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The Spot Scanning Irradiation with ^{11}C Beams

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INTRODUCTION

Heavy ion beams have suitable characteristics for cancer radiotherapy; the excellent physical dose-localization called Bragg peak, a high LET characteristic around Bragg peak and small spreading due to multiple Coulomb scattering in matter. In order to take advantage of this feature, it is strongly desired the irradiation method concentrating dose on tumor and avoiding any unwanted dose exposure to normal tissue around tumor. The range of particle beams in the body of patient is currently estimated by the CT number, which includes some error from the difference in interaction process between photon and particle beams. We have proposed the cancer radiotherapy using the spot scanning irradiation with ^{11}C beams. After the therapy using ^{11}C beams, the dose distribution in the body of patient can be correctly observed by detecting annihilation gamma rays emitted from ^{11}C with use of PET system.

The production and selection system of ^{11}C beams has been constructed in the secondary beam line (SBL) at HIMAC. When the parameters of the SBL are set at the momentum acceptance of $\pm$ 2.5% and transverse one of 40 π mm mrad, the production rate of ^{11}C beams from ^{12}C beams is measured from 0.3% to 0.8%, which mainly depends on their beam energy. An irradiation method with high beam efficiency is required for the radiotherapy using ^{11}C beams. We adopted a spot scanning irradiation consisting of horizontal and vertical scanning magnets and the range shifter made with acrylic plates.[1]

The spot scanning is the irradiation method to superpose the spot beam, which give 3-dimmensionally localized dose, and construct the 3-D conformal irradiation field. The ^{11}C beams with the finite momentum spread have the promising depth dose distribution for construction of the spread out Bragg peak (SOBP). The momentum distribution and the depth dose distribution of ^{11}C beams were measured and the biological SOBP was calculated by superposing the each dose distribution. We found the probability to control the distal fall off of the biological SOBP by selecting the momentum distribution of ^{11}C beams.

SPOT SCANNING AT SECONDARY BEAM LINE

The layout of the SBL at HIMAC is shown in Fig. 1. [2] ^{12}C beams extracted from HIMAC synchrotron are transported to the beryllium target and the secondary beams are produced by the process of the projectile-fragmentation. ^{11}C beams can be selected by an achromatic fragment separator.

The dose spots of ^{11}C beams are arranged in the target volume by the irradiation system of the spot scanning, which is under construction at the downstream of the SBL. The orbits of beams are bent to the lateral position in tumor region by horizontal and vertical scanning magnets. The ranges of the beams are adjusted to the position in depth by inserting the range shifter.

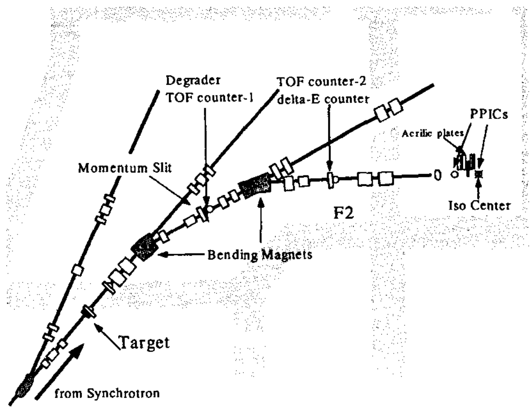

Fig. 1 Secondary beam line at HIMAC

The method controlling the dose distribution of each spot has been investigated for ^{12}C beams, which has monochromatic energy and enough intensity for treatment. [3] The Bragg peak is spread in several mm by the passive device called ridge filter. On the other hand, the method shaping the spot of ^{11}C beams is required to reduce the beam loss because of the lower beam intensity. The method shaping 'minipeak', which is the dose distribution with several-mm spread out Bragg peak, with use of the momentum spread of ^{11}C beams is thought out.

EXPERIMENTAL SETUP

The production rates and the momentum distributions of ^{11}C beams are measured by an intensity monitor for the primary beam, the secondary emittion counter [4], and the particle identify (PI) system. PI system consists of a time of flight (TOF) counter and a delta-E counter as shown in Fig. 1. The TOF counter consists of two plastic scintillators 0.5 mm in thickness and the delta-E counter is a silicon detector 0.5 mm in thickness. [5]

The depth dose distributions of ^{11}C are measured at the Iso Center in Fig. 1. The acrylic plates are set between the two parallel plate ionization chambers (PPICs) as shown in Fig. 1 so as to adjust the residual range of the beam at the exit of the second PPIC.

RESULTS AND DISCUSSIONS

The production rates of ^{11}C beams from the ^{12}C beams, which have the incident energy of 290 MeV/n, were measured as a function of the target thickness. ^{11}C beams have the momentum spread due to the angular spread at the projectile-fragmentation process at the beryllium target and the energy loss dependent on the interaction point in the target. For the condition of the momentum spread of $\pm$ 2.5 %, the production rates are measured from 0.3% to 0.4% and the purity of ^{11}C beams ranges are from 95% to 97% corresponding to the target thickness from 15 mm to 51 mm.

The following results were obtained by ^{11}C (231 MeV/n) with use of the target with the thickness of 27 mm and the ^{12}C-beam energy of 290 MeV/n. The momentum distribution is measured as shown in Fig. 2. The width of the error bar is $\pm$ 0.125%, which is selected by the momentum slit shown in Fig. 1. The central momentum of each transported beam was determined by the excitation of dipole magnets. As shown in Fig. 2, the measured data can be fitted well with

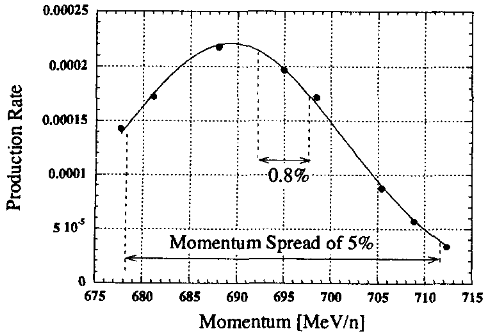

Fig. 2 The momentum distribution of ^{11}C (231MeV/u), produced by 12C (290MeV/n) and the 27 mm-thick target. The measured one shown by the solid circle with the error bar of ± 0.125 %, which is selected by the momentum slit, is fitted to the Gaussian function (line).

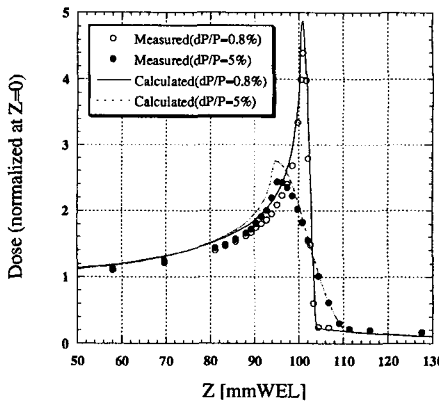

Fig. 3 The measured dose of ^{11}C beams. The open and solid circles are momentum spread of 5 % and 0.8 %, respectively. The dashed and solid lines indicate 'minipeaks' convoluted of the mono-energetic dose distribution calculated with the momentum distribution with the spread of 5 % and 0.8 % as shown in Fig. 2.

a Gaussian function.

In the measurement of the dose distributions of ^{11}C beams, the momentum spread is selected as shown by the arrows in Fig. 2. The solid and open circles in the Fig. 3 indicate the depth dose distributions of the beams with the momentum spread of 5% and 0.8%, respectively. The depth dose distribution of the mono-energetic ^{11}C beams with 231MeV/n was calculated by Sihver's method [6)]. The 'minipeaks' resulted from the convolution of the calculated distribution with (finite) momentum spread are shown in Fig. 3, in which the dashed and solid lines correspond to the momentum spread of 5% and 0.8%, respectively. The measured ones are consistent with their ranges and widths of the 'minipeaks'.

SOBP with the flat region of 60 mm in depth direction was designed with use of the 'minipeak' with the momentum spread of 5%. The biological dose distributions were calculated by the formalism described in the reference 7), which had been developed by Zaider and Rossi [8)] for mixed LET irradiation and found to reproduce the distribution well for the ^{12}C beams. [9)] The contribution weights of 13 'minipeaks', which are shaped by shifting the selected 'minipeak' by (5 x (n-1)) mm in depth direction, were optimized to be 1 GyE in the region of 60mm.

Figure 4 shows the physical dose distribution of the 'minipeaks' (upper) and the biological dose of 60 mm-SOBPs (lower). The dashed lines are calculated for the 'minipeak' that has momentum of 97.5-102.5%. The distal fall off (80-20% of biological dose) of 60 mm-SOBP is 8.9 mm, main contribution of which is the large distal fall of original 'minipeak'. Solid lines show the calculated results by assuming the beams with the momentum of 94.5-99.5%. The distal fall of 60 mm-SOBP is reduced to 2.7 mm with the same momentum spread, 5%. The fluctuation of the biological dose in the region of 34.6-93.6 mm is very small. It is between +2.2% and −3.3% of the prescribed biological dose, 1GyE. Although the further investigation considering the beam intensity is required, the higher dose at the proximal of this 60 mm-SOBP can be reduced by deleting the lower part of the momentum distribution.

CONCLUSION

We have investigated the characterization of ^{11}C beam for radiotherapy with spot scanning irradiation. The depth dose distributions of ^{11}C beam with the momentum spread of 5% and 0.8% were measured. The calculated depth dose distributions using Sihver's method are consistent with the experimental results.

SOBP can be obtained with the superposition of the 'minipeaks', the shape of that is adjustable by the momentum spread of ^{11}C beams. The proposed method of SOBP formation is especially advantageous over conventional one under low ^{11}C-beam intensity, since the beam utilization efficiency is higher because of lack of passive components such as scatterer, ridge filter.

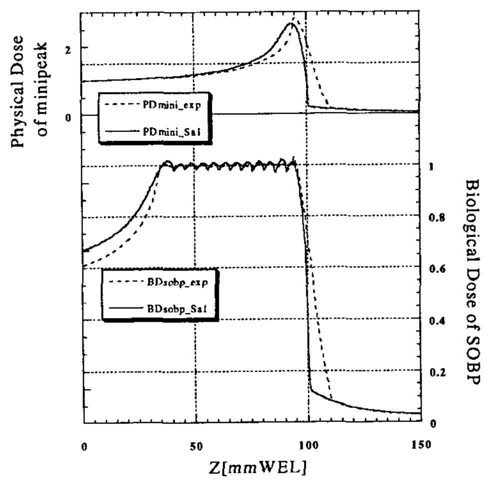

Fig. 4 The physical dose distributions of 'minipeaks' (upper) and the biological dose distributions of 60 mm-SOBPs (lower). The dashed lines are for the momentum of 97.5-102.5% and the solid lines are for 94.5-99.5%.

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