1. Introduction

Today, about one third of the Japanese persons who die will succumb to cancer of one form or another. To address this problem, the Japanese government is investing considerable sums in the “3rd-Term Comprehensive 10-Year Strategy for Cancer Control.” Preventive measures, early discovery, and early treatment are needed to eradicate the disease. The three major treatment methods are surgery, anticancer drugs, and radiation therapy. Of the three, radiation therapy has been found to be able to relieve the patient’s physical burden and provide a high quality of life (QOL). As a result, particularly in Japan’s rapidly aging society, attention is beginning to focus on heavy-ion radiotherapy as an effective treatment method.

One heavy-ion radiotherapy for cancer treatment is irradiating cancerous cells with carbon ion beams whose speed approaches that of light. This is a very powerful way to destroy the cells and has been shown to be effective in treating cancer than methods such as x-ray treatment do not handle well. The method makes it possible to irradiate the cancerous cells in a pin-point manner, thus suppressing damage to normal cells. Consequently, it is considered to be a breakthrough treatment that can reduce the patient’s physical burden and minimize side effects. It also requires considerably fewer irradiations and shorter treatment time than other radiation therapy methods (x-ray, proton beam) and so is considered to have excellent potential for maintaining high QOL.

Many of the advanced technologies Toshiba has developed for its nuclear power business, including those for superconductors, nuclear fusion, and particle accelerators, are finding use in heavy-ion radiotherapy systems for cancer treatment.

Our superconducting and particle accelerator technologies made a major contribution to the “Higgs boson” discovery of 2013. And our heavy-ion radiotherapy systems for cancer treatment are leading examples of our new business creation efforts to apply advanced technologies developed in the energy business field to the medical field.

In 1994, the heavy-ion radiotherapy system Heavy Ion Medical Accelerator in Chiba (HIMAC) was installed at the NIRS, and in 2010, a new treatment facility was completed there with the aim of materializing next-generation cancer treatment methods.

We participated for over 20 years in the development of the NIRS-HIMAC, which enabled us to cultivate the technologies needed for heavy-ion radiotherapy systems. Even today, Toshiba and NIRS continue to work closely together to further develop and upgrade HIMAC.

In addition, in fiscal 2011, Toshiba received an order from the Kanagawa Cancer Center, an ancillary establishment of Kanagawa Prefectural Hospital Organization, for equipment for its heavy-ion radiotherapy...
facility i-ROCK. This is the first such facility whose construction we have been involved in, and development work is currently in progress with the aim of starting cancer treatments there in fiscal 2015.

This report describes the differentiated technologies we have developed that the aforementioned facilities have adopted, as well as our latest technologies targeting the development of next-generation heavy-ion radiotherapy systems.

2. Differentiated technologies supporting heavy-ion radiotherapy systems

The following outline of a heavy-ion radiotherapy facility is based on the bird’s-eye view of i-ROCK in Figure 1.

Heavy ions used in treatments are carbon ions generated in an ion source. After the ions are generated, a straight linear accelerator accelerates them to about 10% of the speed of light and sends them to the main accelerator, a ring synchrotron accelerator. They are then accelerated to about 70% of the speed of light while orbiting approximately a million times in 0.7 seconds inside the primary ring of the accelerator, extracted from the accelerator, and guided to the treatment rooms by a high-energy beam transport system. In the Figure 1 example there are four treatment rooms, each having either a horizontal or vertical fixed irradiation port. The range of the therapeutic radiation to the patient, i.e., the distance the irradiation beam must cover to reach the patient, is changed by changing the energy of the carbon ion beam. The irradiation beam dose is controlled by changing the number of particles in the beam.

The next section discusses our differentiated technologies that have been incorporated into heavy-ion radiotherapy systems.

2.1 High-speed 3D scanning irradiation

One of the technologies is a high-speed three-dimensional (3D) scanning irradiation method we have developed in conjunction with NIRS. Methods for irradiating cancer lesions with a beam are shown in Figure 2; (a) is the high-speed 3D scanning method and (b) is a conventional broad-beam method shown for comparison.

With the 3D method a narrow irradiation beam is directed to the treatment room at high speed so that it scans cells and irradiates those having a cancerous lesion shape. By contrast, with the broad-beam method the irradiation beam is expanded once, after which a multileaf collimator or compensating filter is used in the scanning and irradiating of cells with cancerous lesion shapes. The main advantages of the 3D method are as follows.

(1) High efficiency
No part of the irradiation beam is wasted since, unlike with the broad-beam method, the beam does not need to be partially cut in accordance with the shape of the cancerous lesions.

(2) High irradiation accuracy
The beam scans both vertically and horizontally, enabling it to accurately irradiate cancerous lesions with complex shapes.

(3) High degree of freedom
The beam can be controlled to accurately irradiate cancerous lesions even for parts that move slightly with the patient’s breathing.

(4) Simple device configuration
The number of system parts is reduced since, unlike with the broad-beam method, there is no need for components such as a collimator and compensation filter.
2.2 Patient positioning system

In the treatment room, it is necessary to position the patient accurately prior to the radiation treatment in order to accurately irradiate the cancer lesions. It is also important to position the patient accurately in a minimal amount of time to reduce the patient’s physical burden and achieve efficient operation, since the time required for positioning accounts for much of the use time of the treatment room. We achieved this by adopting a patient positioning system using a robot arm type treatment table. The robot arm is a horizontal multi-joint type with seven joints, providing a large range of motion. This makes it possible to ensure a large free space around the patient table so that the x-ray apparatus can be easily installed and the medical staff can move around freely. The positioning system also performs automatic position correction based on positional displacement between reference images and images taken by the x-ray apparatus, using images previously captured by a computed tomography (CT) device. This allows positioning to be performed quickly and accurately.

2.3 Treatment information system

One of the software features for heavy-ion radiotherapy systems is a treatment information system that supports the large medical staff involved in treatment and enables the work to be carried out smoothly. The system is intended to improve staff operational efficiency by allowing staff members to share information with patients in real time from the time they sign in at the reception desk to the time they undergo radiation treatment. It also has a function for scheduling greater numbers of patients for treatment at optimal times, an important benefit for a wide variety of patients with different treatment sites and treatment plans. Treatment information systems are considered to be essential in order to achieve a safer and more efficient heavy-ion cancer therapy in the future. Currently our treatment information system called Treatment Management System (TMS) is being used to manage the treatment of about 1,000 patients annually in five treatment rooms at NIRS. The number of treatment rooms will be increased to six in the near future.

2.4 Rotating gantry with superconducting magnet

A rotating gantry that rotates irradiation ports, including those for the latest high-energy beam transport systems, is an apparatus that makes it possible to irradiate with heavy ions from 360° in any direction. This provides a much wider therapeutic range than can be obtained merely by irradiating from horizontal or vertical fixed ports. The rotating gantry is expected to enable the number of target treatment sites to be increased, at the same time reducing the physical burden on patients by eliminating the need to incline them. Of particular note is that it makes it possible to expand treatment systems by means of a method called intensity modulation ion beam irradiation, in which irradiation is performed by adjusting the intensity in multiple directions on one slice plane.

Rotating gantries are coming into widespread use in proton beam cancer treatment facilities and are expected to be applicable to heavy-ion beam facilities as well. Some have already been constructed overseas, but their bulkiness and weight (600 t) will inhibit the spread of their use. Since heavy ions have larger mass than protons, they increase the curvature of the deflection electromagnet for the beamline that guides the particles to the irradiation port. As a result, it becomes necessary to have very heavy equipment in a large structure to provide the beamline.

In 2013 Toshiba received an order for construction of a rotating gantry chamber for treatment room G in the new treatment facility at NIRS. One of its features is the use of a superconducting magnet to reduce the gantry weight. In Figure 3, a schematic of the rotating gantry is shown in (a) and the superconducting magnet mounted to it is shown in (b). Our own technologies are used in the magnet, such as a winding technique to achieve a particular shape for it and the use of a cooling technique that does not use liquid helium or any other refrigerant. This enables the gantry weight to be reduced to only about half that of conventional rotating gantries. The room is currently under construction and 2016 is the target year for the start of treatments.

3. Applications to actual facilities

3.1 New treatment facility at NIRS

The Research Center Hospital for Charged Particle Therapy at NIRS is leading the world in terms of both facilities and medical care in heavy-ion radiotherapy.

Its principal facility HIMAC is a heavy-ion radiotherapy system (particle accelerator system) built in order to carry out the world's first heavy-ion radiotherapy for treating cancer. Since it went into operation in 1994, more than 8200 cancer patients have been treated there.

In addition to working together with NIRS to construct HIMAC, Toshiba provided services (mainly relat-
ed to maintenance) to support construction of the new treatment facility, which was completed in 2010. Since one of the missions of NIRS is to further improve and disseminate treatment technologies, the new treatment facility incorporates the highly advanced technologies that have been described in Chapter 2 above. Basement 2 in the building includes a treatment area, three treatment rooms, two CT simulation chambers, and a fixed equipment room. Among those three treatment rooms, horizontal and vertical fixed ports are provided in rooms E and F; treatments started in room E in May 2012 and in room F in September that year. Both are rooms for high-speed 3D scanning irradiation treatment and include the patient positioning and treatment information systems mentioned earlier (Figure 4). By the end of fiscal 2013, around 430 cancer cases had been treated in the rooms. The next step will be to add a rotating gantry chamber to room G, and further extensions can be expected after that.

3.2 Kanagawa Cancer Center

Construction of the i-ROCK facility is in progress at Kanagawa Cancer Center; when it is completed, it will be the fifth ion-beam radiotherapy facility to be established in the country. In December 2011, Toshiba received an order for a set of heavy-ion beam radiotherapy equipment for i-ROCK. There will be four treatment rooms in all, two having a chamber with horizontal and vertical fixed ports and two having one with horizontal fixed ports. All will be compatible with both the high-speed 3D scanning irradiation method and the broad-beam irradiation method.

The flow of heavy-ion radiotherapy treatment starts with diagnosis and continues with treatment planning, treatment, prognosis and observation. To achieve an easy-to-use system incorporating all of these, Toshiba manufactures hardware for particle accelerators, irradiation systems, treatment room equipment, diagnostic equipment, etc. We are also more fully developing technologies used at NIRS, aiming for coordination with software for systems such as those for treatment information and treatment planning. Equipment for the i-ROCK building (Figure 5) is now being delivered,

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**Figure 3.** Rotating gantry with superconducting magnet. Applying a superconducting magnet reduces gantry weight.

**Figure 4.** Treatment room in new treatment facility at NIRS. The room for high-speed 3D scanning irradiation treatment includes a treatment information system and a patient positioning system using a robot arm type treatment table.

**Figure 5.** Panoramic view of i-ROCK. i-ROCK is built on Kanagawa Cancer Center site; treatments scheduled to start in fiscal 2015.
4. Efforts aimed at next-generation systems

In this chapter, the efforts Toshiba is making to develop new technologies for materializing next-generation heavy-ion radiotherapy systems and disseminating their use are described.

4.1 Developing new technologies for next-generation systems

4.1.1 Coping with moving organs

Toshiba plans to implement a high-speed scanning system with breathing synchronization to treat affected areas in organs that move along with breathing, such as the lungs and liver. Two breathing synchronization schemes (external and internal) can be used for this purpose.

With the external scheme, a light emitting diode (LED) attached to the patient’s body converts reciprocating motions accompanying breathing into signals, then the beam irradiation is performed as the gate for a set time interval threshold. Since the aim with irradiation systems in general is to achieve sufficiently high speed, the irradiation dose is kept constant in the irradiation region even if the affected area is moving.

With the internal scheme, beam irradiation is performed while body motions are being detected with x-ray fluoroscopic images. During the radiation treatment, x-ray movements are used to pinpoint the affected areas in real time and ensure they fall within the treatment area, without using the position of a marker embedded in the body or the marker itself. An x-ray system of this type is shown in Figure 6. The system, which shows x-ray images as moving images, comprises a pair of flat panel detectors (FPD) that detect the x-rays from a pair of under-floor oblique x-ray irradiation devices.

The NIRS plan is to carry out clinical trials of scanning irradiation through the use of breathing synchronization, and then use the technique as state of the art medical practice. i-ROCK has a system using this technique.

4.1.2 Development of laser ion sources

A plasma ion source called electron cyclotron resonance (ECR) is currently being used to generate the carbon ions required for therapeutic irradiation. We are working towards developing laser ion sources (LIS) for the next generation. One such source irradiates a solid carbon target with a laser to produce carbon ions. This makes it possible to produce the 6-valent carbon ions needed for treatment without the type of charge conversion device needed for ECR. This technique also makes it possible to obtain a dense group of ions, thereby enabling both the size of the device and the energy it consumes to be reduced.

We have already completed an in-house proof-of-principle test for LIS, and since 2014 we have been working together with the Yamagata University School of Medicine on empirical research closely related to the aspects of actual devices, including their reliability.

4.1.3 Adoption of superconducting technology

Advances in superconductivity technology for deflection electromagnets have already enabled rotating gantries to be reduced in size, and ways to apply this technology to primary accelerators is being studied as a next step. Using superconducting in deflection and focusing electromagnets has enabled the circumference of primary accelerator rings (currently about 60 m) to be cut almost in half. However, it still takes a long time to design heavy-ion radiotherapy systems, including their cooling equipment, and it will be important to apply superconductivity technology to them to reduce their size and increase their dissemination. In the development of superconducting magnets, it is very favorable to use niobium titanium wires in semiconductors such as those for magnetic resonance imaging (MRI) and silicon single crystal pulling. Thus, with an eye on the future, we are also studying applications for high-temperature superconductive wires.

4.2 Efforts to increase dissemination

As has been described, our participation in the development of NIRS’s facilities has enabled us to cultivate needed technologies. It has also enabled the company to achieve full turnkey construction of i-ROCK. Through the experience gained in these development, equipment
design, construction, and testing activities, we are now developing a wide variety of state-of-the-art technologies to enact improvements such as shortened construction periods, rationalized adjustment tests, and reduced operating costs.

We are also carrying out studies with a view to applying the rotating gantry described in Chapter 2 so as to further disseminate systems and facilities throughout the country. The aim is to use it as an example dissemination model for next generation heavy-ion radiotherapy systems.

5. Conclusion

This paper described the latest technologies we are developing for its heavy-ion radiotherapy systems, as well as current technologies and the way they are used in actual facilities. The development of a wide variety of medical systems and techniques has made cancer a disease that is curable, and we believe that we will conquer it through appropriate preventive measures, early detection, and early treatment. In the years to come the company will strive to develop innovative technologies and facilities to promote the widespread use of heavy-ion radiotherapy systems both within and outside Japan, thus providing cancer treatment opportunities to countless numbers of people.

References


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