Development of Advanced Proton Beam Therapy System for Cancer Treatment

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*OVERVIEW: Proton beam*1 therapy is a type of radiotherapy that can provide tumors with a concentrated dose of radiation and is thought to cause fewer side effects. After many years' concentrated effort in the field of acceleration technologies, Hitachi has developed one of the most advanced proton beam therapy systems in the world. This system has been installed at the Proton Medical Research Center (PMRC) at the University of Tsukuba where it is used exclusively for providing treatment as a hospital facility, and it has already produced encouraging results. We are also building a proton beam therapy system at The University of Texas M.D. Anderson Cancer Center, which is the one of the most famous cancer center in the whole of the United States. By combining precise irradiation with short treatment times, Hitachi's proton beam therapy system allows patients to be treated without the pain normally associated with radiotherapy, and with fewer side effects. In some cases it allows treatment to be provided on an out-patient basis over a period of a few weeks, which is just the sort of treatment needed in today's ageing society. We have also developed a proton beam therapy planning system that allows treatment plans to be formulated accurately and quickly, resulting in an overall system that is both highly reliable and easy for medical staff to use.*

INTRODUCTION

IN Japan's ageing society, it is becoming more important to search for better ways of treating the forms of cancer with the highest mortality rates. Cancer can be treated with a range of techniques including chemotherapy, surgery and radiation therapy. Of these, radiation therapy is the least invasive and not as likely to impair the patient's QoL (quality of life) after treatment.

Various types of particle beams have been investigated in the field of radiation therapy, and attention has recently been focused on the use of proton beams and carbon beams. In particular, proton beam therapy is likely to become a popular technique

*1 A group of protons (hydrogen nuclei) all moving in step with each other.

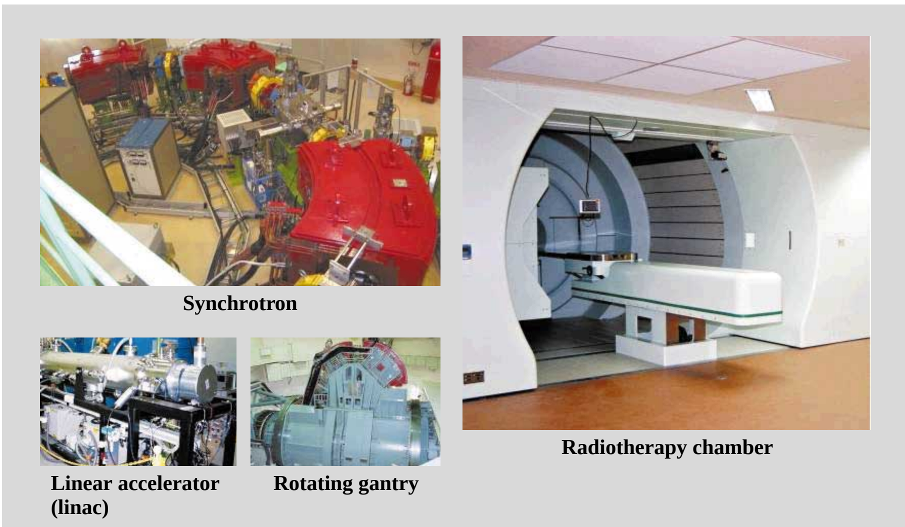

Fig. 1—Hitachi's Proton Beam Therapy System.
This system is installed at the PMRC at the University of Tsukuba. The parts shown here are the synchrotron, which accelerates a beam of protons to 250 MeV, the linear accelerator (linac), which supplies the synchrotron with a 7 MeV proton beam, the rotating gantry, from which patients can be irradiated from any angle, and the radiotherapy chamber.

because it is an economical way of providing therapeutic effects. Unlike X-rays or neutron beams, most of the energy carried by a proton beam is deposited in a peak dosage region (called the Bragg peak) just before the stopping area (the maximum range traveled by the protons in the body). This localized concentration of energy can be exploited to provide a large dose of radiation to the target cancer cells while minimizing its effects on the surrounding normal tissue.

To address the need for proton beam therapy, Hitachi has brought together the technologies it has already developed in the fields of accelerators, particle beam control, radiation diagnostics and image processing, resulting in the completion of two systems: an accelerator system at The Wakasa Wan Energy Research Center (which is used for various purposes including medical research)[1], and a proton beam therapy system at the Proton Medical Research Center (PMRC) at the University of Tsukuba[2] (see Fig. 1). We are also building a proton therapy system at The University of Texas M.D. Anderson Cancer Center, which is one of the world's largest cancer centers.

This paper presents an overview of Hitachi's proton beam therapy system with particular reference to the system at the PMRC at the University of Tsukuba, and discusses the steps we are taking to develop a treatment system that is even more precise and easy to use.

FEATURES OF HITACHI'S PROTON BEAM THERAPY SYSTEM

Overall System is Compact and Reliable

In proton beam therapy, the depth to which the radiation penetrates can be controlled by changing the proton beam energy, allowing the dose to be concentrated on the affected part (target). To exploit this characteristic as a means of supplying a precise dose of irradiation to the target and minimizing the irradiation of surrounding normal tissues, a proton beam therapy system must produce a proton beam whose position and energy are highly stable. On the other hand, if a system of this type is to be used by people without specialist knowledge of beam technology, the system must be easy to operate. By taking these conditions into account, we have developed a proton beam therapy system consisting of a compact synchrotron*2 with the maximum energy of 250 MeV*3, an irradiation nozzle that shapes the

*2 Synchrotron: A type of charged particle accelerator that accelerates particles to high energies of several hundred or more MeV.
*3 eV (electron volt): A unit of energy equal to the energy gained by a proton when it is accelerated by a potential difference of one volt. An MeV (mega electron volt) corresponds to one million eV.

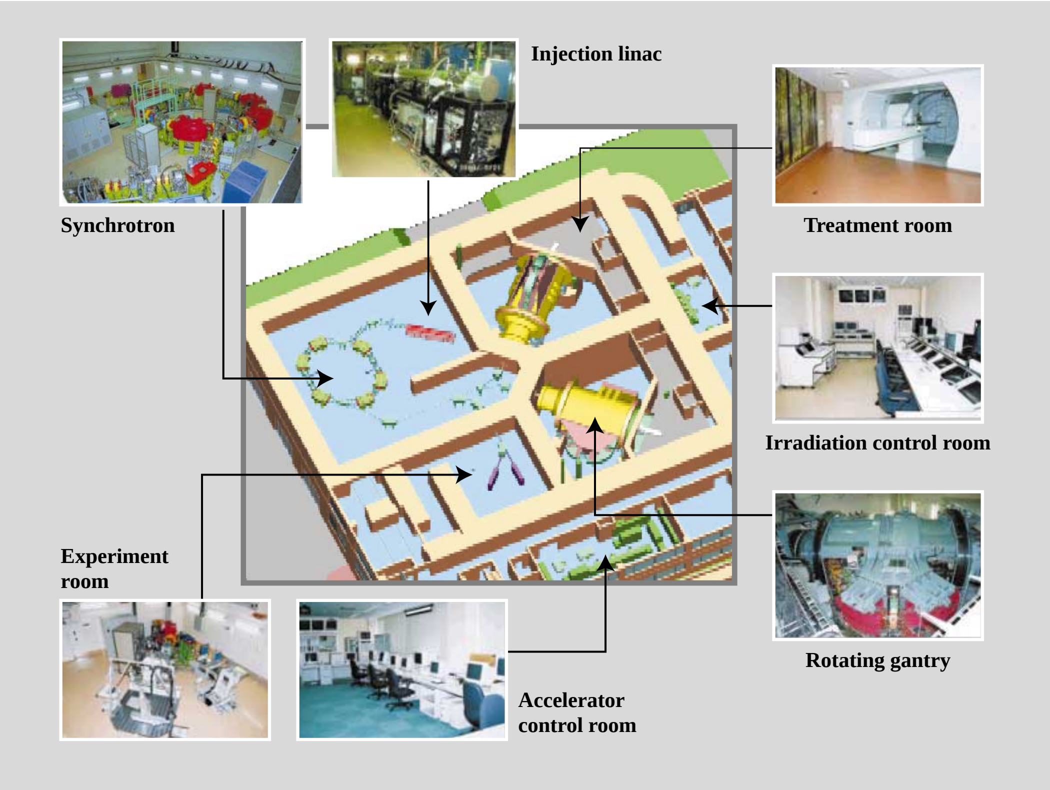

Fig. 2—Overall Configuration of Proton Beam Therapy System at the PMRC at the University of Tsukuba.
This system consists of an accelerator (comprising an injection linac and a synchrotron), two treatment rooms with rotating gantries, an experiment room, and a control room. The entire system is installed in a 40×50 m building.

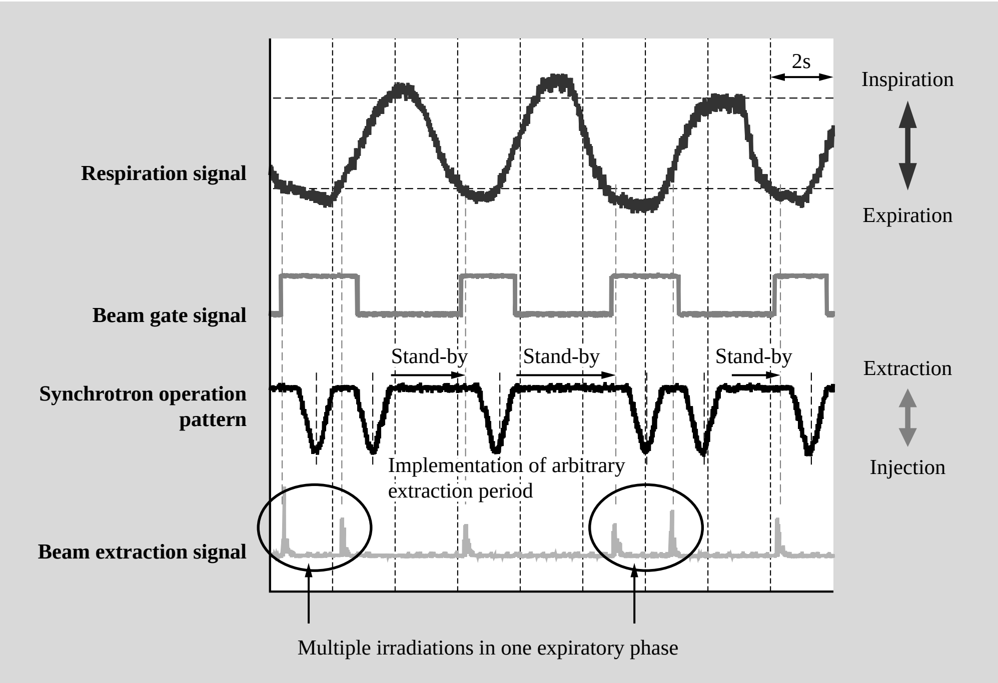

Fig. 3—Irradiation with Breathing-synchronized System.
A beam gate signal (center) is generated at a fixed phase in the respiration signal (top) and is used to operate the synchrotron, causing the proton beam to be emitted from the synchrotron (bottom). In this way it is possible to synchronize the irradiation with a respiratory phase.

proton beam to the shape of the target, and a rotating gantry on which this irradiation nozzle is mounted and which can rotate through ±180° around the patient. The first system of this type was built at the University of Tsukuba's PMRC and was commissioned in September 2001 (see Fig. 2). Since then it has operated without any hitches, and we have confirmed that it produces a highly stable beam with high reproducibility — for example, the variation of the beam position applied during treatment is within 0.5 mm. Furthermore, we have confirmed that the synchrotron produces a very low level of radioactivity. As a result, it is possible to enter the accelerator room just a few minutes after it has stopped operating, allowing daily checks and maintenance to be performed quickly and easily.

In the system at the PMRC at the University of Tsukuba, the 250 MeV synchrotron and irradiation nozzle allow the treatment of targets at depths of up to about 30 cm inside the body. It is also possible to irradiate targets measuring up to 20 cm in diameter. The rotating gantry allows therapeutic radiation to be supplied from various angles, and together with the respiration synchronous irradiation system described below, this system is able to fulfill a diverse range of treatment needs.

Advanced Synchrotron and Respiration Synchronous Irradiation System

Hitachi's proton beam accelerator system employs a synchrotron with a variable repetition rate using a linac as the injector. Using a technique called RF-driven slow extraction[3)], which was developed by Hitachi, the synchrotron accelerates and extracts protons with a repetition period of 2–3 seconds. This extraction method allows the proton beam to be turned on and off at high speed, resulting in the dose rate with good stability and repeatability that is essential for medical equipment. An important requirement for proton beam therapy is that the irradiation is delivered in accurate synchronization with the patient's breathing in order to eliminate the effects of organ movements that accompany respiration. In our system, the radiation is synchronized with the expiratory phase of respiration. To achieve this, the synchrotron is operated with a variable repetition rate and irradiation is performed in synchronization with the patient's breathing. This technique has already been used in practice. By operating the synchrotron with a variable period, it is possible to perform irradiation with the proton beam with high efficiency while allowing the patient to continue breathing normally. Our proton beam therapy systems are the most advanced ones in the world that successfully use this mode of operation in practical applications (see Fig. 3).

Irradiation Nozzle

In the irradiation nozzle, the dose distribution of the proton beam obtained from the accelerator is expanded in the lateral direction by using the double scatterer method or the wobbling method and is expanded in the depth direction (i.e., energy direction)

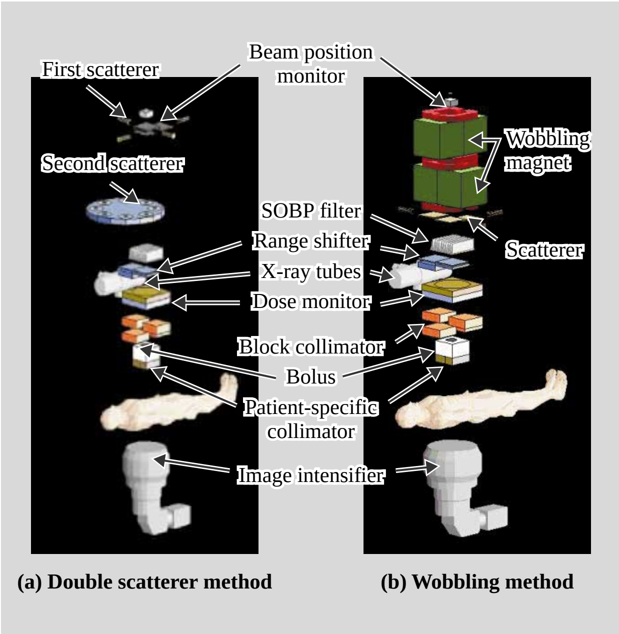

Fig. 4—Configuration of Two Types of Irradiation Nozzle.
Two expanding methods of the proton beam are shown.
(a) Double scatterer method
A pair of scatterers expands the proton beam in the lateral direction and an SOBP filter expands the proton beam in the depth direction. These components are used for making the irradiation field precise and for monitoring the dose rate and/or patient's position.
(b) Wobbling method
A pair of wobbling magnets is used instead of the first scatterer of type (a).

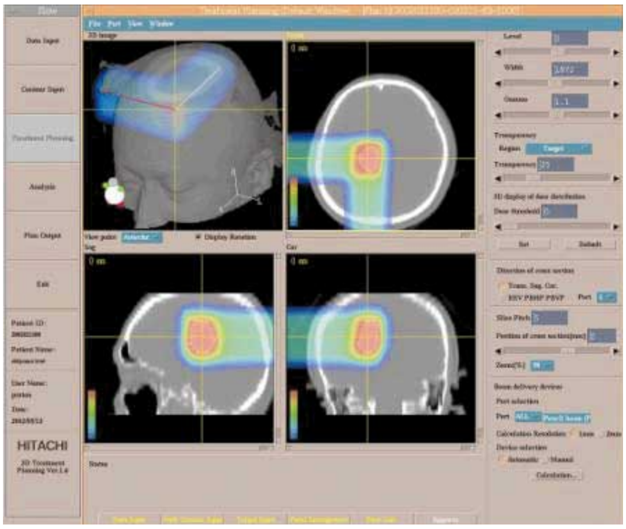

Fig. 5—Screenshot of Proton Beam Therapy Planning System.
This example shows the calculation of the dose distribution for two-port irradiation of the head. The dose distribution is shown superimposed on CT scans. A large dose is delivered to a region inside the patient's head, showing that it is possible to concentrate the irradiation on a target.

by using an SOBP (spread-out Bragg peak) filter, and is then shaped to match the shape of the target (see Fig. 4). The double scatterer method involves using two scatterers whereby the beam that has been expanded by the first scatterer is further expanded by the second scatterer, thereby forming a flat distribution. In the wobbling method, the beam that has been expanded by the scatterer is scanned in a circular shape by a magnet to form a flat distribution. Hitachi is experienced in the use of both methods, and has also established methods for designing the apparatus and evaluating its dose distribution.

Proton Beam Therapy Planning System

The proton beam therapy planning system plays a crucial role in determining the course of treatment by proton beam therapy. This system is used to formulate the most effective irradiation plan for concentrating the required dose on the affected part (target). This involves determining the irradiation angles to which the rotating gantry should be set for multi-port irradiation (i.e., irradiation from multiple directions) and the specific collimator and bolus shapes to be used for each patient as shown in Fig. 4 so as to arrive at a dose distribution that minimizes the damage inflicted on normal tissue. Hitachi has produced and installed proton beam therapy planning systems for the PMRC at the University of Tsukuba and The Wakasa Wan Energy Research Center. A screenshot of the proton beam therapy planning system is shown in Fig. 5.

This system conforms to the DICOM3.0 (Digital Imaging and Communication in Medicine 3.0) standard for medical imaging. It uses CT (computed tomography) images stored on an image server to determine the location of the target region, devises a suitable irradiation plan, and calculates the dose distribution. It also supports MRI (magnetic resonance imaging) equipment, and can be used to input the location of the target region. The proton range, the choice of radiation equipment, the shape of the collimator and the shape of the bolus are calculated automatically based on information such as the depth of the target obtained from CT images (and converted to a water equivalent thickness) and the shape of the target. The dose distribution is calculated based on the resulting irradiation parameters. It calculates the dose distribution by using the pencil beam scanning method, and to simulate dose distributions more realistically, it also takes account of the radiation equipment and the radiation scattering effects inside the patient. These calculations are performed at high speed—for a 10×10×10 cm volume, it takes about two minutes to calculate a 2 mm isotropic mesh. To allow the treatment plan to be evaluated, the system is provided with functions for producing dose distribution graphs, DVH (dose volume histogram) displays and the like, and the resulting plans can be output in various ways such as DRR (digital reconstruction radiography). In the future, we plan to reflect the experience gained in providing treatment by developing a user interface that is even more flexible and easy to use, and to improve its efficiency with systematic optimization algorithms.

PROTON BEAM THERAPY IN PRACTICE

Hitachi's proton beam therapy system was delivered to the University of Tsukuba's PMRC as a specialist facility which is also used for medical treatment. From September 2001 through February 2002 it was subjected to clinical trials to confirm that it provides safe treatment. Once the system had passed these tests, a total of 250 patients were treated in the period up to July 2003. The respiration synchronous irradiation system has successfully facilitated the advanced treatment of organs such as the liver and lungs that occupy about half of the body trunk. In addition, we have confirmed that the system provides therapeutic effects in almost all parts of the body, including the prostate and esophagus.

Although the irradiation time required for each session of treatment was initially 30 minutes or more, we eventually found that this time can be cut to about 10-20 minutes, thereby further reducing the burden on patients. Since this allowed us to increase the throughput, we became able to treat more patients. The number of new patients being accepted for treatment per month is still increasing gradually, and has now reached about 20.

In addition to the PMRC at the University of Tsukuba, Hitachi has installed a multi-purpose proton beam system at The Wakasa Wan Energy Research Center in Fukui Prefecture in the western part of Japan, where it is used for studying cancer treatments with a proton beam of up to 200 MeV. We are also installing a proton beam therapy system at The University of Texas M.D. Anderson Cancer Center, which we are hoping to commission in December 2005. At present, we are making progress with the equipment design, production and facility installation.

FUTURE AIMS

Proton beam therapy systems have already been installed in several facilities both in Japan and abroad. As these systems become more widespread, they are likely to require further refinement and enhancement to respond to the needs of medical staff. In particular, it will be essential to continue working towards irradiation methods that allow the dose distribution to be controlled with the ultimate levels of precision and efficiency, and to develop irradiation equipment that implements these methods.

Over the last few years, research has been progressing into beam scanning methods (where the proton beam is deflected by a varying magnetic field to make it cover the entire area of the target), and further study is required in this area. We will also examine ways of increasing the system throughput by reducing treatment times so as to reduce the burdens both on medical staff and on patients and allow even greater numbers of patients to be treated. For this purpose, it is particularly desirable to develop and standardize better methods for positioning the equipment during irradiation, and to develop a precise multi-leaf collimator that does not have to be produced separately for each patient.

CONCLUSIONS

We have discussed Hitachi's proton beam therapy system with particular reference to the system installed in the Proton Medical Research Center at the University of Tsukuba.

The work to refine and enhance this system as it becomes more widespread sits astride the boundary between the fields of medicine and engineering. At Hitachi we aim to continue making even closer links between medical and engineering technologies in this field, and to develop a proton beam therapy system that is even more accurate and easy to use.

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