POSITRON CAMERA SYSTEM FOR HEAVY-ION RADIOTHERAPY AT HIMAC

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Abstract

The positron camera system was designed and developed at the secondary beam course of HIMAC to measure heavy-ion ranges in bodies of patients. By using the pencil-like beam of positron emitters, such as ^{11}C, the range is checked directly and precisely by detecting pairs of annihilation gamma rays emitted from the stopping point of the beam. The positron camera consists of a pair of Anger-type scintillation cameras. In order to achieve high detection efficiency, each detector is equipped with a large NaI(Tl) crystal having a thickness of 30 mm and a diameter of 600 mm. The test results reveal that the range can be measured with accuracy of less than 1 mm under the limitation that the irradiation dose has to be less than a few percent of the therapeutic one.

1 INTRODUCTION

Energetic heavy-ion beams have been applied to radiation therapy because of their excellent characteristics, such as dose localization and biological effectiveness. The favorable dose localization is due to a sharp peak of the energy deposition near the stopping point, namely, Bragg peak. Precise control of the irradiation field is required so as to concentrate the dose to a target region.

The treatment planning is based on the measurement of X-ray computed tomography at present. This method is subject to some uncertainty in regard to the transfer from X-ray absorption coefficients to ranges in a patient's body.

A new project is in progress at the secondary beam course of HIMAC in order to verify the irradiation field [1]. By using the beam of positron emitter nuclei, such as ^{11}C, we can directly measure its stopping point with a positron camera. This range evaluation gives us an in-situ verification of treatment planning just before the radiotherapy, and therefore, there is a limit on the dose of the evaluation beam to prevent damage to normal tissues surrounding the tumor.

For this purpose, the positron camera is required to have a large detection area, high efficiency for the annihilation gamma rays, and high spatial resolution. Thus, it has been determined that the positron camera should consist of a pair of Anger-type scintillation detectors [2] equipped with large NaI(Tl) crystals having a thickness of 30 mm and a diameter of 600 mm.

The construction of the positron camera system has just been completed, and now we are testing its properties with a checking source and a ^{11}C beam. The spatial resolution of the camera results in 12 mm in FWHM, preliminarily, and the test results have revealed that the range can be measured with accuracy of less than 1 mm.

2 IRRADIATION SYSTEM

The apparatus of the range evaluation system is illustrated in Fig. 1. Some of the devices are shared with the irradiation system for the radiotherapy, that is, the spot-scanning system [3].

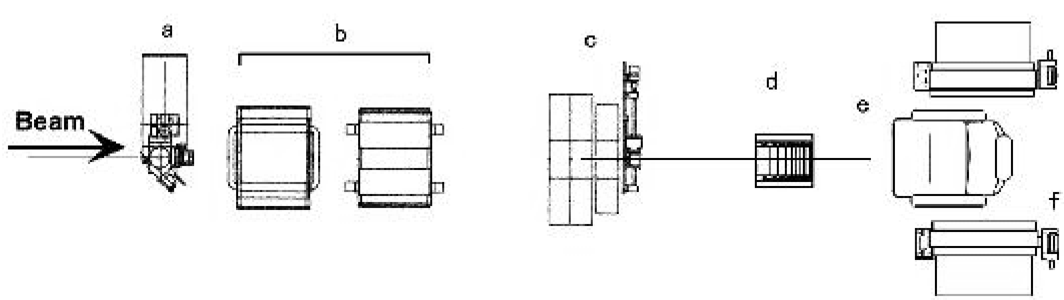

Figure 1: Schematic diagram of range evaluation system. a : pencil beam collimator, b : pair of scanning magnets, c : beam monitors, d : range shifter, e : chair for patient, f : positron camera.

The beam for the range evaluation is collimated with a pencil-beam-collimator so as to be delivered precisely to the desired positions in the patient's body. The beam is positioned laterally with a pair of scanning magnets and in depth with a range shifter. The lateral position is checked with a position-sensitive silicon detector (PSD) beforehand. The number of the irradiation particles is counted with a plastic scintillation detector.

The secondary beams have a wide momentum width [3], and therefore, it is necessary to insert a slit so that the range spread is restricted to less than the margin of the irradiation field. The range spread is 3.7 mm corresponding to 0.8 % of full momentum width (dp/p) in the case of ^{11}C with energy of 300 MeV/n. The depth-dose distribution calculated by HIBRAC [4] is shown in Fig. 2. In view of the need to prevent damage to normal tissues, the irradiation dose is subject to a quantitative limitation. When the peak of the biological dose was 50 mGyE, the limitation of the incident particles resulted in $7.9*10^4$.

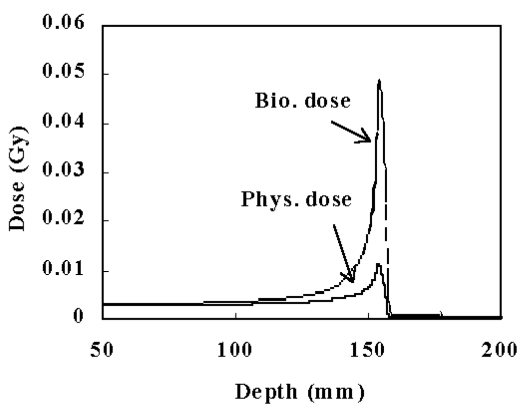

Figure 2: Physical dose and biological dose distributions by HIBRAC. The energy of ^{11}C is 300 MeV/n, and the beam radius is 3 mm.

3 POSITRON CAMERA GEOMETORY

Manufacturing of the positron camera has just been completed. The positron camera is required to measure the ranges with accuracy of less than 1 mm under the limitation of irradiation dose. Thus, the crystal size was optimized as a function of the range accuracy by numerical simulation, and determined to be a diameter of 600 mm and a thickness of 30 mm [5]. In view of the good spatial resolution, the surface of the crystal was thought to be diffusively reflective at the front and absorbent at the edge. 109 2-inch photomultipliers are mounted on a crystal. The area where the outermost photomultipliers are mounted cannot be used for the position calculation, and so the effective area (the field of view) has a diameter of about 500 mm.

In the first trial of the range evaluation, we intend to apply the positron camera to radiotherapy of a head region in a sitting configuration, and thus, a pair of Anger-type scintillation detectors are set horizontally. The distance between two detectors is variable from 500 to 700 mm.

The geometry of the camera is summarized in Table 1.

4 DATA TAKING CIRCUIT

Since the positron emitter sources are injected directly from the accelerator, the positron camera was designed to have features different from those of the conventional scintillation camera.

One of the remarkable differences is that the counting rate of pairs of gamma rays is quite small, less than 1 cps. In order to reduce background events, the trigger signal is generated by a hit logic written on a ROM. The trigger condition, for example, the multiplicity of the photomultipliers, is variable by rewriting the hit logic so as to reduce the background events.

The system can also detect the positron emitters that have short lifetimes, such as ^{10}C. For this purpose, the detection can be synchronized with the interval of irradiation pulse by the external inhibit signals. These nuclei are useful to detect the range without the influence of blood flow as well as to reduce measuring time.

The circuit has a clock generator and its counter so that the data include the information of the time of generating events. This generating time can be used for the nuclei that have short lifetimes to reject background events by decay-curve analysis, and also to study the blood flow.

5 RESULTS WITH CHECKING SOURCE

The performance of the positron camera was measured with a point source of ^{22}Na. The position distribution obtained is shown in Fig. 3. Here, the distance between two detectors was set to be 700 mm, and the source was placed at the isocenter and at 50 mm from the isocenter on beam axis (the accuracy of positioning is about 2 mm). The position of incident gamma ray for each crystal was obtained by centroid calculation. The figure shows the spatial resolution is 12 mm in FWHM, and the position calculated responds well to that placed.

The energy spectrum is shown in Fig. 4, and results in an energy resolution of about 14 % in FWHM. The photopeak of 511 keV gamma rays can be seen clearly. This indicates that the events can be gated in the photopeak region so as to reject the scattered gamma rays in the patients.

The results shown here were analyzed preliminarily, and the spatial linearity of gamma rays incident on a crystal plane will be calibrated by using the imaging data that is obtained with line sources in advance. Moreover, the calculated position will be modified with the curve of position response obtained with the point source.

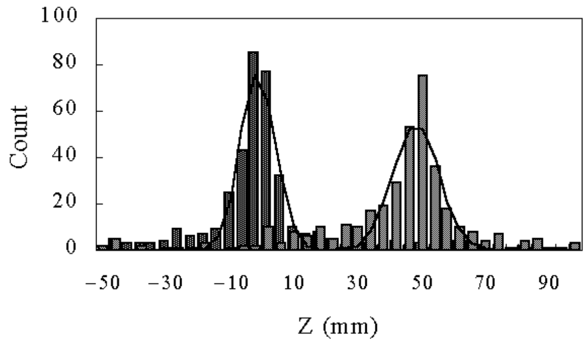

Figure 3: Position distribution measured with checking source. The source was placed at the isocenter and at 50 mm from the isocenter.

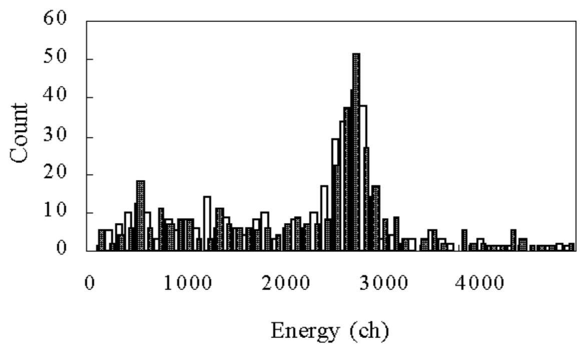

Figure 4: Energy spectra of checking source. The open and the closed bars denote the events detected by detector-1 and detector-2, respectively

Table 1: Positron Camera Property

Crystal size	30 mm in thickness, 600 mm in diameter
Effective area	~ 500 mm in diameter
PMT size	2 inches
Number of PMTs	109 / detector
Detector interval	500 to 700 mm (variable)
Spatial resolution	~ 12 mm in FWHM
Energy resolution	~ 14 % in FWHM (511 keV)

6 RESULTS OF BEAM TEST

The beam test was carried out with a ^{11}C beam having an energy of 355 MeV/n with 0.8 % of momentum width. The pencil-beam, whose diameter was measured to be 8 mm in FWHM at the isocenter, was injected on a Lucite block (250*100*50 mm); the block was placed so that the beam stopped near the center of the measurable region. The number of incident ^{11}C was $3*10^5$ particles, which corresponds to a dose of 190 mGyE.

The position distribution detected within 10 minutes is shown by the shadow bar in Fig. 5. Since the counting rate of the real coincident events was very low, there was a broad hill of the accidental coincidence to background events.

Figure 5 also shows the distribution in the case that the events were discriminated with the energy of photopeak. The distribution became similar to that obtained with the checking source. It has been revealed that the event selection with the energy gate is useful to reduce the influence of the background. The range accuracy of 0.6 mm was obtained by Gaussian fitting.

7 SUMMARY

The positron camera system at the secondary course of HIMAC has been constructed to verify the ranges of the irradiation beams for the heavy-ion radiotherapy. The positron camera was designed with a large crystal on each Anger-type detector so as to have high detection efficiency.

The tests of the positron camera have revealed that the spatial resolution on the camera is 12 mm in FWHM, preliminarily, and the range can be measured with accuracy of less than 1 mm under the limitation of irradiation dose.

We will continue to improve the accuracy of the camera and intend to examine the operation of the system for therapy in beam tests using phantom.

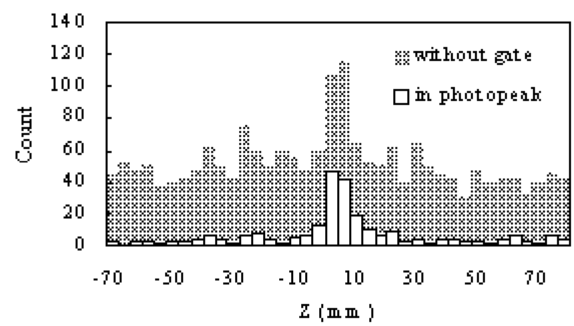

Figure 5: Range distribution in the case of injecting ^{11}C beam. The shadow and the open bars indicate the events without energy gate and in photopeak.

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