ) (MeV/u)</td>
<td>160</td>
<td>150</td>
<td>490</td>
</tr>
<tr>
<td>LET (keV ( \mu )m(^{-1} ))(^a)</td>
<td>0.52</td>
<td>2.2</td>
<td>55</td>
</tr>
</tbody>
</table>

\(^a\)dE/dx in water calculated by ATIMA.

**Fig. 1.** Photographs of the wall-less TEPC, (a) the overview, (b) the detection part and (c) the field tube. unit [mm].

**Fig. 2.** Experimental set-up in HIMAC-BIO (not in scale). The collimated size of the incident beams on the wall-less TEPC is approximately 100 mm in diameter.
Fig. 3. Measured $y_f(y)$ for 490 MeV/u silicon ions with the values calculated by PHITS. The energies and LETs are estimated by PHITS.
beam window and the anode wire were 7 cm apart. The contribution of the delta rays produced in the beam window is estimated to be less than 1% by simulation. In terms of volume percentages, the TE gas consisted of 54.7% propane, 39.7% carbon dioxide, and 5.6% nitrogen.

In this study, 160 MeV proton, 150 MeV/u helium and 490 MeV/u silicon ion beams were used, as listed in Table 1, in order to obtain data using ion beams with wide range of LETs from ~1 keV μm⁻¹ to ~100 keV μm⁻¹. The ATIMA code, which calculates various physical quantities characterizing the slowing-down of heavy ions in matter, was used for the estimation of LET of the ions (the stopping power of ions in water).

Figure 2 depicts the experimental set-up at HIMAC. The beams are widened in the radial direction by a wobbler magnet to 100 mm in diameter and scattered by a thin plate made of tantalum; they are then uniformly incident on the wall-less TEPC. The energies of the beam incident on the wall-less TEPC were varied by placing sets of energy absorbers made of acryl on the beam path.

Pulse height distributions of the ion beams, obtained using a digital storage oscilloscope, were converted into distributions based on energy calibration using a surface source of ⁴⁴Ca (Eα = 5.78 MeV). The distance was kept at 7 mm between the center of the source and the anode during the calibration performed before and after each measurement. The details of the experimental conditions have been reported elsewhere.

The dose-mean lineal energy, \( \overline{y} \), was obtained from the measured energy deposition spectra using the following equation:

\[
\overline{y} = \int_{y_{min}}^{y_{max}} y f(y) dy / \int_{y_{min}}^{y_{max}} f(y) dy
\]

where \( d(y) \) is dose probability density of \( y \), \( y_{min} \) the minimum value of \( y \) and \( y_{max} \) the maximum of \( y \).

The number of secondary electrons per unit length is estimated based on the equation of Butts and Katz as follows:

\[
dn = \frac{C Z^*}{\beta \omega} \frac{d\omega}{d\omega^*}
\]

where \( Z^* \) is effective charge of ion, \( \beta \) velocity of ion, \( \omega \) energy of electrons and \( C \) is constant dependent on materials.

**RESULTS AND DISCUSSION**

The measured \( yf(y) \) values in a 0.72 μm site in the wall-less TEPC are shown in Figs. 3, 4, and 5, along with the microdosimetric calculations by PHITS. The areas under

\[
\int_{y_{min}}^{y_{max}} yf(y) dy
\]

Fig. 4. Measured \( yf(y) \) for 150 MeV/u helium ions with the values calculated by PHITS. The energies and LETs are estimated by PHITS.
the distributions are normalized to unity. The water-equivalent thicknesses of the energy absorbers (binary filters, BFs), the estimated kinetic energy, and the LET of the ions incident on the wall-less TEPC are shown in the figures. The values of energy and LET were estimated by PHITS. The energies shown in Figs. 3–5 were incident energies on the wall-less TEPC and obtained by subtracting a primary energy from energy loss in BFs.

In the calculations using the microdosimetric function of PHITS, the transport and energy deposition by secondary particles produced by nuclear reactions were also treated. The thicknesses of air, a scatter made of tantalum, and vacuum filters made of Kapton film were also considered, and these values are shown in Table 2. Since the uncertainties of the nominal values were not obtained by the authors, the Ta scatter thicknesses were adjusted so as to fit the measurements within the practical range of the thicknesses.

**Lineal energy distributions of silicon ions**

Figure 3 shows the data for 490 MeV/u silicon ions. Eight sets of measurements of the \( yf(y) \) were performed using different thicknesses of BFs. The peaks of the incident silicon ions can be clearly seen in the results of the measured distributions, since the silicon ions have larger \( dE/dx \) values than those of delta rays. The values of the peak positions increase as incident energy decreases. It is noteworthy that the shapes of the distributions for \( y \) below 10 keV \( \mu m^{-1} \) are similar among the results for different incident energies. This tendency is consistent with the results of the Butts and Katz formula, in which it is proportional to the square of the effective charge of the ions and inversely proportional to the square of the velocity.\(^{16}\)

The measured \( yf(y) \) agrees satisfactorily with the values calculated by PHITS in all cases of the different incident energies, although differences are found between the peaks of the incident silicon ions and the saddles of the delta rays in the region from 10 to 20 keV \( \mu m^{-1} \). These differences could result from the parameters of the microdosimetric function of PHITS.

**Lineal energy distributions of helium ions**

Figure 4 shows comparisons of the measured distributions with those calculated by PHITS. The energies and LETs are estimated by PHITS.

### Table 2. Parameters used in the calculation.

<table>
<thead>
<tr>
<th>Ions</th>
<th>Ta scatter</th>
<th>Air</th>
<th>Filters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si(^{14+})</td>
<td>0.15(^a) (0.2(^b))</td>
<td>1050</td>
<td>0.1 (^a)</td>
</tr>
<tr>
<td>He(^{2+})</td>
<td>0.024 (0.02)</td>
<td>1050</td>
<td>0.1</td>
</tr>
<tr>
<td>Proton</td>
<td>0.015 (0.02)</td>
<td>1050</td>
<td>0.1</td>
</tr>
</tbody>
</table>

\(^a\)centimeter unit, \(^b\)Nominal values given by HIMAC.

Fig. 5. Measured \( yf(y) \) for 160 MeV protons with those calculated by PHITS. The energies and LETs are estimated by PHITS.

Fig. 6. Ratios of calculated \( \bar{\gamma}_D \) (\( \bar{\gamma}_{D,cal} \)) to measured one (\( \bar{\gamma}_{D,meas} \)).
for 150 MeV/u helium ions with those calculated by PHITS. Peak positions increase with decreasing the incident energy of the helium ions. The measured distributions agree with those calculated by PHITS fairly well in the peak regions of $y$, in Figs. 4a and 4d. However, the peak positions of the calculated results in the cases of energy of 32 MeV/u and 22 MeV/u are smaller than those measured, though the parameters in Table 2 were changed within the practical ranges so as to fit the measured results. It is found that the reason is not attributable to the energy calibration but further investigation is required.

**Lineal energy distributions of protons**

Figure 5 shows the data for the proton beam irradiations. In the case of energy of 160 MeV, the $y_f(y)$ values monotonously decrease with $y$. Incident proton peak regions are not clearly seen, since the contributions of the incident protons overlap with those of the delta rays. The increase in the $y_f(y)$ in the region of $y$ over 20 keV $\mu$m$^{-1}$ is attributable to the numbers of delta rays produced in the structural materials facing the detection part such as field tubes of the wall-less TEPC. As the energy incident on the wall-less TEPC decreases, broad peaks can be seen in the incident protons, although the distributions of both protons and delta rays partly overlap.

The calculated result for 160 MeV protons agrees fairly well with that measured in the range of $y$ less than 20 keV $\mu$m$^{-1}$, although the measured data are slightly larger than the calculated values in the region of $y$ over 4 keV $\mu$m$^{-1}$. The calculated result for 38 MeV protons agrees well with the corresponding measured data. In the case of 163.67 mm thickness, which is close to the depth of the Bragg peak, the
calculated results agree with the measured values fairly well, although the calculated distribution is shifted to a slightly higher region of $y$ than the measured distribution.

**Comparison of $\gamma_y$ with values calculated by PHITS**

Figure 6 shows the ratios of $\gamma_y$ calculated to the measured values for protons, helium, and silicon ions in all the irradiation conditions. The authors estimated the uncertainties of the measurements to be 14%, considering the energy calibration based on the pulse-height distributions. The values of $\gamma_y$ obtained in the measurements were corrected based on Monte Carlo simulation\(^{17}\) to reduce the contribution of the structural materials of the wall-less TEPC. Using the correction method, the measured values of $\gamma_y$ fell by 3 to 10% in the case of the silicon ion beam, 5 to 11% for the helium ion beam, and 6 to 8% for the proton beam.

In the case of proton irradiation without BFs, the measured $\gamma_y$ is larger than that calculated, because the measured data in Fig. 5a are slightly larger than the calculated values in the region of $y$ over 4 keV $\mu$m$^{-1}$. The values of $\gamma_y$ for 22 MeV/u and 32 MeV/u helium ions are approximately 20% larger than those calculated by PHITS. This is due to the differences between the measurements and calculations shown in Fig. 4b and Fig. 4c. In the case of the silicon beam, the measured results agree with the calculated values within the uncertainties. These results suggest that the data calculated by PHITS agree within 20% with the measured data obtained using heavy ions in a wide range of $\gamma_y$ from ~3 keV $\mu$m$^{-1}$ to ~300 keV $\mu$m$^{-1}$.

**Comparison of $\gamma_y$ with LET**

Figure 7 shows the measured $\gamma_y$ for protons, helium ions, carbon ions,\(^{12}\) and silicon ions in the cases without BFs. The broken line corresponds to the state in which $\gamma_y$ equals LET. The ratios of measured $\gamma_y$ to LET are 4.9 for protons, 1.3 for helium ions, 0.73 for carbon ions, and 0.58 for silicon ions. The differences between the values of $\gamma_y$ and LET increase with LET, as seen in the case of carbon and silicon ions. This is because the escaping energies of delta rays from the site increase with the kinetic energy of the incident ions. On the other hand, the values of $\gamma_y$ for protons and helium ions are larger than those of the LET.

To investigate the dependence of $\gamma_y$ on LET and kinetic energy, the values of $\gamma_y$ were calculated for ions with various energies, using the microdosimetric function of PHITS. Figure 8 shows the calculated ratios of $\gamma_y$ to LET in the case of heavy ions with energies from 1 MeV/u to 1000 MeV/u. The simulated site size is 1 $\mu$m in tissue. The lines among the data points are provided to guide the eye.

The ratio of silicon ions agrees with the one of carbon in the energy below 400 MeV/u and the one of helium ions below 30 MeV/u in Fig. 8a. The ratios for carbon and silicon ions are less than unity and decrease with kinetic energy over 5 MeV/u. The ratios increase beyond unity with kinetic energy in the case of protons and helium ions. Moreover, the ratios are always more than unity in the case of protons. Nikjoo et al. reported values of $\gamma_y$ and LET for a wall-less TEPC in the case of a 50 MeV/u proton beam, and deduced the value of the ratio of $\gamma_y$ to LET to be 1.47.\(^{18}\) Using the microdosimetric function of PHITS, the calculated ratio was 1.44, which is close to the value reported by Nikjoo. This dependence of $\gamma_y$ on LET or kinetic energy can be explained by the relationship between the distance at which each delta ray is produced and the simulated site size.

Calculated average distances for production of delta rays in water, $d_{ave}$, in the case of protons, helium ions, carbon ions, and silicon ions are shown in Fig. 9. It should be noted that the authors here defined $d_{ave}$ as the average distance between points where delta rays with energy more than 100 eV are produced, assuming that a heavy ion passes straight along the path. The energy spectra of delta rays were obtained using an equation by Butts and Katz.\(^{16}\) The values of $d_{ave}$ increase with the kinetic energy of the ions, or with a decrease in LET. The energy loss via delta rays happens discretely, while the direct energy loss by incident ions occurs almost continuously along a beam path.

The values of $\gamma_y$/LET among the ions should be the same at a given energy, since LET is proportional to the square of effective charge of protons and heavier ions, as well as the number of produced secondary electrons per unit length,\(^{10}\) as shown in equation (2). In Fig. 8a, however, the values of $\gamma_y$/LET are partly different among the ion species. For instance, the ratios for silicon are lower than those for proton over 5 MeV/u, for helium over 27 MeV/u and for carbon over 290 MeV/u. The values of $d_{ave}$ are found to be ~0.2 $\mu$m in all the cases of 5 MeV/u proton, 27 MeV/u helium and 290 MeV/u carbon ions in Fig. 9a. Thus, the dependence of $\gamma_y$/LET on the ion species is caused by discrete energy deposition by delta rays in the range of $d_{ave}$ more than ~0.2 $\mu$m. The values of $\gamma_y$ can become larger than LET according to equation (1), because the variance in the $yD$ increases due to discrete events with large amount of energy deposition by delta rays, although the probability of such event occurring decreases with $d_{ave}$. On the other hand, the corresponding values of LET when $d_{ave}$ equals to ~0.2 $\mu$m are found to be approximately 10 keV $\mu$m$^{-1}$ for proton, helium, and carbon ions in Fig. 9b. It is found that discrete energy depositions by delta rays increase in the range of LET below ~10 keV $\mu$m$^{-1}$.

In conclusion, measured lineal energy distributions of protons, helium ions, and silicon ions were obtained using a wall-less TEPC and compared with those calculated by the microdosimetric function of the PHITS code. The measured distributions were found to agree fairly well with the calculated values. The values of $\gamma_y$ calculated by PHITS agree with the measurements obtained using heavy ions within 20% in a wide range of $\gamma_y$ from ~3 keV $\mu$m$^{-1}$ to ~300 keV $\mu$m$^{-1}$. The values of $\gamma_y$ increase in the range of LET below
~10 keV μm⁻¹ because of discrete energy deposition by delta rays, while this relation is reversed above ~10 keV μm⁻¹ due to the increase in the amount of energy escaping via delta rays. The results indicate that care should be taken with respect to the difference between μ and LET when estimating the ionization density that usually relates to relative biological effectiveness (RBE) of energetic heavy ions.

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