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Original paper

Scanned carbon-ion beam therapy throughput over the first 7 years at National Institute of Radiological Sciences

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ABSTRACT

Introduction: In the 7 years since our facility opened, we have treated > 2000 patients with pencil-beam scanned carbon-ion beam therapy.
Methods: To summarize treatment workflow, we evaluated the following five metrics: i) total number of treated patients; ii) treatment planning time, not including contouring procedure; iii) quality assurance (QA) time (daily and patient-specific); iv) treatment room occupancy time, including patient setup, preparation time, and beam irradiation time; and v) daily treatment hours. These were derived from the oncology information system and patient handling system log files.
Results: The annual number of treated patients reached 594, 7 years from the facility startup, using two treatment rooms. Mean treatment planning time was 6.0 h (minimum: 3.4 h for prostate, maximum: 9.3 h for esophagus). Mean time devoted to daily QA and patient-specific QA were 22 min and 13.5 min per port, respectively, for the irradiation beam system. Room occupancy time was 14.5 min without gating for the first year, improving to 9.2 min (8.2 min without gating and 12.8 min with gating) in the second. At full capacity, the system ran for 7.5 h per day.
Conclusions: We are now capable of treating approximately 600 patients per year in two treatment rooms. Accounting for the staff working time, this performance appears reasonable compared to the other facilities.

1. Introduction

Carbon-ion beam treatment has been slowly growing worldwide. A total of 11 carbon-ion beam treatment centers were operating in 2017. The Heidelberg Ion Therapy Center in Germany began using carbon-ion pencil beam scanning (C-PBS) in 2009 and they obtained clinical gains from treating over 2300 patients [1–4]. The National Centre of Oncological Hadrontherapy (CNAO) in Italy also treated over 800 patients using C-PBS since 2012 [5,6]. Japan has five treatment centers, including our center in Chiba. Several facilities are under construction, including two more in Japan. We have performed passive scattering treatment for over 25 years, and initiated C-PBS treatment in 2011. Over the ensuing 7 years, we have treated approximately 2300 patients [7]. From our clinical experiences, clinical results in C-PBS were equivalent to those in the passive scattering treatment [8–12].

Our facility has one immobilization room, two simulation rooms (SIM1 and SIM2) and three treatment rooms (Room E–G). Our research activities were integrated into C-PBS [13–21]. The irradiation method is carbon-ion pencil beam raster scanning with phase-control [22], with beam energy controlled by an accelerator [23]. Treatment planning involves calculating carbon-ion beam dose distribution using relative biological effectiveness (RBE), and designing intensity-modulated carbon-ion therapy and 4D treatment plans [15]. Image-guidance systems are managed by the patient handling system (PTH), which includes a robotic arm treatment bed, immobilization devices, and related software to support the treatment workflow [24].

While proton PBS treatment was started earlier than carbon-ions at the Paul Scherrer Institute (PSI) in Switzerland [25] in the 90, and now over 20 proton beam facilities treated using PBS. Their research activities and clinical experiences were useful information to construct our facility [26,27].

As most treatment centers have less experience including respiratory gating with this system, we thought it would be valuable to share our experience and introduce our treatment workflow and

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Table 1
Operation from startup to current time in the NIRS new treatment facility.

Month	Year	Event
June	2010	Start installation of treatment equipment
May	2011	Start clinical trial without respiratory gating
November	2011	Complete clinical trial without respiratory gating
September	2012	Start routine treatment (Room E and F)
February	2015	Start clinical trial with respiratory gating (markerless tumor tracking)
August	2015	Complete clinical trials with respiratory gating
April	2016	Start operating at full capacity (Room E and F)
October	2017	Start routine treatment with markerless tumor tracking

throughput. Here, we summarize treatment workflow time in our center from facility startup to operation at full capacity.

2. Materials and methods

2.1. Facility startup to operation at full capacity

Table 1 shows operation from startup to operation of the C-PBS treatment facility at full capacity. Since we previously published our clinical experiences for the first year in 2011 [7], we will not repeat the details here.

With the cooperation of the vendors, it took about one year to start C-PSB treatment (May 2011) after the beginning of treatment equipment installation in June 2010.

All patients who received C-PBS treatment in the first clinical trials (November 2011) were followed up. We complied with all regulations prior to starting up Room F. Routine non-gated C-PBS treatment commenced on September 2012.

A clinical trial of respiratory gating was started in February 2015 [28]. It took about 4.5 years from the completion of the non-gated clinical trials to start respiratory-gated C-PBS treatment. The gating trial treated a total of ten patients using fluoroscopic-based markerless tumor tracking and was completed in August 2015 [8,9,28]. Then Room F, which had been used for research, was modified to meet legal requirements for clinical use, going online in March 2016. Since only Room E was used for treatment during this time, the treatment schedule was extended into the afternoon.

Beginning in April 2016, Room E and Room F were used for routine C-PBS treatment, including respiratory-gated treatment. The existing passive scattering beam facility is not used for treatment except for some cases such as eye treatment; most patients are treated at the new PBS facility.

Mean days of operation per year are 180 (except in 2011, when the figure rose to 280 days with shorter working hours due to the Tohoku earthquake). There are usually 4–5 working days per week. Approximately 1.5 months per year are dedicated to maintenance of all treatment rooms, during which treatment is not carried out.

2.2. Treatment workflow

Our treatment workflow includes the following five steps: (i) immobilization, (ii) planning CT, (iii) treatment planning, (iv) quality assurance (QA) and (v) treatment.

2.2.1. Immobilization

Since our treatment rooms have two orthogonal fixed-beam ports, the treatment couch can rotate to allow a greater range of beam angles (maximum ± 20°). If there are > 2 treatment couch rolling angles or patient positions, multiple immobilization sets are prepared. We usually assign 45 min for the immobilization procedure.

Table 2
Number of patients, and number of treatment fractions in protocol and averaged over all patients. Some treatment sites have different treatment protocols.

Treatment sites	Number of fractions	
	Under protocols	Averaged over all patients
Prostate	16,12	12.3
H&N	16,12	16.0
B&S	16,12,8	14.9
Uterus	20,16	19.1
Lacrimal gland	16,12	12.4
Kidney	4	4.0
Esophagus	12,8	10.2
Breast	4	4.0
Rectum	16,12	15.8
Lung	16,12,4,1	4.5
Pancreas	12,8	11.8
Lymph node	16,12	12.2
Liver	12,4,2,1	3.2
Average		10.8

2.2.2. Planning CT

Two different CT scanners are used, a 320 multi-slice CT (Aquilion One Vision edition, Toshiba Medical Systems, Japan) in SIM1, and a large-bore 16 multi-slice CT (Aquilion LB, Toshiba Medical Systems) on rails in SIM2. The CT couch can be rotated at the same angle as that planned for treatment [29]. We assign 15 min for prostate and 30 min for other treatment sites. If this time assignment is expected to be insufficient, we assign twice the time.

2.2.3. Treatment planning

We routinely use a commercial treatment planning system (TPS) [15] and in-house 4D software to perform 4D dose calculations [30]. When multiple planning CT data sets with different couch roll angles and/or different patient position (supine and prone) (often used for head and neck [H&N] and lung) and/or 4DCT data sets (thoracoabdominal regions) are used, treatment planning time may increase. The number of treatment fractions for respective treatment sites is summarized in Table 2 [31–37].

2.3. Quality assurance

After approval of the treatment plan, patient-specific QA and daily QA (accelerator [synchrotron] and particle beam scanning system and imaging and robotic couch systems) are usually completed no later than one day before starting treatment [38].

2.4. Treatment

For treatment, the patient enters the preparation room and changes into an examination gown. The patient then enters the treatment room and lies on the treatment couch. The patient is then fixed by immobilization. The treatment couch is automatically put into the treatment position. Patient setup is performed by 2D-3D auto-registration function using a pair of radiographs and planning CT data [39]. The patient setup time for the thoracoabdominal region is longer than that for other treatment sites, because it requires registration of both bony structures and tumor positions to the reference positions in consideration of the beam range. However, not all thoracoabdominal patients are ideally registered at the first instance and require adjustment. If tumor positional difference was within the setup margin, patient position was shifted to register the tumor position to the reference position. While if tumor positional difference was larger than the setup margin, patient sit up in the treatment couch and retried to patient setup. This is a different setup concept from that of photon beam therapy. Patient setup time includes double check time by the oncologist (~1 min each).

The irradiation then commences according to the plan. After the