Microdosimetric Evaluation of Secondary Particles in a Phantom Produced by Carbon 290 MeV/nucleon Ions at HIMAC

Satoru ENDO1, Masashi TAKADA2, Yoshihiko ONIZUKA3, Kenichi TANAKA1, Naoko MAEDA4, Masayori ISHIKAWA2, Nobuyuki MIYAHARA2, Naofumi HAYABUCHI6, Kiyoshi SHIZUMA7 and Masaharu HOSHI1

Microdosimetry/Carbon beam/Particle therapy/Fragment/HIMAC.

Microdosimetric single event spectra as a function of depth in a phantom for the 290 MeV/nucleon therapeutic carbon beam at HIMAC were measured by using a tissue equivalent proportional counter (TEPC). Two types of geometries were used: one is a fragment particle identification measurement (PID-mode) with time of flight (TOF) method without a backward phantom, and the other is an in-phantom measurement (IPM-mode) with a backward phantom.

On the PID-mode geometry, fragments produced by carbon beam in a phantom are identified by the ΔE-TOF distribution between two scintillation counters positioned up- and down-stream relative to the tissue equivalent proportional counter (TEPC). Lineal energy distributions for carbon and five ion fragments (proton, helium, lithium, beryllium and boron) were obtained in the lineal-energy range of 0.1–1000 keV/μm at eight depths (7.9–147.9 mm) in an acrylic phantom. In the IPM-mode geometry, the total lineal energy distributions measured at eight depths (61.9–322.9 mm) were compared with the distributions in the PID-mode. Both spectra are consistent with each other. This shows that the PID-mode measurement can be discussed as the equivalent of the phantom measurement. The dose distribution of the carbon beam and fragments were obtained separately. In the depth dose curve, the Bragg peak was observed.

Relative biological effectiveness (RBE) for the carbon beam in the acrylic phantom was obtained based on a biological response function as a lineal-energy. The RBE of carbon beam had a maximum of 4.5 at the Bragg peak. Downstream of the Bragg peak, the RBE rapidly decreases. The RBE of fragments is dominated by Boron particles around the Bragg peak region.

INTRODUCTION

By using the carbon beam at the incident energy of 290, 350 and 400 MeV/nucleon to the energy degrader, such as ridge filter, charged particle therapy has been carried out at the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS). The beam qualities of the therapeutic carbon beam at HIMAC were studied by several techniques: the measurement of absorbed doses using an ion chamber and of secondary particle fluxes by ΔE-E counters, solid state detectors, plastic and inorganic scintillators and Monte Carlo calculations. Also, biological studies were done by several researchers at HIMAC. The data are used for the basic data of the charged particle therapy. To investigate the radiation quality for charged-particle therapy, a microdosimetric study has been carried out. Microdosimetric spectra are useful to investigate biological effects for charged particles in a body. In previous work the microdosimetric spectra of primary and secondary particles produced by carbon ions 400 MeV/nucleon were measured to obtain the RBE. However, the fragments increase with the incident carbon energy as calculated by SHIELD-HIT code in a reference. The fragment contribution for different carbon energy of 290 MeV/nucleon,
of which energy is very often used for the therapy, is needed. In this study the initial carbon energy was changed from 400 MeV/nucleon to 290 MeV/nucleon and to measure the contribution from scattered charged particles from the backward phantom part (albedo particle), other detection geometry was added. The additional geometry is better to evaluate the therapeutic charged-particle beam because of its close resemblance to human body. Two types of measurements were performed to evaluate the characteristics of the carbon beam. By using the tissue-equivalent proportional counter microdosimetric spectra have been measured. In the microdosimetric spectra each components of the charged-particle species was separated by using time-of-flight (TOF) methods and the pulse heights of them the plastic scintillator upstream of the TEPC. The microdosimetric spectra of each particle are useful to discuss the fragments produced in different phantom geometries.

In this report, we present the microdosimetric lineal-energy distributions of incident carbon in body-simulated acrylic phantom and fragments produced by the 290 MeV/nucleon carbon ion. To consider beam quality for clinical irradiation, RBE as a function of depth in the acrylic phantom is evaluated.

**MATERIALS AND METHODS**

Microdosimetric lineal-energy spectra for the 290 MeV/nucleon carbon beam have been measured by using a tissue-equivalent proportional counter (TEPC, Far East Technology Inc. LET counter 1/2 inch model) which consists of a 12.7 mm diameter cavity with a 3.7 mm thick Al50 plastic wall covered with a 0.18 mm-aluminum cap. TEPC was filled with tissue-equivalent gas (based on propane gas) at a pressure of 44 kPa; particle energy depositions in the counter gas is the same as a 1 μm spherical site in tissue (ICRU 36 1983). The TEPC was operated at a 580V counter bias. Pulse heights were calibrated using a built-in $^{244}$Cm alpha source. To cover the wide lineal-energy region from 0.1 to 1000 (keV μm$^{-1}$), signals from the TEPC integrated by using a pre-amplifier were divided into three amplifier modules (ORTEC 671); signals from each of the amplifiers were referred to as high, medium and low-gain signals. From the high-gain signals, trigger signals to start the data acquisition system were made through a timing-single-channel-analyzer (ORTEC Timing-SCA) module. An acrylic phantom (300 mm width, 300 mm height and 0–330 mm thickness, density 1.17 g cm$^{-3}$, chemical composition C$_4$H$_6$O$_2$ Mitsubishi Kasei) was used to measure lineal-energy spectra with depth. The incident carbon beam size was set to about 1 cm square in order to fit the TEPC cavity. This beam size was confirmed by ZnS plate at two positions of upstream and downstream of the phantom. Experimental geometries are shown in Figs. 1 A and B. Setup A is the measurement for the particle identification (PID) mode. In Figs.1 A and B, PSC, FSC and BSC were the pickup scintillation counter (NE102A, 30 mm diameter × 0.5 mm thickness), forward scintillation counter (EJ201, 20 mm diameter and 3 mm thickness) and backward scintillation counter (NE102A, 250 mm width, 250 mm height and 3 mm thickness), respectively. The PSC, FSC and BSC were positioned as shown in Figs. 1 to identify charged particles going into the TEPC at the upstream from the phantom, from TEPC and at 290 cm downstream from TEPC, respectively. From the PSC signals registration of the carbon beam incident on the phantom was ensured. The signals from the PSC, also, were used for trigger signals of the data acquisition by the coincidence with signals from the TEPC. By means of signals from the FSC, charged particles incident to the TEPC cavity were identified. By signals from the BSC, a part of the charged particles passing through the TEPC cavity was measured. To improve particle discrimination by using the FSC, a time-of-flight (TOF) method was used.

**Fig. 1.** Schematic diagram of the measurement for the microdosimetric spectra of carbon and fragment particles produced. Setup A is the measurement for the particle identification (PID) mode. The ΔE measured by the FSC, and also time of flight (TOF) was measured between the FSC and BSC (290 cm flight length). Setup B is the measurement for the in-phantom measurement (IPM) mode. The TEPC is actually positioned in the phantom.
added. Between the FSC and BSC, the TOF was measured at the 290 cm flight length. The time difference was measured at a time-to-analogue converter (TAC) module (ORTEC). The data were acquired by a peak sensitive ADC (ORTEC AD811). From two dimensional plots of energy deposition in the FSC or BSC, and TOF, particles were identified. The pulse height data from the TEPC, PSC, FSC and BSC, and the TOF were obtained by using the CAMAC controller (TOYO cc/7700).

In the irradiation geometry, setup A, no acrylic phantom was set downstream from the TEPC; however, it has different characteristics from those of a human body. For an irradiation geometry, setup B, a phantom was added downstream from the TEPC to simulate the irradiation to human body. By the measurement at setup B, in-phantom measurement (IPM) mode, the lineal energy spectra of secondary particles produced in a phantom with and without the backward phantom were compared to verify the effects of the backward phantom. Except for the presence of the backward acrylic phantom and BSC, irradiation geometries were the same. The TEPC was actually inserted in the phantom. Lineal-energy spectra in a phantom in PID- and IPM-mode were measured at depths from 7.9 to 147.9 mm and from 61.4 to 322.9 mm, respectively. The Bragg peak depth of carbon, 290 MeV/nucleon, is about 140 mm in acrylic. Measured depths cover the Bragg peak of 290 MeV/nucleon carbon ions.

RESULTS AND DISCUSSION

PID-mode measurement

Data acquisitions were started by the trigger signals of TEPC. By using signals from the FSC, charged-particle species incident into the TEPC were identified in off-line analyses.

In the PID-mode measurement, particles incident into the TEPC were separately identified for carbon, boron, beryllium, lithium and helium using the previously reported ΔE-TOF methods. In our system, deuteron and triton fragments could not be separate from proton fragment. These two fragments are treated as proton. Based on the pulse height of each discriminated particle, the microdosimetric single event spectra were obtained. Acquired and discriminated particle pulse heights were sorted into logarithm-bins of lineal-energy, y. The frequency distribution, f(y), which is the number of events normalized by the number of incident carbon beam pulses recorded in each lineal-energy bin.

The BSC covers a part of the particles passing through the TEPC (but some particle flux lost). The solid angle of BSC is magnified from 1.5 to 5 msr from the previous publication, however, escape events (particles detected by both the FSC and TEPC; however, not detected by the BSC) have to be corrected. In this analysis, the same correction technique with previous publication has been applied to escaped event correction. To estimate the flux of each fragment, the total fluence distribution, f_{tot}(y), was obtained by fitting the measured distribution for each fragment given by

\[ f_{\text{tot}}(y) = a_Cf_C(y) + a_Bf_B(y) + a_{\text{Be}}f_{\text{Be}}(y) + a_{\text{Li}}f_{\text{Li}}(y) + a_{\text{He}}f_{\text{He}}(y) + a_pf_p(y). \] (1)

Here, \( a_i \) (i = C, B, Be, Li, He and H) is the respective fitting parameter for each beam fragment. For carbon, \( a_C \), this is Table 1. Fitting results for the PID-mode. Each parameter \( a_i \) is averaged over the depth.

<table>
<thead>
<tr>
<th>Particle</th>
<th>( a_i )</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>2.44</td>
<td>± 0.25</td>
</tr>
<tr>
<td>He</td>
<td>1.63</td>
<td>± 0.09</td>
</tr>
<tr>
<td>Li</td>
<td>1.01</td>
<td>± 0.17</td>
</tr>
<tr>
<td>Be</td>
<td>1.05</td>
<td>± 0.14</td>
</tr>
<tr>
<td>B</td>
<td>1.08</td>
<td>± 0.15</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>–</td>
</tr>
</tbody>
</table>

![Fig. 2.](image) Fraction of fragment particle flux. The carbon beam has drastically decreased with increasing fragment particles around 140 mm depth. The lines are eye guide.
taken as 1 because of the very small flux of particles which escape or stop in the counter. The parameters $a_i$ also indicate the ratio of the escape event to the number of the particle-identified events. The parameters, $a_i$, are the ratios of the number of the total fragment flux to that of detected fragments by using the BSC. The fitting results are shown in Table 1, the fitted results of each $a_i$ for B, Be and Li are consistent with unity within the errors. The fraction of each fragment corrected by the escaped events is shown in Fig. 2. The convoluted spectra using the correction for escape are shown in Fig. 3 at eight depths (7.9, 103.9, 140.9, 141.4, 141.9, 142.4, 142.9 and 147.9 mm) that cover the plateau, the Bragg peak and over range region of carbon beam. All $f_{\text{tot}}(y)$ distributions were reproduced well by the convolution of fragment particle distributions. The main carbon beam decreased with depth. Reason of remaining the carbon

![Graphs of distributions $f(y)$ at different depths](image-url)

**Fig. 3.** Distributions $f(y)$ at the PID-mode, at depths in a phantom from 7.9 to 147.9 mm, corrected by escape-event ratios. In the distributions $f(y)$ each fragments were discriminated clearly each other.
components at 147.9 mm-depth is caused by a spherical active volume of TEPC. The wall thickness is ranged from 3.7 to 10 mm due to spherical active volume of 12.7 mm in diameter. This shows that the depth resolution is about 7 mm. The lineal-energy spectra over 30 keV/μm were dominated at the second largest component by boron fragments. The next high y component was caused due to helium fragments.

From the $f_{ed}(y)$ distribution, the dose distribution of $y \, D(y)$ for carbon and fragments in the PID-mode are shown in Fig. 4. It is clearly shown that the fragment contributions to dose are enhanced with increasing depth. It was found that $y \, D(y)$ components are dominated by boron fragments at the Bragg peak. He fragments are dominated in the second. The $y$ value of He fragment is located at 10 keV/μm, equivalent to about 150 MeV helium particle energy.

**Fig. 4.** Dose distributions $y \, D(y)$ on the PID-mode measurements at depths in a phantom from 7.9 to 147.9 mm, corrected by escape-event ratios. The dose distributions $y \, D(y)$ are clearly separated into each fragments.
**IPM-mode measurement**

For the IPM-mode measurement, the \(f(y)\) distribution at each depth (61.9, 109.9, 138.5, 140.7, 141.7, 143.6, 272.6, 306.9 and 322.9 mm) is shown in Fig. 5. Though the result for the IPM-mode is utilized for dose estimation in the following section, the \(f(y)\) distributions are compared between IPM- and PID-mode to consider whether or not the PID-mode can also be used for it. For this purpose, the lineal-energy distribution \(f(y)\) between the PID- and the IPM-mode were compared at 103.9 and 109.9 mm, 140.9 and 140.7

![Fig. 5. Distributions \(f(y)\) of total particles, primary plus fragments, at depths in a phantom from 61.9 to 322.9 mm, plotted by blue lines for the IPM-mode (without a backward phantom). Pink and green lines show PID-mode data (with a backward phantom) in closed depth. The measured lineal-energy spectra of PID- and IPM-mode are consistent with each other.](image-url)
mm, 141.9 and 141.7 mm and 142.9 and 143.6 mm depths for the PID- and IPM-mode, respectively. Good agreement has been obtained the lineal-energy spectra in the two different geometries. As a result, quite similar spectra were obtained for the PID- and IPM-mode though the comparing depths are not exactly the same. This shows the escaped-particle correction succeeded quantitatively and there was only a small effect of downstream phantom material.

The dose distributions, $yD(y)$ in the IPM-mode measurements are shown in Fig. 6. To confirm the effects of the backward phantom, both the dose distributions at depths of 61.9 to 143.6 mm in a phantom, were compared with PID-

![Graphs showing dose distributions](image)

**Fig. 6.** Dose distributions, $yD(y)$, plotted by blue lines for IPM mode, from 61.9 to 322.9 mm. Dose distributions on the IPM-mode geometry in depths closed to those of the PID measurements were added as pink and green lines. The measured lineal-energy spectra at the both geometries are consistent with each other.

mode, as shown in Fig. 6. The similar dose distributions are observed for both of the IPM- and PID-mode, which confirmed the unobvious effects of the downstream phantom.

Based on these considerations, the results of both the IPM- and PID-mode are utilized for dose estimation as the data for the geometries simulating a human body. In other words, the particle identification by the PID-mode is considered to be usable in the IPM-mode as well in the present study.

Relative depth dose distribution

The relation between absorbed dose ($D$) and frequency of the mean lineal energy: $\bar{y}_F \left( \bar{y}_F = \int f(y)dy \right)$ is

$$D = nk \bar{y}_F,$$

where $k$ is a constant related to the diameter of the counter, 0.204/$d^2$ for the actual radius of the spherical TEPC, and $n$ is the flux of incident particles, where $n = 1$ for one carbon ion. The frequency mean lineal energy $\bar{y}_F$ was calculated from:

$$\bar{y}_F = \frac{\int yf(y)dy}{\int f(y)dy} = \frac{\int yf_i(y)dy + \int yf_{He}(y)dy + \int yf_{Li}(y)dy + \int yf_{Be}(y)dy + \int yf_{B}(y)dy}{\int f(y)dy} = \sum_i y_i f_i,$$

where $y_i f_i = \int yf_i(y)dy / \int f(y)dy$ and $i = H, He, Li, Be, B$ and C. From Eqs. 2 and 3, the relative dose spectrum of the total (primary plus fragments) and the fragments, measured in the PID- and the IPM-mode geometries, as a function of depth was calculated, as shown in Fig. 7. In present data, the measured $y$ ranged 0.1 to 1000 keV/$\mu$m. To estimate uncertainty from particles with $y$ greater than 1000 keV/$\mu$m, we calculated doses using the spectrum at 140.9 mm depth and the spectrum extrapolated to 2000 keV/$\mu$m by a line. The ratio of dose using the upper cut-off at 2000/keV/$\mu$m to that at 1000keV/$\mu$m is 1.014. This shows uncertainty due to the upper $y$ cut-off of 1000 keV/$\mu$m is 1.4%. The relative doses

![Fig. 7. Relative dose distribution as a function of residual range defined by (depth - Bragg peak depth) in a phantom: closed circles and open circles on the PID- and the IPM-mode geometries, respectively. Open triangles summed up fragments of p, He, Li, Be and B in the PID-mode measurement, show the fragment dose produced by the incident carbon beam. The whole lines are eye guide. Previous data for 270 MeV/nucleon by Scholz et al.11) and 400 MeV/nucleon by Endo et al.7) are also shown. The 270 MeV/nucleon data is close to the present results. The black and red lines are eye-guide.](image)
from fragments are also shown as a value of \[ D = n_k \sum_{i} y_{f_i}. \]
Near the Bragg peak, the relative dose by carbon ions charged drastically by a factor 2. At deeper positions than the depth of the Bragg peak in a phantom, the dose is mainly caused by boron and He fragments. The dose distributions for the 270 MeV/nucleon\(^{11}\) and the 400 MeV/nucleon\(^{7}\) are also shown in Fig. 7. The 290 MeV/nucleon data is lower than that for 400 MeV/nucleon at the plateau region. A ratio of the plateau dose to the Bragg peak dose has an energy-dependence. Values of the ratio for 279 and 391 MeV/nucleon carbon are about 0.2 and 0.37, respectively, from a reference.\(^{13}\) These values show the same trend to our result. The present result is quite similar to the Scholz’s data.\(^{11}\) The dose distribution on Scholz’s data shows narrower shape than our results. This is caused by spherical cavity shape of our TEPC which is measured as broader Bragg peak.

**RBE estimation**

Relative biological effectiveness (RBE), defined by biological response for radiations, is an important parameter to evaluate the radiation quality. RBE, in clinical radiation fields, is estimated from microdosimetric spectrum using a 2Gy biological response of fractional cell survivals; \( r(y) \) which was given by Tilikidis et al. (1996)\(^{12}\) as

\[ RBE = \int_0^\infty r(y) y f(y) \, dy. \] (4)

RBEs estimated from the total lineal-energy spectra at various depths in a phantom, in the PID- and the IPM-mode measurements, are shown in Fig. 8. The estimated RBE shows a sharp peak structure in both the geometries near the Bragg peak.

The components of the RBE \( (RBE_i) \) of primary carbon and fragments are calculated from the lineal-energy spectra of each fragments and carbon as;

\[ RBE_i = \int_0^\infty r(y) y f_i(y) \, dy \quad (i = H, \, He, \, Li, \, Be, \, B, \, C). \] (5)

This expression is useful in estimating each particle contribution to the RBE depending on beam properties. By summing the RBEs, the RBE of the total particles produced by

![Fig. 8.](image-url)
the carbon beam was obtained. The RBEs for the fragments p, He, Li, Be, B were obtained, as shown in Fig. 8 (a). At shallower depths in the acrylic phantom than the carbon 290 MeV/nucleon Bragg peak depth, the RBE was dominated by initial carbon; however, beyond the carbon Bragg peak depth, the RBE reached its maximum value, 4.5, at the Bragg peak of carbon 290 MeV/nucleon. It was smaller than the value of 5.5 of carbon 400 MeV/nucleon. The phantom thickness could be increased in 1 mm step, then the depths from the Bragg peak for both measurements have discrepancy of 1 mm at most. This discrepancy might be a reason for the difference of RBE values. Both the closed and open squares data for the 400 MeV/nucleon, are quite similar dependence on the residual range defined by (Bragg peak depth – phantom depth). However, the data show slightly higher contribution of fragments to the RBE. Figure 8 (b) shows the RBE for the sum of the fragments and also the components p, He, Li, He and B in the fragments. The fragment RBE is dominated by boron fragments around the Bragg Peak.

CONCLUSION

The microdosimetric single event spectra for the 290 MeV/nucleon carbon beam at HIMAC have been measured as a function of a simulated phantom depth. Fragments of B, Be, Li, He and p in the acrylic phantom produced by the carbon beam were identified by ΔE-TOF measurements. The lineal-energy spectra of the fragments produced in the phantom were compared with the actual in-phantom spectra; both spectra are consistent with each other. The results of both the IPM- and PID-mode are utilized for dose estimation as the data for the geometries simulating a human body. In other words, the particle identification by the PID-mode is considered to be usable in the IPM-mode as well in the present study.

The RBEs of the carbon beam in the PID- and IPM-mode geometries are evaluated. RBEs in both geometries have peak structure at around the Bragg peak which is 4.5 smaller than the maximum RBE of carbon 400 MeV/nucleon carbon ions. The RBE of fragments is dominated by boron particles around the Bragg peak region.

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