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Proton Therapy Facility Project in National Cancer Center, Korea

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A Proton Therapy Center has been established this year in National Cancer Center (NCC), Korea, to treat cancer patients and to perform forefront cancer research. The proton therapy facility will include two gantry treatment rooms, one fixed beam room and one experimental station for multi-disciplinary users. Another treatment room is reserved for the third gantry in view of future expansion. Contract for the major proton therapy equipments was made with a Belgian company IBA in July this year. A 230 MeV fixed energy cyclotron will provide each treatment room with proton beams. The beam energy can be varied to 70–230 MeV by a graphite energy degrader. Features of our proton therapy system are compared to those of other system. The building design is currently almost complete, and construction will begin soon. The design of radiation shielding walls has been analytically performed, and more detailed calculation is underway.

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I. INTRODUCTION

After the use of proton beams has been suggested for therapy by R. Wilson [1], the proton therapy was initiated in nuclear science laboratories equipped with proton accelerators, and continued for several decades in non-hospital settings. The first hospital-based proton machine was rather recently installed at Loma Linda University Medical Center, its operation being started in 1990 [2]. Constructions of dedicated medical accelerators have then followed at several places in Japan and US, and a few projects are newly under proposal [3]. In Korea the Health and Welfare Ministry approved the establishment of a proton therapy center last year. Progress has been made this year toward contract of equipments with IBA [4] in June and toward completion of building design in December. We plan to complete the building in the mid 2004, and treat patients in 2005.

A major objective in radiation treatment is to deliver a prescribed dose to the Planning Target Volume (PTV) and a minimum outside of it. Especially when Organ At Risk (OAR) is near the PTV, efforts are made to further reduce the dose on the OAR relative to other parts of normal tissue. Proton radiation is considered a better modality compared to X-ray or electron beam radiations due to the presence of Bragg peak, which allows more localized dose delivery. The Bragg peak appears at the end of energy deposit because energy losses depend on the inverse square of particle velocity. The dose is usually delivered in a fractionated form rather than in a large single dose to enhance differential cell sensitivity between healthy and malignant cells. The radiation therapy is effective on cancer treatment because malignant cells are more radio-sensitive than healthy cells.

Limitations on dose confinement partly result from physical interactions between proton beam and body constituent. Multiple Coulomb scattering broadens the beam laterally resulting in lateral penumbra, and energy spread induces a slower fall-off beyond the Bragg peak. Some protons also undergo nuclear reaction, thereby their fluence being reduced.

We chose a cyclotron-based therapy system as cw beam from cyclotron better suits beam scanning [5]. The beam scanning is a high-end technique in radiation therapy as it can omit the use of mechanical beam shapers such as aperture and block. Unlike in conventional therapy a real 3-d scanning is feasible with hadron beams by the beam energy variation. This property of hadron beams renders Intensity Modulated Proton Therapy (IMPT) [6] to be one of the most advanced forms in radiotherapy.

The facility's major components such as cyclotron, two gantries, beamline, therapeutic beam forming devices (named nozzle), and control system are parts of the equipment package that will be delivered by IBA. In fact a similar system has been used at Northeast Proton Therapy Center (NPTC) in Massachusetts General Hospital, which was the first such system built by IBA [7]. The NCC system will be an improved version helped with experiences at the NPTC.

Radiation shielding is an important issue in the building design. The basic framework of our shielding design comes from the works performed at the NPTC. Based on their analytic evaluation and measurement we have first assessed our shielding analytically. Monte-Carlo (MC) simulation is to be performed soon for more detailed as-

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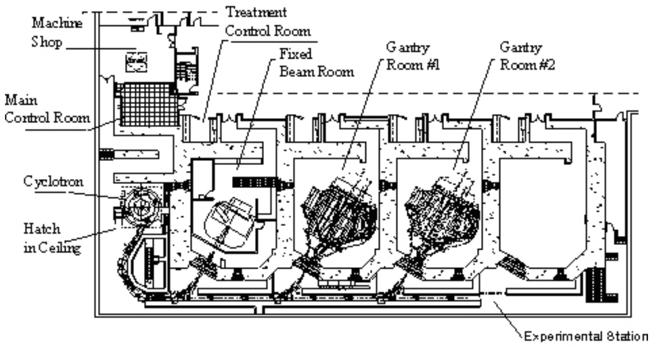

Fig. 1. Layout of proton therapy part of the building showing treatment rooms, cyclotron and beamlines.

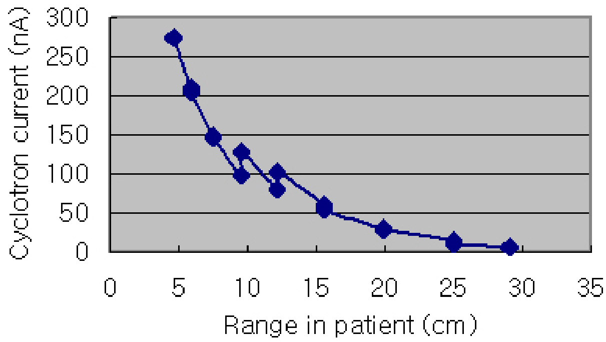

Fig. 2. Cyclotron current as a function of proton range in patient at a dose rate of 2 Gy/min.

sessment. As part of radiation safety measures the radiation monitoring system, which is connected to the accelerator operation, is located in the main control room and also locally in each treatment control room. The neutron detectors will cover the entire proton beam area while the gamma detectors will be installed in cyclotron and gantry areas to monitor residual activities.

II. MAIL THERAPY EQUIPMENTS

The facility will have three treatment rooms equipped with two gantries, one fixed beamline and one experimental station as shown in Fig. 1. One more gantry will be added in the second phase to increase patient throughput. The experimental station is located at the end of the beam transport course. The proton beam is produced by a 230 MeV fixed energy cyclotron, and its energy is varied with an energy degrader made of graphite to the range of 70–230 MeV. Collimators and slits downstream select the precise beam energy and clean up the beam suitable for treatment. Figure 2 shows the primary beam current as a function of range in patient when a patient receives a dose at the rate of 2 Gy/min. To reach the range below 5 cm the cyclotron current is needed to be around 300 nA, which is set to be the upper beam current in the therapeutic use. After the beam passes thru the energy selection system (ESS), the maximum current in treatment rooms is limited below 20 nA for the radiation shielding and safety reasons.

The gantry is 360° rotating device and is built to be a truss and frame structure for stiffness to maintain isocentricity within 1 mm of radius. The rotation diameter is about 11 m, so that the gantry takes up more than two floor space. A more compact but heavier gantry has been devised and used in PSI, Switzerland, and further development is planned [8]. The horizontal beamline has a chair to treat patient in sit-down position, which is convenient, *e.g.*, for eye or head and neck treatments. A major demerit of chair comes from the fact that CT images for treatment planning are usually taken in supine position. Probable mismatches between image and target are worrisome for clinicians. Immobile parts of the body are usually considered to be safely treated in a chair.

III. THERAPEUTIC BEAM FORMATION

The beam is shaped for therapy at the end of beamline called nozzle. Two gantries may be equipped with two kinds of nozzles, standard and Pencil Beam Scanning (PBS) nozzles. Installation of the latter will depend on approval as an adequate medical device at the time of nozzle delivery. The standard nozzle can be used to perform both scattering [9] and wobbling methods in therapeutic beam formation. The PBS nozzle is optimized to make a small-size beam using extra quadrupole magnets and to perform raster scanning [10]. Schematic views of two kinds of nozzles are given in Fig. 3.

Another known method of scanning is the spot scanning. Two conspicuous facilities using this technique are PSI and HIMAC in Japan [11]. In the spot scanning the beam dwells at a spot to deliver the prescribed dose with beam energy changed to cover up the full depth of the

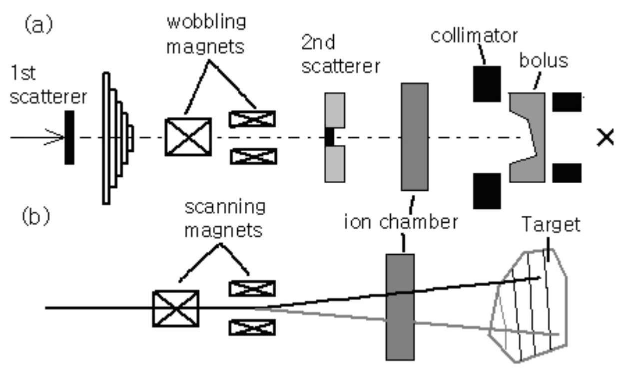

Fig. 3. (a) IBA nozzle to perform both single or double scattering and wobbling. (b) Pencil Beam Scanning nozzle.

PTV before the beam is moved to a different spot. The spot scanning may be slower than the raster method due to stopping prior to each positional change.

The scanning is considered superior to the scattering method as it can allow a true 3-d conformation, but it has a drawback of higher susceptibility to organ motion, primarily due to respiration. One way to circumvent this problem is to use beam gating according to respiration signals. More active method is to steer the beam with the tumor position sensed, which is being studied by a PSI group [12]. The control software required to perform the scanning is more complicated so that a current major effort for the IBA system is devoted to improve software.

The sharp Bragg peak needs to be broadened in the beam direction to cover the tumor volume. The flat dose region is called Spread Out Bragg Peak (SOBP). Two practical methods to achieve variable SOBP are to employ 1) rotating wheel, 2) static ridge filter [13]. A cw beam from cyclotron can use both kinds comfortably while the static method is preferred for the synchrotron beam in general. Dozen sets of ridge filters are needed to cover a wide range of SOBP although the width of SOBP for the same ridge does not strongly depend on the primary beam energy.

Actual dose deposit in patient is calibrated to radiation detectors in beamline such as ionization chambers of transmission type [14]. These detectors are calibrated with measurements in a water phantom using small ionization chambers, or using radiochromic films. The ion chamber in the beamline should cover the entire beam domain with position and beam current measured.

The clinical parameters of the system are listed in Table 1. Definitions of range in patient, dose uniformity and distal dose falloff are shown in Fig. 4. SAD is a parameter measuring the beam parallelism which is important to reduce unnecessary skin doses. Lateral penumbra listed in the table is a contribution from the dose delivery system itself. The penumbra due to theoretical multiple scattering in the body amounts to about 6 mm for the 230 MeV beam. The delivered dose accuracy is mainly determined by the control software. Most of these conditions are met with the wobbling mode of operation in the IBA system. Currently only the scattering method is approved by Food & Drug Administration of US, and efforts are on going to obtain approval for the wobbling method with trials at the NPTC.

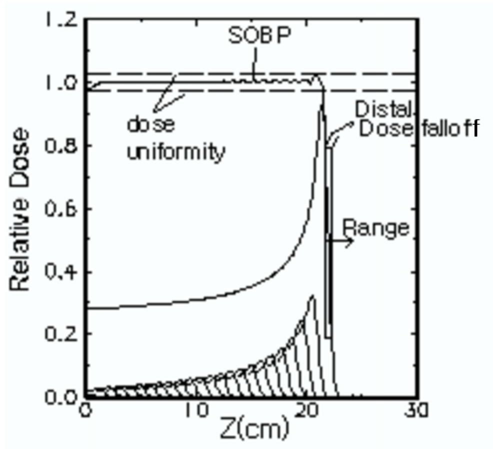

Fig. 4. Definition of SOBP, beam range, distal dose falloff, and dose uniformity.

IV. RADIATION SHIELDING

The design of building to house the equipments is almost complete, and groundbreaking will take place soon. Unlike in existing PTC's the proton beam treatment rooms of the NCC are located in second basement floor as conventional electron linacs occupy first basement floor. This requires deeper digging and longer equipment rigging, but it may be favorable from the shielding point of view.

An important issue in the building design is to optimize the shielding against radiation dose. We have utilized the results of shielding calculations and measurements made for the NPTC in choosing the wall and ceiling thicknesses. The dose outside of shielding is currently evaluated using an analytic expression used for similar proton beam energies [15]. The facility usage pattern assumed is the treatment time schedule for different cancers utilized at NPTC. The receptor for evaluation is placed near the ESS boundary taking into account the high radiation of the region and the proximity to the parking lot in the same floor. The cascade neutrons are assumed to be produced on copper target. The major beam losses in different locations are shown in Fig. 5. Figure 6 shows the dose at the receptor as a function of concrete-equivalent wall thickness. Our effective thickness is above 6 m to reduce the dose below 1 mSv/yr for the public access.

It is not easy to analytically estimate the dose outside of the maze. MC simulation was initially used for the NPTC shielding design, and measurement results have been recently published [16]. A rather large dose observed near the maze door should be reduced with an effective longer maze of the current design. Overall the analytic estimation tends to overestimate the dose, and MC results agree more reasonably with measurements. We plan to carry out full-scale MC simulations for our building configuration in collaboration with a local radiation shielding consulting group.

The neutrons will be monitored in treatment rooms, in treatment control rooms, and in some public access areas with area monitors equipped with BF3 proportional counters surrounded by a polyethylene moderator. The gamma radiation will also be checked with Geiger-Mueller type area monitors in the ESS and patient treatment rooms. But it is generally known that activation is low with a normal use of therapeutic beams. Con-

Table 1. Major clinical parameters of the therapy system.

item	Value
Range in patient	3.5 - 30 g/cm^2
Range modulation step	$<$ 0.5 g/cm^2
Average dose rate	$>$ 1 Gy/min for 25 $\times$ 20 cm at 30 g/cm^2
Maximum field size	40 $\times$ 30 cm
Dose uniformity	$\pm$4%
SAD (source-to-axis distance)	$>$ 2 m
Distal dose falloff (80 - 20 %)	$<$ 0.25 g/cm^2
Lateral penumbra (80 - 20 %)	$<$ 2.5 mm
Delivered dose accuracy	$\pm$2 %

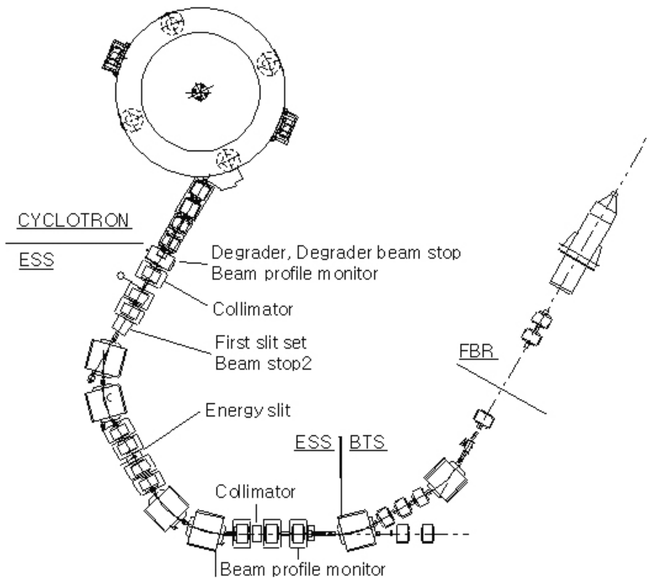

Fig. 5. Major locations of proton beam losses in the ESS area.

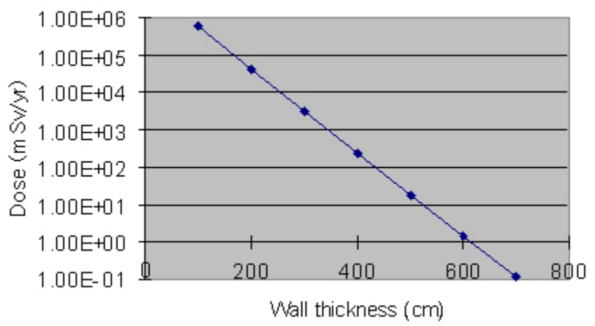

Fig. 6. Dose output of the shielding wall near the ESS region facing the parking lot versus concrete-equivalent wall thickness.

tamination of underground water by tritium production was evaluated for the NPTC assuming proton losses on copper, and is concluded to be lower than required. We plan to perform a similar analysis.

V. USAGE OF EXPERIMENTAL ROOM

The main uses of the experimental room will be: radiation damage tests, nuclear science, biomedical experiments and development of beam manipulation techniques [17]. First a commercial use of radiation damage study has been pursued at several PTC's in the US as space-based electronics testing appears to be demanding. We expect some users also from nuclear science community as the cyclotron may produce the proton beam of highest energy in Korea within a foreseeable future. On the other hand, radiation biology using proton beams has been an active research subject. The hadron radiation can simulate, *e.g.*, partial damage on a localized portion of organ. Also, systematic studies on animal models can be performed to study fundamental radiobiological questions concerning normal and cancerous tissues for various treatment modalities. Finally the beam manipulation techniques can be tested.

VI. CURRENT STATUS

The building construction will begin early next year, and is planned to be complete in June, 2004. Some issues still remain on the timing of equipment rigging as they have to be further clarified with more detailed analysis of the construction schedule. The patient treatment may begin in 2005. Other major unknown factors to begin with the clinical operation of the facility include commissioning period and approval for the clinical use by Korea Food & Drug Administration.

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