World-first Proton Pencil Beam Scanning System with FDA Clearance

—Completion of Proton Therapy System for MDACC—

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OVERVIEW: The proton therapy facility constructed by Hitachi at the M. D. Anderson Cancer Center in Texas in the USA has been completed and the four treatment rooms are now in use. Proton therapy has attracted attention as a form of radiotherapy that can concentrate irradiation dose on the tumor with minimal effect on the surrounding healthy tissue. Use of scanning irradiation systems, which represent the latest technology, is expected to improve the quality of treatment and therefore plans are in progress around the world to install these systems. The facility described here commenced its scanning irradiation treatment on May 19 2008, making it the first in the world to use a commercial scanning system with FDA clearance.

INTRODUCTION

PROTON therapy is a form of cancer radiotherapy. Protons accelerated to high energy by an accelerator pass through the treatment device and are applied to the patient. Demand for proton therapy has been growing in recent years because of its ability to target

(a) (b) (c)

Fig. 1—Overview of Proton Therapy Facility at M. D. Anderson Cancer Center (MDACC) (left), Rotating Gantry Treatment Room (top right), and Synchrotron Accelerator (bottom right).
An overview of the proton therapy facility at the M. D. Anderson Cancer Center is shown on the left. The facility consists of an underground synchrotron accelerator (bottom right) and four treatment rooms where the proton beam generated by the accelerator is used for treatment. The equipment was manufactured and commissioned by Hitachi, with the work being completed in September 2008.

the location of the cancer, resulting in fewer side effects compared to previous radiotherapy treatment methods that use X-rays.

As of fall 2008, proton therapy systems were in use at six sites in Japan and 21 sites outside Japan. There are also a number of plans in progress for the construction of new facilities in the world. Applying accelerator technology acquired by joining various accelerator project for research use, Hitachi was amongst the first to start developing proton therapy systems[(1),(2)]. This has included supplying a multi-purpose accelerator system[(3)] to The Wakasa Wan Energy Research Center and a proton therapy system[(4)] to the Proton Medical Research Center at the University of Tsukuba. In December 2002, an order for a proton therapy system was received from the M.D. Anderson Cancer Center (MDACC), one of the world's leading cancer treatment centers, and the system was handed over after commissioning of all equipment was complete in September 2008. The proton therapy system at MDACC consists of one scanning and three scattering treatment units. This article focuses on the scanning irradiation system in particular as it represents the leading edge of current technology.

PROTON CANCER THERAPY

Features of Proton Cancer Therapy

Proton cancer therapy uses a high-energy proton beam formed of protons accelerated up to 40 to 60% of the speed of light (corresponding to energies of 70 to 250 MeV).

Fig. 2 shows a graph comparing the dose distribution relative to depth into the body for protons with that for the X-rays used by previous radiotherapy techniques. The higher the dose, the greater the energy absorbed by the body tissue and the more cells are killed. Accordingly, effective radiotherapy can be achieved if the dose can be concentrated on the tumor to destroy the cancer cell while minimizing the dose in regions away from the tumor so as to keep side effects to a minimum. Whereas the intensity of X-rays falls gradually with the distance from the surface of the body, a characteristic of protons is that the dose has a peak where it delivers a high level of energy at a location deep in the body. This is called the Bragg peak. Because the depth in the body at which the Bragg peak occurs can be adjusted by controlling the energy of the proton beam, this allows the proton beam to be targeted at the tumor.

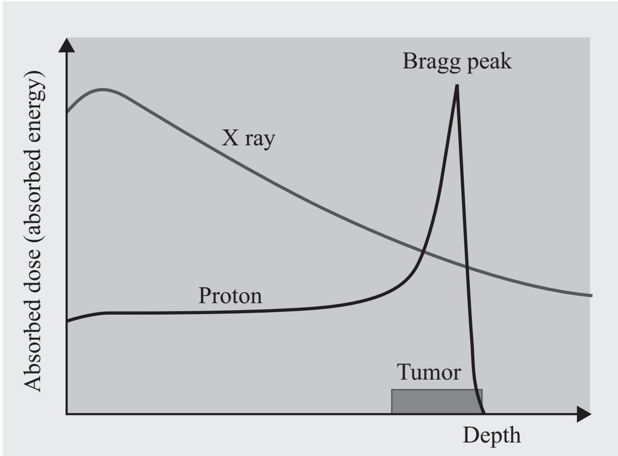

Fig. 2—Comparison of Absorbed Dose Distributions Relative to Depth for Proton Beams and X-rays.
A graph compares the absorbed dose distribution relative to depth into the body for proton beams and X-rays. The proton beam provides effective radiation treatment because it can be concentrated on a tumor located deep in the body.

Proton Therapy Techniques

Techniques for irradiation can be broadly divided into scattering and scanning methods. Fig. 3 shows the configuration of machines used for scattering and scanning respectively. The scattering method uses a scatterer consisting of a metal plate to spread the narrow beam generated by an accelerator then passes the beam through a hole in a collimator to form the target shape. In the depth direction, range modulating device expands and adjusts the energy distribution of the proton beam to form a region of uniformly high-dose region called an SOBP (spread out Bragg

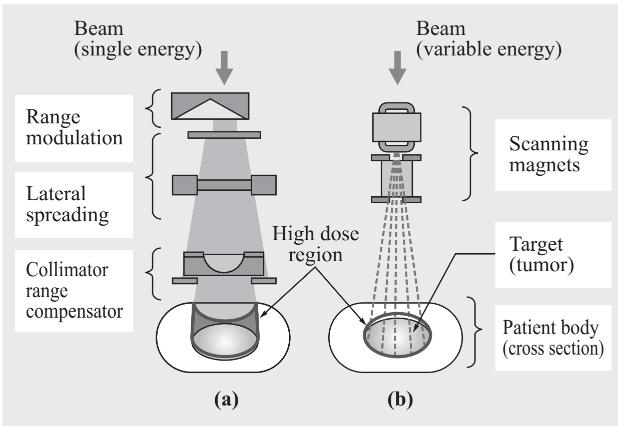

Fig. 3—Comparison of Equipment Configurations for Scattering and Scanning Methods.
In the scattering method (a), the beam, which spreads in the lateral and depth directions, is formed into the target shape laterally. In the scanning method (b), the beam is scanned in a three-dimensional pattern by the electromagnet and accelerator.

peak). Finally, a range compensator is used to form this high-dose region into the shape of the deepest part of the target. Because the thickness in the depth direction of the high-dose region formed by the scattering method (the SOBP width) is constant and equal to the maximum thickness of the target, it extends into the healthy tissue outside the tumor.

In the scanning method, the narrow beam from the accelerator is scanned over the three-dimensional target region. The target region is scanned three-dimensionally by using two scanning magnets to adjust the beam in the directions perpendicular to the beam direction and by progressively varying the accelerator energy to control the depth. In this way, a high-dose region is formed that matches the target shape. Fig. 4 shows example calculations of dose distribution for the scattering and scanning methods. This shows how the high-dose region (the region shown in red) formed by the scanning method is a better fit to the target shape (shown by the yellow line) than the scattering method.

The scattering method also requires a collimator and range compensator to be prepared for each irradiation field so that they can be matched to the shape of the patient's tumor and this carries the associated costs of manufacture, installation, and disposal. Because the scanning region produced by the scanning method is generated and set electronically in the form of operational setup data for the scanning magnets and accelerator, there are no components like the collimator or range compensator that need to be prepared individually for each irradiation field. Another advantage of scanning is that, because it does not use a scatterer or collimator, the level of secondary neutron production is minimized.

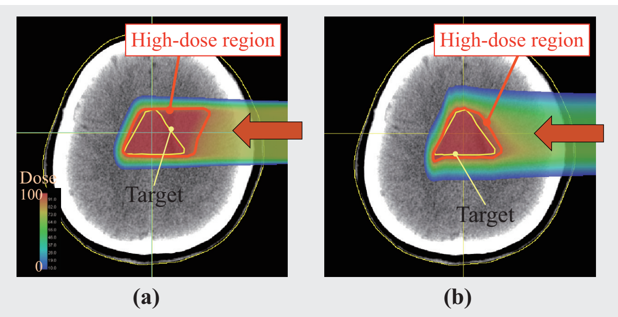

Fig. 4—Comparison of Dose Distribution in Scattering and Scanning Methods.
In the scattering method (a), the thickness of the high-dose region in the depth direction is constant and extends outside the target area. In the scanning method (b), the high-dose region is closely matched to the target area.

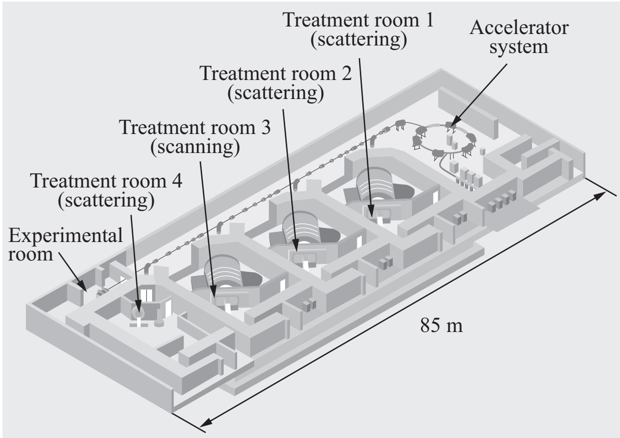

Fig. 5—Bird's Eye View of MDACC Proton Therapy System.
The facility uses a synchrotron as its beam source and has four treatment rooms and one experimental room. The treatment room with a rotating gantry uses the scanning method and the other treatment rooms use the scattering method.

HITACHI SCANNING IRRADIATION SYSTEM

Configuration of Proton Therapy System at MDACC

The MDACC is the largest cancer treatment center in the USA. Fig. 5 shows a bird's eye view of the proton therapy system. The facility consists of four treatment rooms and one experimental room. The proton beams for each room are supplied by a synchrotron accelerator system that has a 7-MeV linac as an injector. Protons accelerated up to a maximum of 250 MeV (60% of the speed of light) by the accelerator are delivered to the treatment rooms at a distance of several tens of meters away under the control of magnetic fields. The three treatment rooms closest to the accelerator have rotating gantry which allows the beam to be delivered to the patient from any direction (360°). The scanning nozzle that is an irradiation instrument used for the scanning method is installed on the rotating gantry in treatment room 3 and the other treatment rooms use scattering nozzles.

Scanning Nozzle

The proton beam from the synchrotron travels via the high-energy beam transport line and gantry beam transport line to the scanning nozzle. Fig. 6 shows the configuration of the scanning nozzle used at the MDACC. The unit has a length of about 3 m. The beam is bent by two scanning magnets in the X and Y directions perpendicular to the incident beam to direct it at a point in a 30 cm × 30 cm region. To reduce beam spread caused by scattering, the thickness of each device is kept as thin as possible. Similarly, to minimize scattering by air

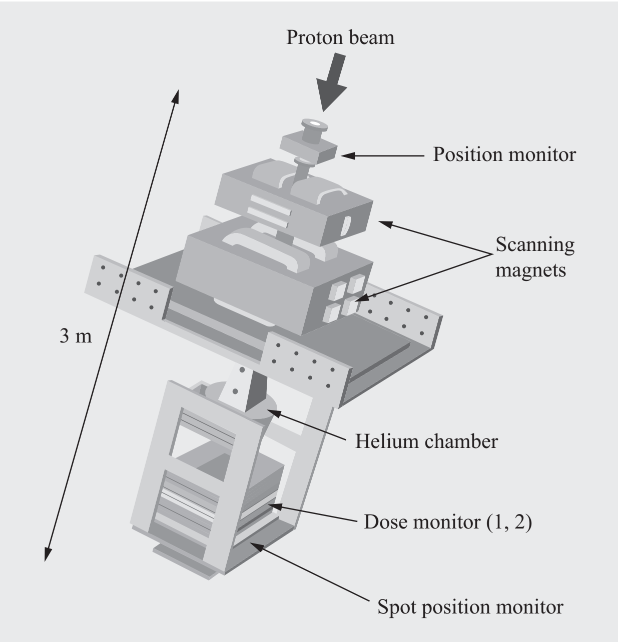

Fig. 6—Configuration of Scanning Nozzle.
The nozzle is approximately 3 m long. The scanning magnets bend the beam to scan a two-dimensional region. The dose monitor controls the treatment dose and the two position monitors monitor the beam position.

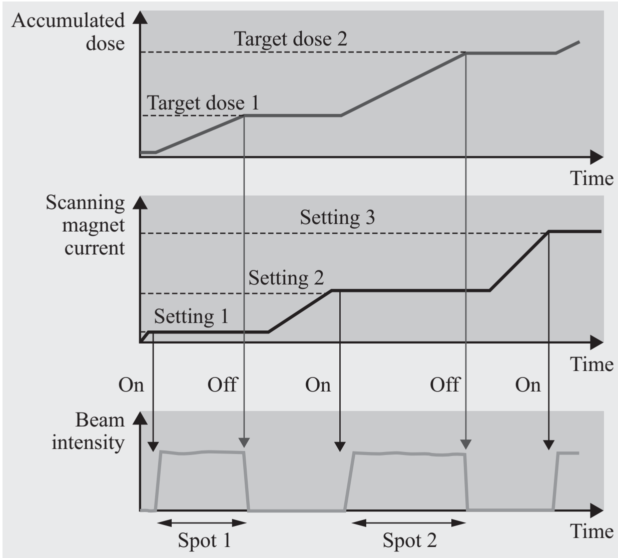

Fig. 7—Timing Chart for Spot Irradiation.
The system uses the discrete spot scanning method whereby the beam is applied to a particular spot until the accumulated dose reaches the set value. The beam is then turned off while the current to the scanning magnets is changed.

along the path of the beam, the beam passes through a sealed chamber filled with helium which has lower scattering effect. The beam size at high energies is approximately 5 mm.

Two dose monitors measure the amount of passing through the parallel plate ionization chamber. One of these, called the "main dose monitor," is used to control the dosage as explained in the following section. The other is called the "sub-dose monitor" and is used to monitor the dose. A beam position monitor located at the entrance of the nozzle and a spot position monitor located close to the irradiation surface measure the distribution of the passing beam in the multi-wire ionization chamber to check its position and size.

Spot Irradiation Control

The scanning method produces the desired dose distribution by using the beam to irradiate each individual small area (spot) within the target region with the appropriate dose for that spot. To irradiate a large number of spots in succession, a discrete spot scanning scheme is used whereby the beam is held in a fixed position while irradiating each spot and then turned off for the move to the next spot. As this technique does not move the beam to the next spot until it has confirmed that the current spot has received the required beam dosage, control of the dosage, beam position, and other parameters is relatively simple.

Fig. 7 shows a timing chart for spot irradiation. The progress of spot irradiation is controlled based on the dosage measured by the dose monitor. When the accumulated dose reaches the set value, the beam off signal is output to turn off the beam for that spot. Next, the current to the scanning magnets is changed to reposition the beam to the next spot. After this change in current completes, the signal to turn the beam on again is output and irradiation starts for the next spot. The beam progresses through the spots one at a time with irradiation typically lasting for 0.5 to 5 ms per spot and movement between spots, including the various checks, taking approximate 3 ms. Turning the beam on and off is handled from the synchrotron by the fast beam switching technique described later. By repeating this process, irradiation is completed for all spots that require a particular energy and then the synchrotron acceleration is set to generate the proton beam at the next energy level and spot irradiation continues. Treatment of typical tumors completes in about one minute.

Accelerator System

The scanning method requires a high level of operational control of the accelerator system used to generate the beam based on the progress of spot irradiation. The following sections describe the features of the Hitachi synchrotron system that make this possible.

(1) Beam extraction control

The discrete spot scanning scheme requires high-speed beam on/off control and good stability for the beam position and size. The key technology for achieving this is RF (radio frequency) -driven extraction[5]. The synchrotron beam follows a stable circulating orbit formed by a magnetic field. Beam extraction utilizes the phenomenon of resonance resulting from a nonlinear magnetic field created by sextupole magnets to destabilize a part of the beam so that it detaches from its circulating orbit and is gradually extracted to the outside of the synchrotron.

Whereas the beam in conventional synchrotrons is extracted by controlling the electromagnets so that the unstable region of the beam gradually spreads, RF-driven extraction leaves the electromagnet settings constant and instead applies a high-frequency electric field so that the circulating beam gradually spreads, slowly forcing it out to the unstable region where the beam is extracted. The features of this technique are suited to the scanning method, not only because leaving the electromagnet settings unchanged keeps the position, size, energy, and other parameters for the extracted beam stable without any variations along with timeline, but also because functions such as high-speed beam on/off control and beam intensity control are easy to implement by controlling the power of the high-frequency electric field.

(2) Energy scanning operation

The operation cycle of the synchrotron is a repeating cycle of accelerating the injection beam from the injection linac and extracting the accelerated beam and then preparing for the next injection. Because the scanning method involves progressively changing the energy of the extracted beam, it is necessary to change the settings to those for the next required energy after each acceleration-extraction cycle is over. Hitachi's synchrotron features an energy scanning operation whereby it can progressively step through a number of preset energies. The settings of the beam transport line that carries the beam to the irradiation units must also be changed to match the energy being used. Even when using energy scanning operation, this system can control the position of the beam at the irradiation units 60 m from the accelerator with an accuracy of +/- 0.5 mm.

(3) Variable flat-top/variable cycle operation

The number of spots to be irradiated with each energy depends on the tumor shape and can vary widely from a few spots up to a thousand spots. Typical synchrotrons cycle through their operation in a fixed time during which they produce an accelerated beam for a fixed time (from several hundred milliseconds to several seconds) and then prepare to accelerate the next beam. The time after the acceleration phase during which the beam is being produced is called the flat-top period. However, this fixed-cycle-time operation with a constant flat-top period is very inefficient when using the scanning method where the required dosage can vary by two or more orders of magnitude. Hitachi's synchrotron can decelerate the remaining beam immediately after the required dosage has been extracted, dispose of the beam at low energy, and then accelerate the next beam. The accelerator's flat-top period can be varied between several milliseconds to five seconds with an associated operating cycle period of between two and nine seconds. By varying the time at each energy dynamically, this method avoids wasting time. This variable flat-top/variable cycle operation was developed as part of the respiration-synchronized operation technique for the synchrotron. Respiration-synchronized irradiation is a technique for improving the accuracy of irradiation by synchronizing the irradiation timing with the patient's breathing phase. It is used with scattering-method treatment of torso regions that move as the patient breathes. Hitachi developed variable flat-top/variable cycle operation for the proton therapy system supplied to the University of Tsukuba where it became the first accelerator in the world to achieve respiration-synchronized variable flat-top/variable cycle operation. The same technique is used effectively with the scanning method.

Monitoring and Safety System

Scanning irradiation requires highly accurate control of beam dose and beam position, and the monitoring and safety system that monitors these parameters plays an important role. The following sections describe the monitoring and safety functions associated with beam control.

(1) Irradiation dose management

As described earlier, the beam dosage is measured by the main dose monitor and beam on/off control is performed using this information. The beam turns off approximately 100 μs after a beam off signal is issued.

The spot dose measured by the sub-dose monitor is compared with the treatment plan and irradiation is halted if the dose exceeds the plan by a specified fixed amount in case this indicates a fault in the beam shutdown function. The integrity of the dose monitors is also checked by comparing the ratio of outputs from the sub and main dose monitors.

The spot irradiation time is also measured and irradiation is halted if this is abnormally long in case it indicates a fault in the dose measurement function or beam shutdown function. Together, this timer and the main and sub-dose monitors provide three dose monitoring functions.

(2) Spot position management

The beam position is controlled by the scanning magnets. While beam irradiation is in progress, the excitation current in the scanning magnets is monitored and irradiation halted if the current deviates from the set value by more than the allowed tolerance.

The actual position through which the beam passes is measured and checked for each spot by the spot position monitor near the irradiation surface. Irradiation is halted if the deviation of the measured beam position from the plan value exceeds the allowed tolerance. The spot position monitor measures the beam size as well as its position and halts irradiation if the deviation from the plan value exceeds the allowed tolerance. This provides multiple monitoring functions for the beam position.

(3) Beam energy check

The beam energy is controlled and verified with a high level of accuracy by the synchrotron accelerator. The excitations of the bending magnets in the high-energy beam transport line used to deliver the extracted beam to the treatment rooms are also monitored in such a way as to prevent any beam arriving with the maladjusted energy from reaching the treatment rooms.

(4) Irradiation pause and resume

If any abnormality is detected, the beam is turned off immediately and treatment halted. Beam extraction can be turned off in 100 μs by turning off the high-frequency electric field used to extract the beam. Irradiation is reliably shut down by multiple methods, the others being turning off the beam supplied to the synchrotron by the injector linac and using the fast beam stopper, which can close in approximately 0.3 s, to block the beam transport path. Except in the case of a serious fault, treatment can be restarted again after it halts at the discretion of the operator. In this case, treatment restarts correctly from the spot after the spot for which treatment halted.

SCANNING NOZZLE BEAM PERFORMANCE

The following sections describe the beam performance based on data obtained from testing of the MDACC scanning nozzle.

Spot Position Control

Fig. 8 shows a plot of the deviation between the measured and planned spot positions for two-dimensional scanning of a 30 cm × 30 cm region of approximately 10,000 spots. The position error

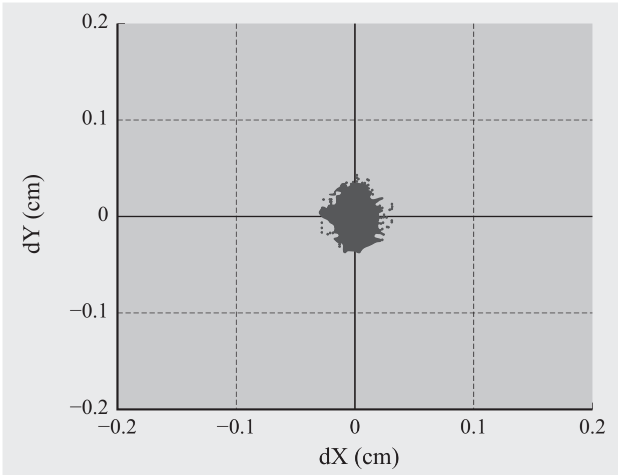

Fig. 8—Spot Position Control Performance (Two-dimensional Scanning).
This plot of spot position error for two-dimensional scanning of approximately 10,000 spots using the MDACC scanning nozzle shows that the accuracy is within +/-0.5 mm.

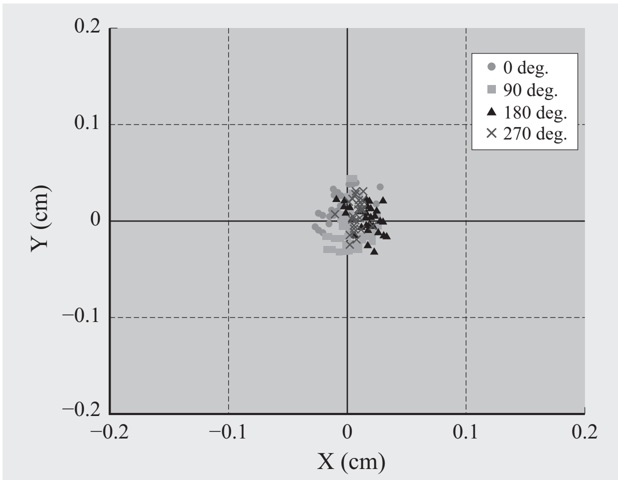

Fig. 9—Spot Position Control Performance (Energy Scanning).
This plot of spot position error for energy scanning of 47 energy levels using the MDACC scanning nozzle shows that the accuracy is within +/-0.5 mm for all four irradiation directions.

is within +/- 0.5 mm. Fig. 9 shows a plot of the spot positions for each energy for energy scanning operation covering 47 energy levels. The results from rotating the gantry beam to perform irradiation from four different angles are also plotted on the same graph and the position error is within +/- 0.5 mm under all conditions. These measurements verify that the beam position can be controlled with a very high level of accuracy.

Volumetric Irradiation

Fig. 10 shows an example measurement of an SOBP in the depth direction using 47 different energies. The result shows that a highly uniform dose distribution has been achieved over a depth range from 10 to 30 cm.

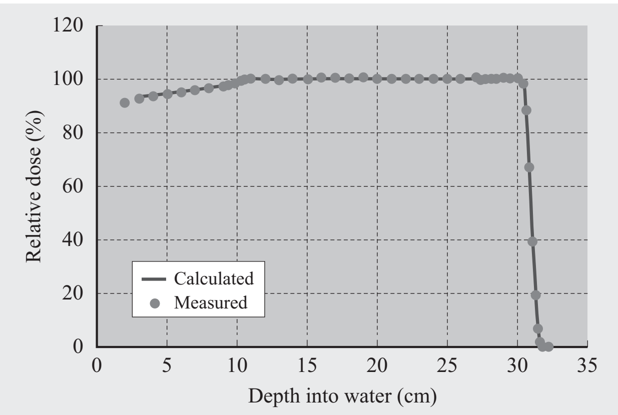

Fig. 10—Uniform Distribution with Respect to Depth.
These example measurements from the MDACC scanning nozzle indicate a uniform dose distribution in the depth direction. The results show a SOBP (spread out Bragg peak) with constant dose for depths from 10 cm to 30 cm.

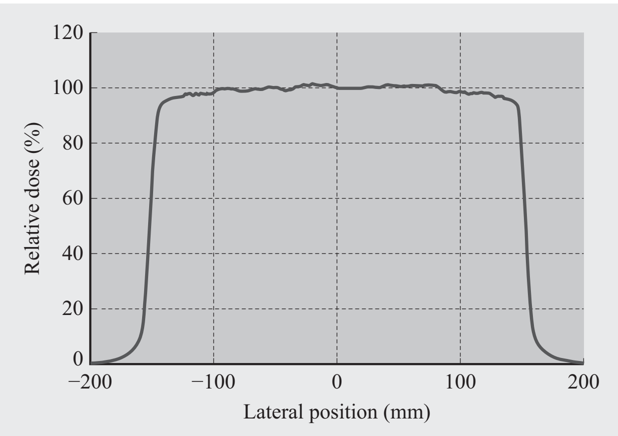

Fig. 11—Dose Distribution in Lateral Direction.
These example measurements obtained from the MDACC scanning nozzle using radiation film show a uniform distribution in the lateral direction and demonstrate a uniformity performance of +/-3%.

Fig. 11 shows an example distribution measurement on a radiation film for a uniform distribution over a 30 cm × 30 cm lateral region. This demonstrates that a uniformity of +/- 3% can be achieved.

Also, testing of dose reproducibility by repeatedly irradiating a 1-L region over a week demonstrated that a very high level of reproducibility could be achieved with variation of less than +/- 0.3%.

CONCLUSIONS

This article has described the scanning nozzle used by the proton therapy system supplied to the MDACC.

The MDACC scanning system has received FDA (U.S. Food and Drug Administration) clearance and the first commercial scanning treatment commenced on May 19 2008. Full handover of all facilities took place in September 2008 and, together with the three scattering nozzles, the system is now treating more than 80 patients per day. The success of this project has greatly accelerated the move toward adopting scanning systems in proton therapy. Hitachi intends to continue contributing to the field of radiotherapy by pursuing even greater performance and by developing and supplying very safe and reliable systems.

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