Commissioning and Validation of a Dedicated Scanning Nozzle at Samsung Proton Therapy Center

Kwangzoo Chung*, Younyih Han*, Sung Hwan Ahn*, Jin Sung Kim[†], Hideki Nonaka[‡]

*Department of Radiation Oncology, Samsung Medical Center, Sungkyunkwan University School of Medicine, [†]Department of Radiation Oncology, Yonsei Cancer Center, Yonsei University College of Medicine, Seoul, Korea, [‡]Division of Industrial Equipment, Sumitomo Heavy Industries Ltd., Niihama, Japan

In this study, we present the commissioning and validation results of a dedicated scanning nozzle. The dedicated scanning nozzle is installed in one of the two gantry treatment rooms at Samsung Proton Therapy Center. Following a successful completion of the acceptance test, the commissioning process including the beam data measurement for treatment planning system has been conducted. Extended measurements have been conducted as a validation of the clinical performance of the nozzle and various quality assurance protocols have been prepared.

Key Words: Pencil beam scanning, Commissioning, Proton therapy

Introduction

The possibility of therapeutic use of fast protons is introduced in 1946.[1] Ever since the introduction of radiological use of fast protons, there have been uninterrupted development of proton beam therapy and recently, number of proton therapy centers in operation or in preparation is rapidly increasing.[2] One of the most noticeable contemporary trend in proton therapy is the wide adaptation of pencil beam scanning technique in newly installed proton therapy systems. While there are still significant advantages in passive scattering mode of proton beam delivery over conventional x-ray radiation therapy, the pencil beam scanning technique can maximize the benefits of proton therapy considering the intensity modulation and dose conformality (especially in proximal region).

The Samsung Proton Therapy Center (Samsung PTC) is the first private hospital based proton therapy center in Korea,[3] and it has provided stable scanning beam treatments for many patients since its first operation of the dedicated scanning nozzle. Even though there are several reports on commissioning of pencil beam scanning nozzles recently published, the proton therapy system (Sumitomo Proton Therapy System, Sumitomo Heavy Industries, Ltd.) installed at Samsung PTC has its own unique characteristics for both wobbling nozzle and line scanning nozzle compared to other proton therapy systems provided by other vendors. In addition, there is no published study about Sumitomo's system as far as we know. It is our main purpose to report the details of commissioning and validation of the dedicated scanning nozzle at Samsung PTC, and thus provide a practical guide for upcoming proton therapy centers.

Materials and Methods

The dedicated scanning nozzle at Samsung PTC has a maximum field size of 30 cm×40 cm and its detailed specification can be found elsewhere.[4] In principle, the line-scanning nozzle can be also operated in spot-scanning mode as both beam delivery methods share the same hardware. Nevertheless, in practice, the selected line-scanning mode was exclusively implemented, as the spot-scanning mode would require a separate

control sequence. The nozzle was installed by the vendor (Sumitomo Heavy Industries, Ltd.). The dedicated scanning nozzle differs from the multi-purpose nozzle, which is installed in the other treatment room at Samsung PTC in several aspects. All the nozzle components related to the wobbling method have been removed and a helium gas filled chamber has been located at the down stream of the nozzle to improve beam quality mainly by reducing in air scattering of the proton beam.

The modeling of a line scanning nozzle has required an additional process in the treatment planning system's viewpoint. In RayStation (RaySearch Laboratories, AB, Stockholm, Sweden), the existing dose calculation algorithm for spot scanning proton beam has to be converted to a new algorithm for the line scanning proton beam. The simplest approach was to use a concept of "line segment" which is equivalent to an individual spot in spot scanning method. While there were modifications in the dose calculation algorithms with the vendor provided machine limits (minimum scan speed, maximum scan speed, and maximum dose rate), the fundamental requirement for beam data measurement remains the same as the spot scanning beam modeling: integrated depth dose curves, absolute dose measurements, and in-air spot profiles (for selected beam energies). As recommended in the beam data requirements, we have selected 30 different beam energies including the maximum and minimum beam energies can be delivered in the nozzle. These selected beam energies have been used for all beam data measurements. The integrated depth dose curve for each energy has been measured using a Bragg peak chamber (PTW, Freiburg, Germany). The water-equivalent thickness (WET) of the chamber window has been applied either as an offset in the measurement setup or as a shift in the acquired integrated depth dose (IDD) curves. The absolute dose measurement was performed with a parallel plate chamber for those selected beam energies. The measurement depths have been chosen from points in the plateau region (around the mid-point from the entrance surface to the half distance of the maximum range) of the integrated depth dose curves. This is a practical and reasonable choice as the dose gradient near the Bragg peak is fast-changing compared to that of the plateau region. After taking the entire beam data required, the data have been sent to RaySearch for beam modeling. Along with the measured beam data, the related hardware specifications (maximum field size, maximum and minimum dose rate, etc.) have also been sent. As this was the first use case of RayStation for Sumitomo Proton Therapy System (PTS), another dataset has to be sent for validation purpose. For this validation dataset, we have selected different beam energies for additional IDD curves, and various geometrical plans have been created for measurements. After a successful validation of the beam model, the first ever-modeled Sumitomo line scanning nozzle in RayStation has been delivered to Samsung PTC.

Using the delivered machine model, we have started the commissioning of the dedicated scanning nozzle at Samsung PTC. The commissioning procedure evolved in three steps including physical, clinical, and total commissioning. In the physical commissioning, the main focus was in the physical properties of the line scanning nozzle. It started with the most fundamental item, the standard quality assurance (QA). The standard QA is a daily output calibration and thus needs to be conducted every morning prior to daily patient treatments. The standard QA plan has been designed to deliver a uniform two Gy dose in a 10 cm^3 cube with a maximum energy layer of 230 MeV in water. Based on the result of the standard QA, a correction factor (beta-value) for count/Gy would be determined and recorded in the treatment control system client (TCSC) database. In addition to the daily output calibration, scan patterns for two different beam energies have been prepared for a daily QA. The SOBP range has also been measured as a daily QA item by using a multi-layer ionization chamber (MLIC). After the settlement of daily QA procedure, the daily QA has been conducted routinely. As the performance of the line scanning nozzle is highly sensitive to the cyclotron beam current, if necessary, the cyclotron beam current table has to be re-generated every four hours.

The clinical commissioning was prepared with an anthropomorphic phantom (ATOM, Computerized Imaging Reference Systems, Inc., Virginia, US). For various disease sites, the phantom has been CT-scanned with appropriate immobilization devices and setup position. Following the prepared proton plan protocol for a given disease site, treatment plans for nine different patient cases were created in RayStation (version 5.0) and exported to the MOSAIQ system. All the patient cases went through the patient-calibration procedure which is a requirement for treatment beam delivery in the Sumitomo PTS.

The patient specific QA for scanning plan includes both the patient-calibration and a gamma evaluation of two dimensional dose distribution in 2 or 3 different depths depending on the maximum range of treatment fields. For a selected case, we have measured two dimensional dose distribution in every 1 cm depth considering the resolution of the 2D detector (OCTAVIUS 729XDR, PTW Freiburg, Germany), and then reconstructed a three dimensional dose map of the treatment field out of the multi-depth measurements. This method has also been used to evaluate the gamma passing rate in longitudinal planes (XZ and YZ planes, where Z is the beam direction) which was one of the remained item of the acceptance test due to the technical challenges.

The total commissioning of the dedicated scanning nozzle was an integrated end-to-end test of line scanning treatment. Using the clinical commissioning phantom cases, the whole procedures including simulation, treatment planning, patient specific QA, treatment data transfer through MOSAIQ system, image verification using orthogonal X-ray images or CBCT images, and actual beam delivery in treatment mode.

Results

The IDD curves of a spot proton beam have been measured for 30 different proton beam energies as shown in Fig. 1. From the measured IDD curves, clinical ranges D90 (distal 90% of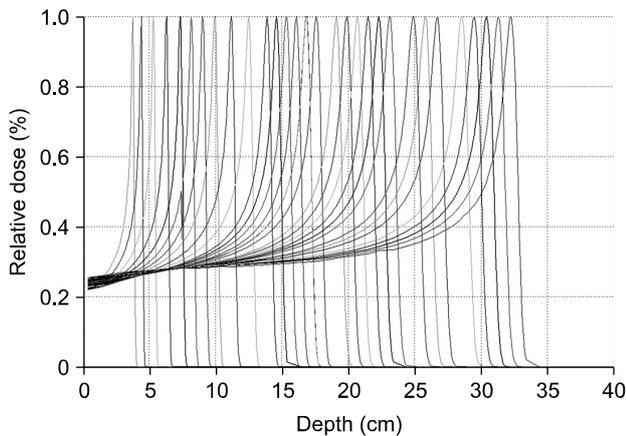 the integrated depth dose curve for a given proton beam energy) have been determined. As a validation, scanned mono-energy plans (10 cm×10 cm) have been created in the treatment planning system for the selected beam energies and then delivered for MLIC measurements. The ranges have been compared as shown in Fig. 2. The ranges measured for beam modeling and for validation have agreed well within the resolution of MLIC (2 mm with a single measurement).

For those selected beam energies, in-air spot profiles have been measured on the planes with different distances from the isocenter (-20, -10, 0, 10, 20 cm). We have used a pin-point chamber in a 2D scan mode of OmniPro Accept (IBA Dosimetry GmBH, Germany). The spot profiles in x-axis and y-axis have been extracted from the scanned 2D distributions. In order to determine the spot size at the center of isocenter plane for different beam energies, we have first read the FWHM (Full Width Half Maximum) values from the spot profiles and then converted to 1-sigma values using the relation between FWHM and 1-sigma of a single Gaussian function. For the maximum (minimum) beam energy, the spot size is 2.9 mm (9.0 mm). The spot sizes for several beam energies are shown in Fig. 3.

For daily output calibrations, $10 \times 10 \times 10$ cm^3 cube plan (2 cGy uniform dose) has been used. This cube plan is the same plan used for the absolute MU calibration of the nozzle. At the time of the absolute MU calibration, the beam model in RayStation was not available and thus the cube plan has to be

Fig. 1. The integrated depth dose curves for the selected beam energies (normalized at peak values).
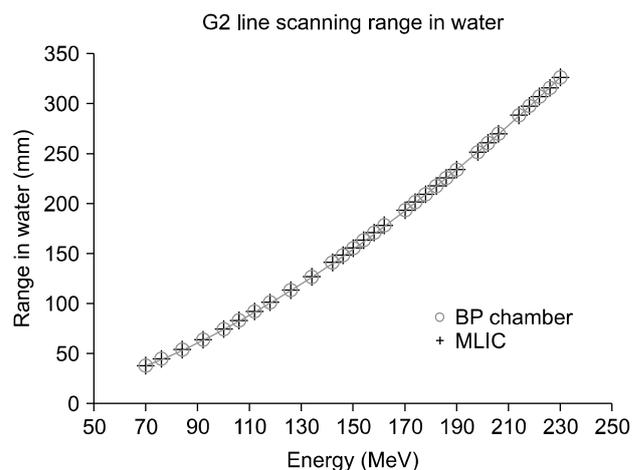

Fig. 2. The clinical range (D90) of the dedicated scanning nozzle at Samsung PTC measured by PTW Bragg peak chamber and MLIC.

generated by a manual weighting of 10×10 cm^2 single layered (mono energy) components with relevant beam energies. The initial weights were analytically calculated from the measurements of each layer. After several iterations of adjustment of weights and measurements, the final weights have been decided with a satisfactory flatness and uniformity. In the line scanning nozzle, the absolute output can be controlled by dose rate and scan speed. The lower dose rate yields lower output while the lower scan speed yields higher output. Both dose rate and scan speed have their own physical limit specified by the relevant machine components. Within the machine limits, in principle, the same output can be achieved by a certain combination of the dose rate and scan speed. At the final stage of the standard QA plan set up, the dose rate of the composite layers in the cube plan has been fine-tuned to get

Fig. 3. The spot size calculated in one sigma for selected beam energies.

an exact 2 cGy output reading. The same cube plan has also been used for daily range verification. In addition to the standard output calibration plan, a 2D dose verification of a geometric scan pattern (Fig. 4) has been added into the daily QA. The two dimensional dose distributions on the same effective depth as the detector plane (0.9 mm water-equivalent-thickness without a build-up material) have been measured and compared with the dose plane exported from the treatment planning system. The gamma passing rates were all above 95% with 3%, 3 mm criteria, although the passing rates were dependent on beam energies. Later on, the scan pattern has been replaced by a simplified geometry to avoid casual interruptions due to machine limit approaching beam conditions.

The output calibration for a treatment plan is a mandatory procedure in Sumitomo PTS. Based on the output calibration result, a correction factor (gamma-factor) is determined and recorded in the treatment control system database. Patient specific QA plans are generated by painting the treatment field dose on a solid water phantom registered in the treatment planning system. The output measurement points are decided in relatively uniform dose region where the point dose is similar to the originally specified dose on the point of interest. Two dimensional dose distributions were additional measured for the patient specific QA. The measurement depths always include the same depth of the output measurement, one shallow depth (2 cm), and optionally one more depth in between in case the maximum range of the treatment field is relatively long. At the commissioning stage, we have practiced patient specific QA for nine selected patient cases as listed in Table 1. All the output calibration results were well within 3% and the gamma
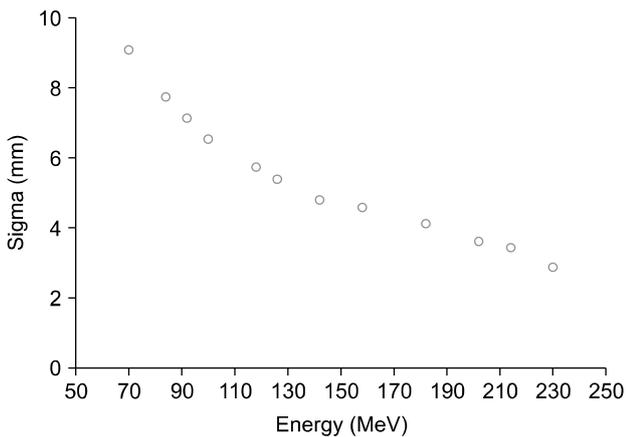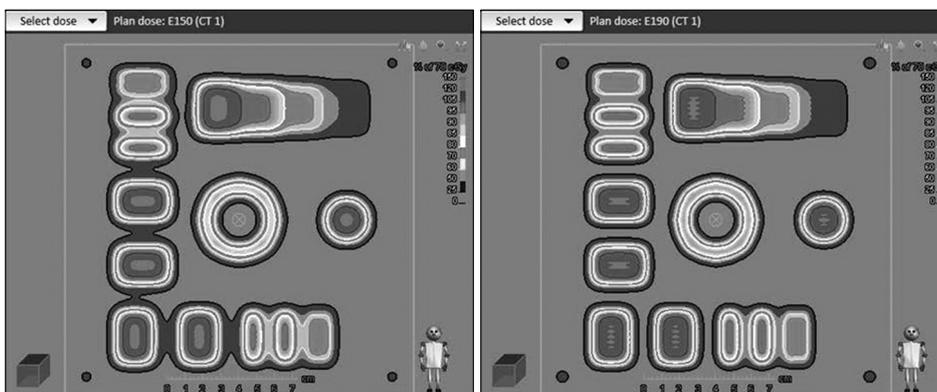

Fig. 4. Example of mono energetic scan patterns (Left: 150 MeV, Right: 190 MeV) created for validation and daily QA. The gamma passing rates were all above 95% with 3%, 3 mm criteria for both beam energies.

Table 1. Selected rehearsal cases for the physical and clinical commissioning of the dedicated scanning nozzle.

Case number	Dx. Site	*2D Dose QA	Note
1	PED	99.0%	CSI
2	HCC	97.8%	
3	Brain	98.1%	
4	Lung	98.5%	
5	PED	99.5%	Brain
6	Recurrent rectal	98.8%	
7	Head and neck	99.3%	
8	Prostate	99.5%	Definitive
9	Esophagus	97.5%	Long Y-extent

*2D Dose QA: the gamma passing rate of the treatment field with the lowest value.

passing rate of the 2D dose measurements were above 97.5% as listed in Table 1. A special 2D dose distribution verification has been performed for the case number 4. The OCTAVIUS 729XDR has two dimensional array of ionization chambers with a spacing of 1 cm in both horizontal and vertical direction. A finer resolution can be obtained by merging a set of measurement with shifted detector planes. The analysis software for OCTAVIUS 729XDR provides a function of manual dose map editing. Using this feature, we have reconstructed a pseudo 3 dimensional dose distribution from a multi-depth measurement in every 1 cm depth as shown in Fig. 5. With 3% and 3 mm gamma evaluation criteria, all XY, XZ, and YZ planes have a passing rate of 100%. When tighter criteria were applied (2% and 2 mm), the passing rates were above 89%. Not only a measurement of three dimensional dose distributions, but also a measurement of dose distribution in longitudinal direction is very challenging as there is no perfect solution available at least to our knowledge. Even though the multi-measurement method is practically inefficient for daily QA, it can be used as an excellent validation method, and we have indeed adopted this method successfully to finalize the remained AT items.

Conclusion

We have presented commissioning and validation results of the dedicated scanning nozzle at Samsung PTC. Despite of a tight schedule and limited resources, we have successfully fin-
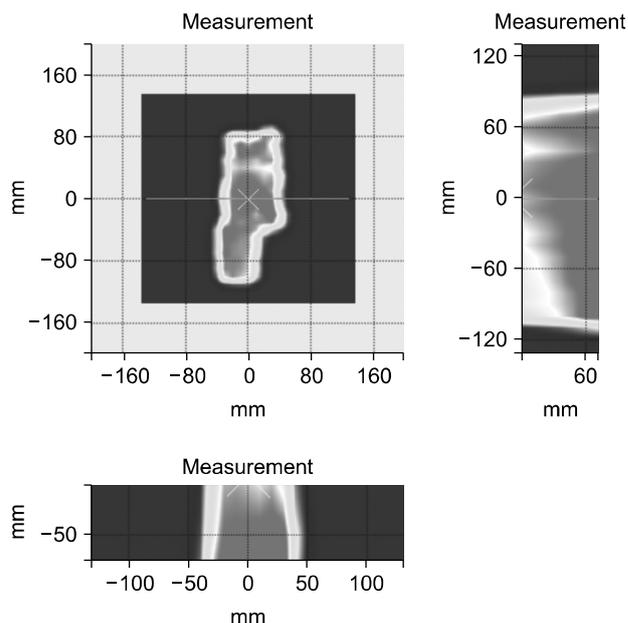

Fig. 5. Pseudo 3D dose distribution reconstructed from multi-depth measurement of 2D dose map (With 3% and 3 mm criteria, all XY, XZ, and YZ planes have a passing rate of 100%).

ished the end-to-end test of the nozzle including the beam modeling for treatment planning system, the validation of the beam model, physical and clinical commission, and the integration of all composite parts. We have also verified that the accuracy and precision of the treatment nozzle stay within the clinical specifications, and developed the QA protocols to guarantee the stability of the nozzle performance.

Compared to the well-known and relatively simple photon radiotherapy devices, the clinical set up of a proton therapy system in general requires a prodigious resources and experiences. By representing the commissioning and validation experiences at Samsung PTC in this study, we would expect that it could be used as a pivotal guide to imminent proton therapy centers.

References

1. R. R. Wilson: Radiology 47, 487 (1946)
2. M. Jermann: Int J Particle Ther. 2, 50 (2015)
3. K. Chung, Y. Han, J. Kim et al: Radiat Oncol J. 33, 337 (2015)
4. K. Chung, J. Kim, D.-H. Kim, S. Ahn, and Y. Han: J. Korean Phys Soc. 67, 170 (2015)