NEW HEAVY-ION CANCER TREATMENT FACILITY AT HIMAC

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Abstract

Based on more than ten years of experience with HIMAC, we have proposed a new treatment facility for the further development of therapy with HIMAC. The new facility, as an extension of the existing one, has been designed, and the related R&D work has been carried out. The new treatment-facility project was approved at December 2007.

INTRODUCTION

The first clinical trial of cancer treatment with carbon beams was conducted in June 1994 at the Heavy Ion Medical Accelerator in Chiba (HIMAC) [1].The total number of patients treated until May 2008 was more than 4000. Based on more than ten years of experience with HIMAC, we have proposed a new treatment facility for the purpose of further development toward adaptive cancer therapy [2]. Thus the new facility employs a 3D pencil-beam scanning method for a fixed target, a moving target and/or a target near to critical organs. This facility, which is connected with the HIMAC synchrotron, consists of three treatment rooms: two rooms equipped with fixed beam-delivery systems in the horizontal and vertical directions and one room with a rotating gantry. In both the fixed beam-delivery and rotating gantry systems, since the beam control for the size, the position and the time structure plays an essential role in the 3D beam scanning with the irradiation gated with patient's respiration, the R&D study has been carried out with the HIMAC synchrotron since 2006. We report the design and R&D studies toward the construction of the new treatment facility.

DESIGN CONSIDERATION

Ion Species, Energy and Field Size

A ^{12}C beam is mainly used for treatments that have been carried out in the existing HIMAC treatment. Different ion species will also be employed for the further development of HIMAC therapy. In addition, positron-emission beams, such as ^{11}C and ^{15}O, will be used to verify the irradiation area and their ranges in a patient's body. Thus R&D study has been carried out in order to obtain positron-emission beams accelerated directly through the HIMAC accelerator [3], instead of using the projectile-fragmentation method.

The statistics of the more than ten-year treatment period at HIMAC, further, shows that the residual range requires more than 25 cm to cover most of the patients treated with HIMAC [4]. Thus, the maximum ion energy is designed to be 430 MeV/n in the fixed beam-delivery system, which brings the residual range of 30 cm in a ^{12}C beam and that of 22 cm in an ^{16}O beam. The maximum lateral-field and SOBP sizes are 20 cm × 20 cm and 15 cm, respectively, in order to cover almost all treatments with HIMAC. On the other hand, the rotating gantry system employs the maximum energy of 400 MeV/n, the maximum lateral-field of 15 cm × 15 cm and the maximum SOBP size of 15 cm in order to downsize the gantry size.

Irradiation Method

In HIMAC treatments, sometimes, we have observed shrinkage of the target size and a change of its shape during the entire treatment. In order to keep the sophisticated conformations of the dose distributions even in such cases, it has been required that treatment planning is carried out just before each fractional irradiation, which we call adaptive therapy. For this purpose, 3D scanning with a pencil beam should be employed, because it does not use any bolus and patient collimators, which take a long time to be manufactured. It is also well-known that 3D scanning has brought about a highly treatment accuracy in the case of a fixed target. However, this method has not yet been applied to treating a moving target with breathing in practical use. Therefore, we have developed the phase-controlled repainting (PCR) method [5] to treat a moving target. A rotating gantry [6] also employs the PCR method in order to relieve the patient's load, such as face-downward position. Further, the rotating gantry can increase the treatment accuracy for a tumour near to a critical organ through multi-field optimization [7].

Facility Planning

The new treatment facility is connected with the upper synchrotron at HIMAC. In the treatment hall, placed underground of the facility, three treatment rooms are prepared in order to treat more than 800 patients per year. Two of them are equipped with fixed beam-delivery systems in both the horizontal and vertical directions, and the other is equipped with a rotating gantry. Two treatment-simulation rooms are also prepared for patient positioning as a rehearsal, and for observing any change of the target size and shape with X-ray CT during the entire treatment. Further, six rooms are devoted to patient preparation before irradiation. Schematic views of the new treatment facility and the treatment hall are shown in Fig. 1.

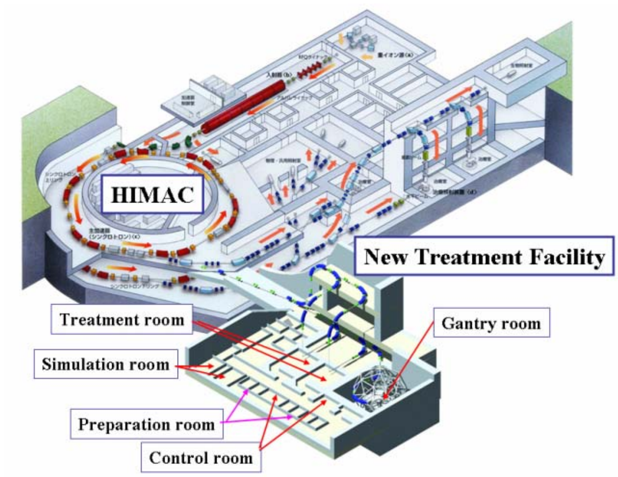

Figure 1: Schematic view of the new treatment facility.

DESIGN AND R&D STUDIES

Design of BT and Beam-Delivery System

In the new treatment facility, beam transport (BT) lines are designed to make energy scan [8] possible. Thus all of the magnets will be manufactured with laminated iron plates. The beam optics is designed to realize dispersion free in the fixed beam-delivery system, and the beam size can be changed from 2 to 8 mm at one-sigma by using the final Q-triplet. The beam-position change due to undesirable parameter change of the synchrotron and the BT line is monitored by a non-destructive screen monitors and can be corrected by a pair of steering magnets in both horizontal and vertical directions in the beam-delivery system.

The fixed beam-delivery system is designed to realize the PCR method with the fast raster scanning [5] and to be same configuration in both the horizontal and vertical directions. The system consists of a pair of scanning magnets, dose monitors, a ridge filter and a range shifter. The total length of the system is around 9 m. The beam-scanning speed is designed to be 100 mm/ms for fast scanning. Two dose monitors, which are parallel-plate ionization chambers with an effective area of 250 mm^2, are used for dose management. The beam position and size are monitored by multi-wire proportional counters. Considering the slice thickness, the Bragg peak is slightly spread out by a mini ridge filter. The range shifter is utilized to change the slice in the target. Thus, the range shifter should be as close as possible to the iso-center in order to avoid any change of the beam size by multiple scattering through the range shifter.

It is important for the gantry design to avoid any change of the beam size depending on the rotation angle. Thus, we will adapt a compensation method of the asymmetric phase-space distribution [9].This method is based on multiple scattering by a thin foil placed at the position with the optimum beam-optical parameters in the BT line. Further, the final dipole magnet is divided into 30-degree and 60-degree magnets, and two scanners are placed between the two dipole magnets in order to extend the effective length from the scanners to the iso-center. The total weight of the rotating-gantry system is around 350 tons.

Improvement of Time Structure of Extracted Beam Through RF-KO Slow Extraction

We developed the RF-KO slow extraction method [10] for a respiration-gated irradiation system using the broad-beam irradiation (wobbler) method. This method has a huge spill ripple due to the coherency in its extraction mechanism. However, the huge spill ripple has never disturbed the dose distribution in the wobbler method, because the ripple frequency of around 1 kHz is much different from the wobbling one of around 60 Hz. In the beam-scanning method, on the other hand, the huge spill ripple affects the lateral dose distribution. As a result of study, we proposed the dual FM method and the separated function method [11], which were already verified by the experiment and has been routinely utilized. Further, the intensity modulation of the extracted beam is an essential feature of the PCR method. Thus we have also developed the global-spill (Hz-order) control method [12]. Since this control method can predict the extra-dose occurred when the beam moves between raster points, the scanning speed can be increased by five times compared with the conventional one [13].

Intensity Upgrade and Extended Flat-Top Operation

The beam intensity extracted from the synchrotron has been increased in order to complete single-fractional irradiation with one operation cycle. In this case, the efficiency of the gated irradiation will be increased, because we can extend the flattop infinitely in principle. The extended flattop operation will save considerably irradiation time. In order to increase the beam intensity, we have thus carried out a tune survey during beam injection. As a result, it was found that the 3rd-order coupling resonance caused beam loss. This resonance was corrected by four sextupole magnets, and the beam lifetime in the injection-energy level was increased by more than 5 times. In addition, we tried multi-harmonics operation of the RF acceleration system in order to suppress the space-charge effect after bunching. This operation increased the acceleration efficiency by around 40% [14]. Consequently, around 2×10^{10} carbon ions can be accelerated to the final energy. This intensity is sufficiently high to complete single-fractional irradiation for almost all tumours treated with HIMAC when using the 3D-scanning method with beam-utilization efficiency more than 90%. The extended flattop operation was successfully tested at the HIMAC synchrotron, and the stability of the beam-profile was investigated. The horizontal and vertical beam profiles during extraction duration of 100 s were measured by a multi-wire proportional counter, as shown in Fig.2. As a result of an analysis of the measurement, it was estimated that both the position and the size for an extraction duration of 100 s were stabilized within ±0.5 mm at the iso-center.

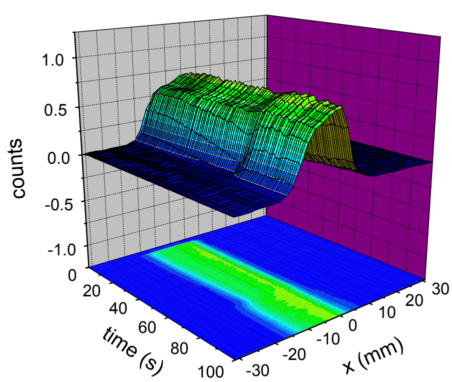

Figure 2: Horizontal profile measured during 100 s extraction. Vertical one was similar result.

Fast raster-Scanning Experiment

Since fast raster-scanning is one of key technologies for the PCR method, we have carried out a fast raster-scanning experiment by using the HIMAC spot-scanning test line [15]. The irradiation control system was slightly modified so as to be capable of raster scanning irradiation instead of spot-scanning one. At the present stage, we have adapted the measured dose response of the pencil beam with energy of 350 MeV/n, corresponding to a 22-cm range in water. The beam size at the entrance and the width of the Gaussian-shaped mini-peak were 3.5 and 4 mm at one standard deviation, respectively. The validity of the beam model and the optimization calculation had already been verified experimentally [16]. Using the dynamic intensity control system, the beam intensity was kept almost constant during irradiation. In the experiment, a spherical target of 4 cm in diameter was irradiated so as to produce a uniform physical dose field. As shown in Fig.3, the measured dose distributions were in good agreement with the calculation result at different penetration depths. Owing to both the extra-dose prediction and the extended flattop operation, the irradiation time was shortened by around ten times compared with that of the conventional spot scanning. The scanning experiments including QA have been continuously carried out at HIMAC [17].

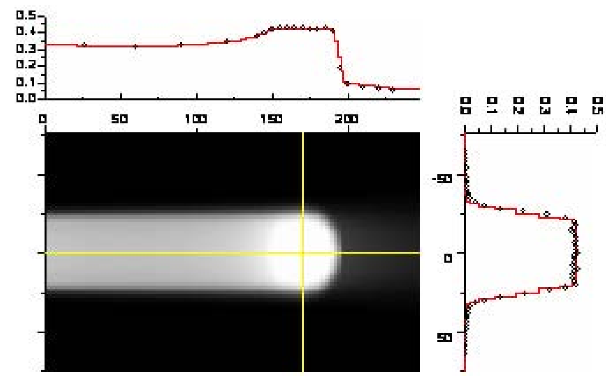

Figure 3: Dose distribution by the fast raster scanning.

SUMMARY

During more than ten-years of clinical trials with HIMAC, both the beam-delivery and the accelerator technologies have been significantly improved. It has brought the good result of the clinical trial. Therefore we proposed the new treatment facility project for further development of the HIMAC treatment. In this project, a patient positioning system, treatment planning system for the PCR method and Carbon-RT information system have been developed as well as that of the accelerator and beam delivery systems since April 2006. At December 2007, the Japanese government approved this project.

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