HEAVY ION RADIOTHERAPY FACILITY IN JAPAN

K. Noda[#], T. Furukawa, T. Inaniwa, Y. Iwata, M. Kanazawa, K. Katagiri, N. Kanematsu, A. Kitagawa, S. Minohara, E. Takeshita, T. Murakami, M. Muramatsu, S. Sato, E. Takada, Y. Takei

National Institute of Radiological Sciences, Chiba, Japan

Abstract

On the basis of both accelerator and beam-delivery technologies developed by NIRS, Gunma University constructed a pilot facility of standard carbon-ion radiotherapy facility in Japan, and its treatments have been successfully carried out since March 2010 on schedule. NIRS, on the other hand, has carried out the new treatment research facility project for further development of the HIMAC treatment since 2006.

1. INTRODUCTION

The first clinical trial with carbon beams generated from the HIMAC [1] was conducted in June 1994. The total number of patients treated reaches to about 6,000 as of December 2010. In the view of the significant growth in the number of protocols, in 2003, the Japanese government approved the carbon-ion radiotherapy (RT) with HIMAC as an advanced medical technology. For wide spread use of carbon-ion RT in Japan, therefore, NIRS proposed a standard carbon-ion RT facility in Japan, based on ten-years of experience with the HIMAC. NIRS designed the standard facility and developed the key technologies of the accelerator and beam-delivery systems from April 2004 to March 2006, with the main thrust being focused downsizing the facility for cost reduction [2]. Gunma-University Heavy-Ion Medical Center (GHMC), in collaborating with NIRS, constructed a pilot facility of the standard version, and the clinical study has been successfully carried out since March 2010. NIRS, on the other hand, has developed a fast 3D scanning technology for the further development of the therapy with the HIMAC, which is called “New Treatment Research Facility Project” [3]. The development of the heavy-ion therapy technologies is reported.

2. PROGRESS OF HIMAC

The carbon-ion radiotherapy with HIMAC has been progressed, and the treatment number has been increasing year-by-year as shown in Fig. 1. The HIMAC beam-delivery system has employed the beam-wobbling and ridge filter method, which is one of the broad beam methods, in order to deliver its dose safely and reliably. Using this method, at present, around 100 irradiations a day at maximum are carried out under one-shift operation, and around 750 patients a year were treated under 180 days operation. Since the HIMAC treatment was initiated in 1994, we have developed both accelerator and beam-delivery technologies in order to obtain higher irradiation accuracy.

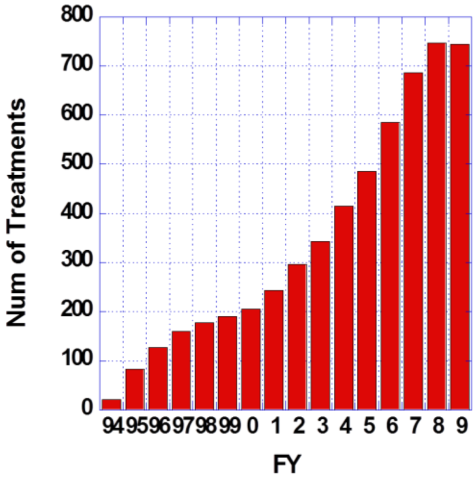

Fig. 1. Treatment number with HIMAC since 1994. The total number is around 6,000 in December 2010.

2.1 Respiratory-gated irradiation

Damage to normal tissues around tumor was inevitable in treatment of a tumor moving along with respiration of a patient. A respiratory-gated irradiation system, therefore, which can respond quickly to irregular respiration, was developed [4]. In this system, the irradiation-gate signal is generated only when target is at the design position and the synchrotron can extract a beam. The beam is delivered by the RF-KO extraction method [5], according to the gate signal. This method has been applied to liver, lung and uterus cancers since February 1996.

2.2Layer-stacking irradiation method

In a conventional beam-wobbling method, the fixed SOBP (Spread-Out Bragg Peak) produced by a ridge filter results in undesirable dosage to the normal tissue in front of target, because the width of an actual target varies within the irradiation field. In order to suppress the undesirable dosage, thus, the layer-stacking irradiation method was developed [6-8]. A schematic drawing of this method is shown in Fig. 2. This method is to conform a variable SOBP to a target volume by controlling dynamically the conventional beam-modifying devices. The thin SOBP with several mm in WEL, which is produced by a single filter, is longitudinally scanned over the target volume in a stepwise manner. The target volume is longitudinally divided into slices, to each of which the small SOBP is conformed using the MLC (Multi Leaf Collimator) and the range shifter, and a variable SOBP coinciding to the target volume is to be formed. This method has been utilized routinely since 2004 [9].

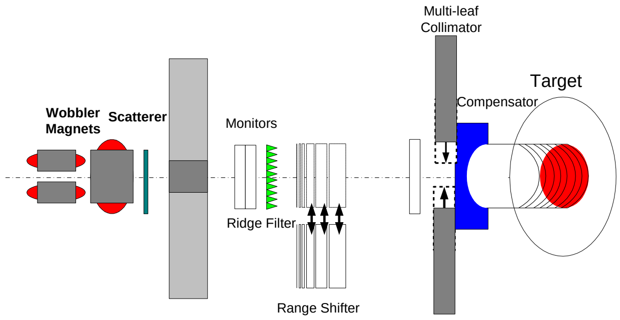

Fig. 2. Schematic drawing of the layer-stacking irradiation method.

2. STANDARD CARBON-ION RADIOTHERAPY FACILITY IN JAPAN

For wide spread use of carbon-ion RT in Japan, NIRS designed a standard carbon-ion RT facility, which was a downsized version of the HIMAC facility, in order to reduce the construction cost. NIRS, further, developed the key-technologies for the standard facility. GHMC, in collaborating with NIRS, constructed a pilot facility of standard carbon-ion RT facility, which can be downsized to one-third compared with the HIMAC facility. Treatments with the pilot facility have been successfully carried out since March 2010 on schedule.

2.1 Design Considerations and Specifications

Considering the clinical statistics accumulated for more than ten years with HIMAC, specifications such as residual range, maximum beam energy and irradiation-field size were determined so as to cover the HIMAC treatments.

The maximum residual range was designed to be 25 cm. The residual range depends not only on the beam energy, but also on the forming method of a lateral irradiation field. When the range loss mainly due to scatterer can be suppressed to less than 2.5 cm, carbon ions with energy of 400 MeV/n, corresponding to a 27.5 cm range in water, have a residual range of 25 cm. For the purpose, the spiral beam-wobbling method was developed [10], which can suppress a range loss in scatterer to less than 2.5 cm. The maximum energy, thus, was determined to be 400 MeV/n. On the other hand, the minimum energy was determined to be 140 MeV/n for eye melanoma treatment.

A field diameter of 22 cm and an SOBP of 15 cm can cover almost all types of patient treated with HIMAC. A larger field size of more than 20 cm has been required mainly for the treatment of oblong tumors. In such cases, it is important to maintain the field length rather than the diameter. The SOBP size should be changeable from 4 to 15 cm.

The irradiation-dose rate is required to be 5 GyE/min/l, the same as that at HIMAC. The dose rate corresponds to an intensity of $1.2{\cdot}10^9$ pps, extracted from the synchrotron by assuming a beam-utilization efficiency of 30% at the beam-delivery system. According to the beam-intensity schedule for the compact facility, the synchrotron requires a C^{6+} intensity of more than 200 eμA from the injector linac cascade, and the ion source should provide a C^{4+} beam with an intensity of more than 260 eμA.

Both of the respiratory-gated irradiation and the layer-stacking irradiation methods are required to sufficiently suppress undesirable dose.

The number of treatments a year requires to be more than 600 patients for an economic reason. Since the average number of fractions per treatment is 14 on average at HIMAC, the total irradiation number is estimated to be 9800/year for the treatment of 700 patients/year. Considering a single irradiation time of 25 min on average, including patient positioning, 3600 irradiations/year can be carried out in one treatment room under the following working schedule: 6 (hr/day) × 5 (days/week) × 48 (weeks/year). It should be noted that 2 hours are needed to prepare for the stand-up time of the whole system and QA/QC. From this, it is clear that the new facility requires three treatment rooms. Further, the ratio of the treatment frequency with the horizontal irradiation port (H-port) to that with the vertical one (V-port) is around 5:4. Therefore, the three treatment rooms should be equipped with H-port, V-port and H&V-ports.

The specifications of the standard carbon-ion RT facility in Japan are determined according to the design considerations mentioned above. The specification is summarized in Table 1.

Table 1. Specifications of standard C-ion RT facility

Ion Species	Carbon
Energy	400 – 140 MeV/n
Range/SOBP/Lateral-Size	250/40-150/220mm
Max. Dose Rate	5 GyE/min/*l*
Beam Intensity	$1.2{\cdot}10^9$ pps
Treatment Room	3: H&V, H, V
Irradiation Method	Gating/Layer Stacking

2.2 Pilot Facility

On the basis of the design study and R&D works of the standard facility, GHMC constructed a pilot facility since 2006, and the first patient was successfully treated on March 2010. This facility has an ECR ion source, an RFQ and an APF-IH linac cascade, a synchrotron ring, three treatment rooms and one experimental room for basic research. In this pilot facility, a C^{4+} beam, which is generated by a compact 10-GHz ERC source [11], is accelerated to 4MeV/n through the injector cascade consisted of the RFQ and APF-IH linacs [12]. After the

C^{4+} beam is fully stripped by a thin carbon foil, the C^{6+} beam is injected into the synchrotron through the multi-turn injection scheme and is accelerated up to a maximum of 400 MeV/n. All magnets in the beam transport lines are made of laminated steel in order to permit a change in the beam line within one minute. The beam-delivery system employs a spiral beam-wobbling method for forming uniform lateral dose distribution with a relatively thin scatterer.

The specifications are summarized in Table 1, and an image view of the Gunma University facility with a full complement of equipment is shown in Fig. 3.

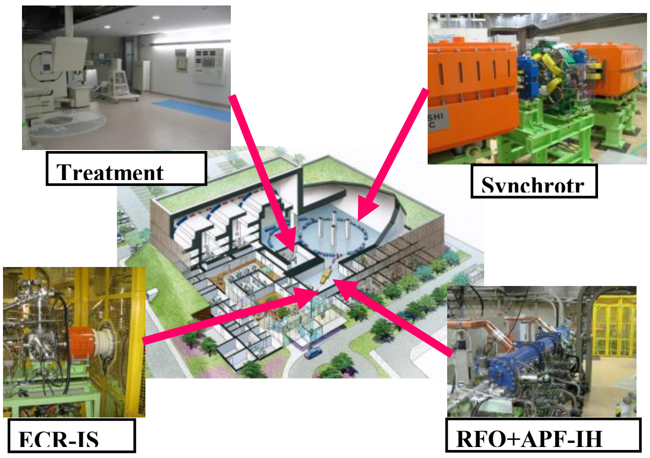

Fig. 3. Layout of the pilot facility constructed by GHMC.

3. NEW TREATMENT RESEARCH FACILITY

Design and R&D works on a new treatment research facility with HIMAC has been carried out with a view to the further development of the carbon-ion therapy. The facility has been constructed since February 2009 in order to apply the new technologies developed to the practical clinical study.

3.1Specification

A main specification such as ion species and irradiation-field size in the new treatment research facility was determined by considering the clinical statistics with HIMAC, as summarized in Table 2.

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. On the other hand, the rotating gantry system employs the maximum energy of 400 MeV/n and the smaller lateral-field size of 15 cm × 15 cm in order to downsize the gantry size. Further, 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. The R&D work has been carried out in order to obtain positron-emission beams accelerated directly through the HIMAC accelerator [13], instead of using the projectile-fragmentation method.

Table 2. Main specification

Ion Species	^{12}C, ^{16}O, (^{11}C, ^{15}O)	
	Fixed Port	Rotating Gantry
Energy	140-430 MeV/n	140-400 MeV/n
Lateral Field	22cm×22cm	15cm×15cm
SOBP	15 cm	15 cm

3.2 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. The new facility should employ a pencil-beam 3D scanning method for a fixed target, a moving target and/or a target near critical organs, toward the target of the implementation of adaptive cancer therapy. 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 a phase-controlled rescanning (PCR) method [14] with a pencil-beam, especially for treatment of moving target. In the PCR method, rescanning completes the irradiation of one slice during a single gated period corresponding to the phase between the end of expiration and the beginning of inspiration, because the organs are most stable during this gated period. Further, since the average displacement of the target over a single gated period is close to "zero", we can obtain uniform dose distribution even under irradiation of a moving target. For realizing the PCR method, the following technologies were developed: (1) intensity-modulation technique for a constant irradiation time on each slice having a different cross-section and (2) fast pencil-beam scanning technique for completing several-times rescanning within a tolerable time. These techniques were developed by using a test irradiation port, which was installed in the HIMAC facility, and the performance of the PCR was successfully verified [15,16]. In the design of the rotating gantry [17], thus, the PCR method has been employed in order to realize high irradiation accuracy through the multi-field optimization.

3.3Facility planning

The new treatment research facility is connected with the upper synchrotron of 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. 4.

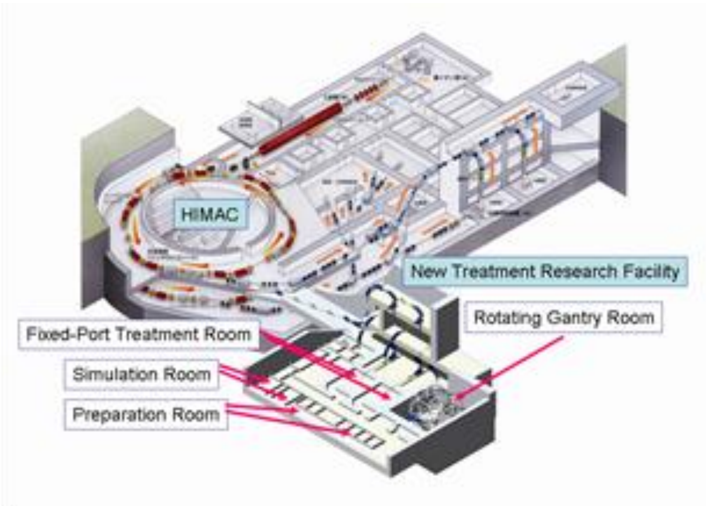

Fig. 4. Schematic view of the new treatment research facility.

4. CONSTRUCTION PLANNING OF C-ION RT FACILITY

Following on from the pilot facility constructed at GHMC, two additional projects for carbon-ion radiotherapy have been initiated in Japan: the Saga Heavy Ion Medical Accelerator in Tosu (Saga-HIMAT) and the Kanagawa Prefectural project. The Saga-HIMAT project was initiated on February 2010, and its construction has been carried out since in February 2011. This is based on the design of the standard facility and will be opened in 2013. Although this facility has three treatment rooms, initially two of them will be opened and use the spiral beam-wobbling method: one will be equipped with horizontal and vertical beam-delivery systems and the other with horizontal and 45-degree beam-delivery systems. In the next stage, the third room will be opened, using horizontal and vertical beam-delivery systems with the fast 3D rescanning method developed by NIRS. The Kanagawa Prefectural Government has decided to construct a carbon-ion radiotherapy facility in the Kanagawa Prefectural Cancer Center. This will also be based on the design of the standard facility. Design work on the facility building began in April 2010 and opening is foreseen for 2014.

4. SUMMARY

More than 600,000 persons are diagnosed with cancer every year in Japan, and it is forecast that this number will continue to rise. In such a situation, the newly-opened Gunma University facility, following those at HIMAC and the Hyogo Ion Beam Medical Center, is expected to boost applications of carbon-ion radiotherapy in Japan. By 2014, five carbon-ion facilities and eight proton facilities will be operating as shown in Fig. 5. They will certainly play an important role in cancer radiotherapy.

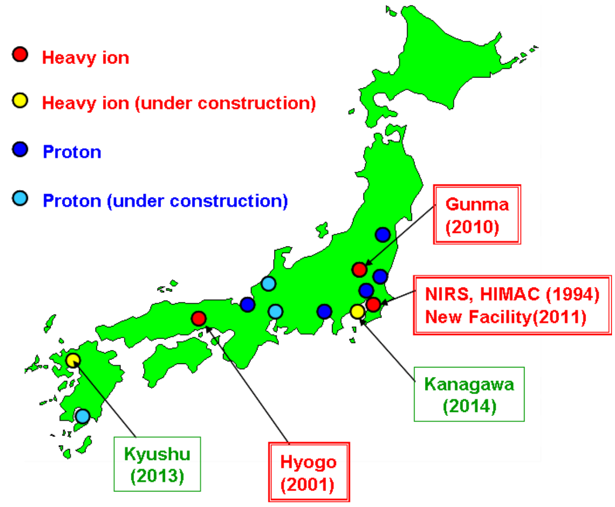

Fig. 5. Carbon-ion and proton cancer therapy facility in Japan in 2015.

REFERENCES

[1] Y. Hirao *et al*., Nucl. Phys. **A538** (1992) 541c-550c.
[2] K. Noda *et al*., J. Radiat. Res., **48** (2007) A43-A54.
[3] K. Noda *et al*., Nucl. Instrum. Meth. B **266** (2008) 2182-2185.
[4] S. Minohaya *et al*., Int. J. Radiat. Oncol. Bio. Phys. **47**(4) 1097.
[5] K. Noda *et al*., Nucl. Instrum. Meth. A **374** (1996) 269.
[6] T. Kanai *et al*., Med. Phys. **10**, 344 (1983).
[7] Y. Futami, *et al*., Nucl. Instr. Meth. **A430** (1999) 143.
[8] N. Kanematsu *et al*., Med. Phys. **29**, 2823 (2002).
[9] T. Kanai *et al*., Med. Phys. **33**, 2989 (2006).
[10] M. Komori *et al*., Jpn J. Appl. Phys. 43 (2004) 6463.
[11] M. Muramatsu *et al*., Rev. Sci. Instr. 75(2004) 1925.
[12] Y. Iwata *et al*., Nucl. Instrum. Meth. A **572** (2007) 1007.
[13] S. Hojo, T. Honma, Y. Sakamoto, S. Yamada, Nucl. Instrum. Meth. B **240** (2005) 75.
[14] T. Furukawa *et al*., Med. Phys. **34**, 1085 (2007).
[15] T. Furukawa *et al*., Medical Physics, **37**, 4874-4879, (2010).
[16] T. Furukawa *et al*., Medical Physics, 37(11), 5672-5682, (2010).
[17] T. Furukawa *et al*., Nucl. Instrum. Meth. B **266** (2008) 2186-2189.