Clinical Commissioning of a Pencil Beam Scanning Treatment Planning System for Proton Therapy

Jatinder Saini, MS1; Ning Cao, PhD2; Stephen R. Bowen, PhD2,3; Miguel Herrera, BS1; Daniel Nicewonger, BS4; Tony Wong, PhD1; and Charles D. Bloch, PhD2

1Seattle Cancer Care Alliance Proton Therapy Center, Seattle, WA, USA
2Department of Radiation Oncology, University of Washington School of Medicine, Seattle, WA, USA
3Department of Radiology, University of Washington School of Medicine, Seattle, WA, USA
4Texas Center for Proton Therapy, Irving, TX, USA

Abstract

Purpose: In this report, we present the commissioning and validation results for a commercial proton pencil beam scanning RayStation treatment planning system.

Materials and Methods: The commissioning data requirements are (1) integrated depth dose curves, (2) spot profiles, (3) absolute dose/monitor unit calibration, and (4) virtual source position. An 8-cm parallel plate chamber was used to measure the integrated depth dose curves by scanning a beam composed of a single spot in a water phantom. The spot profiles were measured at 5 different planes using a 2-dimensional scintillation detector. The absolute dose/monitor unit calibration was based on dose measurements in single-layer fields of size 10 × 10 cm². The virtual-source position was calculated from the change in spot spacing with the distance from the isocenter. The beam model validation consisted of a comparison against commissioning data as well as a new set of verification measurements. For end-to-end testing, a series of phantom plans were created. These plans were measured at 1 to 3 depths using a 2-dimensional ion chamber array and evaluated for gamma index using the 3% and 3 mm criteria.

Results: The maximum deviation for spot sigma measured versus calculated was 0.2 mm. The point-dose measurements for single-layer beams were within ± 3%, except for the largest field size (29 × 29 cm²) and the highest energy (226 MeV). The point doses in the spread-out Bragg peak plans showed a trend in which differences > 3% were seen for ranges > 30 cm, field sizes > 15 × 15 cm², and depths > 25 cm. For end-to-end testing, 34 planes corresponding to 13 beams were analyzed for gamma index with a minimum pass rate of 92.8%.

Conclusion: The acceptable verification results and successful end-to-end testing ensured that all components of the treatment planning system were functional and the system was ready for clinical use.

Keywords: protons; treatment planning system; pencil beam scanning; commissioning

Introduction

Pencil beam scanning (PBS) is a technology in proton therapy [1] that can reduce the need for field-specific hardware (apertures and compensators) and offers better dose conformity to the target. In our PBS beam delivery system, a 3-dimensional target is divided into layers that are positioned at a user-defined interval. The dose is delivered...
from the most distal layer to the most proximal layer sequentially. Within each layer, the dose is deposited through individual spots that can have unique intensities and positions. One advantage of PBS is that inverse planning provides the ability to have multiple dose levels in a target within a single field (dose painting). In addition, PBS beams can be optimized to provide both distal and proximal dose conformity to the target volume.

In the United States, there are multiple commercial systems that offer the capability of planning with PBS, including CMS XiO (CMS Software, Elekta, Stockholm, Sweden), Varian Eclipse (Varian Medical Systems, Palo Alto, California), and RayStation (RS; RaySearch Americas, Garden City, New York). Gillin et al [2] provided their experiences of commissioning the Varian Eclipse system on a Hitachi ProBeat delivery system at the University of Texas MD Anderson Cancer Proton Therapy Center (Houston, Texas). Another study done at the same institute by Zhu et al [3] compared the beam models based on single and double gaussian approximations of the in-air spot profiles. Both of these studies were done for the Eclipse planning system and the ProBeat delivery system. Thus far, to our knowledge, there are no published reports about the commissioning of RS for the IBA (Louvain-La-Neuve, Belgium) universal-nozzle PBS system. Accordingly, the purpose of this investigation was to report details of the commissioning and verification process for PBS in the RS. We believe that our study can be a valuable guidance document for many proton centers.

Materials and Methods

The Fixed Beam Pencil Beam Scanning System

The Seattle Cancer Care Alliance Proton Therapy Center (SCCA-PTC) fixed pencil beam delivery system is an IBA universal nozzle that provides the proton beam at a single horizontal angle [4]. The proton beam is magnetically scanned through each layer of the target volume. Each position within a layer can have a unique monitoring unit (MU), ranging from 0.02 to 11. The system provides the range in water from 7.5 to 32.6 cm corresponding to energies from 98.5 to 228.5 MeV. For treatments of shallow targets that require ranges < 7.5 cm, a range shifter is required. A range shifter [5] is a flat, uniform slab of material in the beam path to reduce the range of the beam while producing minimal additional scatter. In this report, the commissioning of range shifters is not included because there are many additional considerations for such commissioning that a full description will be provided in a separate article.

The maximum available field size at the isocenter plane is $40 \times 30$ cm$^2$. The variation of spot size with the proton beam energy at the isocenter plane is shown in Figure 1. Because of the fact that x- and y-steering magnets lie at different locations along the beam line, there is an asymmetry between x- and y-directions in beam divergence and spot sigmas.

The RS Treatment Planning System

The RS treatment planning system (TPS), version 4.51, distributed by RaySearch America, was commissioned for delivery of PBS treatments. The RS models proton fluence through air (before entering the medium) using a single gaussian approximation. Correspondingly, the transport in the medium is performed using a 2-gaussian approximation. The first gaussian accounts for the small-angle multiple-coulomb scattering, whereas the second gaussian accounts for the nuclear interactions and larger-angle multiple-coulomb scattering also called the nuclear halo. To accurately account for the lateral inhomogeneities within the medium, each spot is split into 19 subsots for dose calculations.
Measurement of Beam Commissioning Data

Per the RS recommendation, the data were acquired at 18 energies (Table 1) selected from the continuum of available energies. All of the beam data were packaged and sent to RS for a beam model because they do not yet have a tool for users to create a beam model. The physics manual briefly describes the proton dose calculation engine, but no information is provided detailing the exact process for beam model generation.

***Integrated Depth Dose Measurements***

The integrated depth doses curves (IDDCs) were obtained for 18 proton energies by scanning a large-area detector in a single, narrow, monoenergetic proton-beam incident on the central axis. The IDDCs were measured using an 8-cm-diameter integrating Bragg peak (BP) ionization chamber (PTW Inc, Freiburg, Germany) and a PC Electrometer (Sun Nuclear Corp, Melbourne, Florida). Even though there is some loss of charge outside the 8 cm BP chamber, it was considered adequate for commissioning because no larger chamber was available at that time.

Integrated charge measurements at 1-mm spacing were acquired for the entire range of each BP. The measured IDDCs were shifted to account for the water-equivalent thickness (WET) of the tank wall and the effective point of measurement of the BP chamber (4.2 mm WET). The IDDC peaks were normalized to the same nominal value of 100 for all 18 beams (Figure 2).

**Spot Sigma Size and Virtual Source Position**

A Lynx 2-dimensional scintillation imager (IBA Dosimetry, Schwarzenbruck, Germany) was used to measure in-air spot profiles at 5 different planes relative to isocenter: −10, −20, 0, +10, and +20 cm. The TPS assumes that spot shapes are invariant with respect to lateral displacement in the scanned field. Spot sigmas were measured at 5 different lateral positions within each plane, with average values used in the TPS. Figure 3 shows the spot profiles for 3 energies. The change in average spot spacing with distance from the isocenter was used to calculate the virtual source position for the x- and y-axes.

**Absolute Beam Calibration**

The absolute beam calibration is based on measurements made in uniform, single-layer fields. Square 10 × 10-cm² fields were created with spots arranged in a uniform grid with center-to-center spacing of 2.5 mm. Each spot was assigned a value of

---

**Table 1.** Eighteen energies were used for beam data measurements.

| Energy, MeV | D90 range, mm | Depth of measurement, cm | MU | MU/Spot | Scanning Area, 10.5 cm² | Spot Grid Spacing, cm | Total Dose Preliminary Beam Model, cGy | Scaled Dose Final Clinical Model, cGy |
|-------------|----------------|--------------------------|----|---------|------------------------|-----------------------|----------------------------------------|---------------------------------------|
| 98.5        | 75.1           | 3                        | 1849 | 1       | 10.5                  | 0.25                  | 176.2                                 | 146.2                                 |
| 106.0       | 85.6           | 3                        | 1849 | 1       | 10.5                  | 0.25                  | 171.3                                 | 142.2                                 |
| 113.5       | 96.6           | 3                        | 1849 | 1       | 10.5                  | 0.25                  | 167.6                                 | 139.1                                 |
| 121.0       | 108.2          | 3                        | 1849 | 1       | 10.5                  | 0.25                  | 165.2                                 | 137.2                                 |
| 128.5       | 120.3          | 4                        | 1849 | 1       | 10.5                  | 0.25                  | 169.1                                 | 140.3                                 |
| 136.0       | 132.9          | 4                        | 1849 | 1       | 10.5                  | 0.25                  | 166.7                                 | 138.3                                 |
| 143.5       | 146.0          | 4                        | 1849 | 1       | 10.5                  | 0.25                  | 164.7                                 | 136.7                                 |
| 151.0       | 159.6          | 4                        | 1849 | 1       | 10.5                  | 0.25                  | 162.6                                 | 134.9                                 |
| 158.5       | 173.7          | 5                        | 1849 | 1       | 10.5                  | 0.25                  | 164.2                                 | 136.2                                 |
| 166.0       | 188.2          | 5                        | 1849 | 1       | 10.5                  | 0.25                  | 163.5                                 | 135.7                                 |
| 173.5       | 203.2          | 5                        | 1849 | 1       | 10.5                  | 0.25                  | 162.6                                 | 134.9                                 |
| 181.0       | 218.6          | 5                        | 1849 | 1       | 10.5                  | 0.25                  | 160.7                                 | 133.4                                 |
| 188.5       | 234.4          | 6                        | 1849 | 1       | 10.5                  | 0.25                  | 162.8                                 | 135.1                                 |
| 196.0       | 250.7          | 6                        | 1849 | 1       | 10.5                  | 0.25                  | 163.1                                 | 135.3                                 |
| 203.5       | 267.4          | 7                        | 1849 | 1       | 10.5                  | 0.25                  | 161.7                                 | 134.2                                 |
| 211.0       | 284.5          | 7                        | 1849 | 1       | 10.5                  | 0.25                  | 161.4                                 | 134.0                                 |
| 218.5       | 301.9          | 8                        | 1849 | 1       | 10.5                  | 0.25                  | 162.5                                 | 134.9                                 |
| 228.5       | 325.8          | 8                        | 1849 | 1       | 10.5                  | 0.25                  | 162.5                                 | 134.9                                 |

Mean (SD) 164.9 (3.9) 136.9 (3.2)

Abbreviation: MU, monitoring unit.
1 MU to create a uniform lateral profile. The RS requires the measurements to be made between 1 cm depth and a position corresponding to one-half of the depth of the BP maximum. A water tank was set up with an Accredited Dosimetry Calibration Laboratory (ADCL)-calibrated PPC05 parallel plate ion chamber and electrometer for these measurements. The physical doses measured were scaled up by a factor of 1.1 to account for proton relative biological effectiveness (RBE) (Table 1).

Figure 2. Integrated depth doses acquired using an 8-cm-diameter Bragg peak chamber.

Figure 3. Spot profiles for 3 energies at isocenter plane in air.
One of the considerations for absolute calibration is the ability to generate a flat spread-out BP (SOBP), which can be used to adjust the output of the machine. By placing an ADCL-calibrated ion chamber in the flat SOBP region, IAEA TRS-398 [6] protocol can be performed, thus establishing the dose/MU relationship. Unfortunately, however, without having a TPS model, it is not feasible to generate a flat SOBP. However, a preliminary beam model using the point-dose measurements in single layers (Table 1) and measured integrated depth doses (IDDs) will have correct relative weights between the layers because the energy dependence of the nozzle MU chamber is minimal. This preliminary model can be used to generate any desired SOBP beam using inverse optimization and thus can be used for TRS-398.

Verification of Beam Model

The verification of the beam model consisted of the evaluation of (1) spot profiles, (2) depth doses for single-layer plans, (3) absolute dose versus field size for single-layer plans, (4) depth doses of inversely optimized SOBP plans, (5) absolute doses for SOBP plans, (6) lateral dose profiles, and (7) patient-specific quality assurance of phantom plans.

Various phantom plans with a single spot located on the central axis were generated. The spot characteristics at the surface of the phantom obtained from the TPS were compared with measurements with the Lynx. A maximum discrepancy of 0.5 mm for SOBP plans, (6) lateral dose profiles, and (7) patient-specific quality assurance of phantom plans.

Verification of Beam Model

The verification of the beam model consisted of the evaluation of (1) spot profiles, (2) depth doses for single-layer plans, (3) absolute dose versus field size for single-layer plans, (4) depth doses of inversely optimized SOBP plans, (5) absolute doses for SOBP plans, (6) lateral dose profiles, and (7) patient-specific quality assurance of phantom plans.

Various phantom plans with a single spot located on the central axis were generated. The spot characteristics at the surface of the phantom obtained from the TPS were compared with measurements with the Lynx. A maximum discrepancy of 0.5 mm was allowed between measured and calculated spot sigmas.

To evaluate the variation of output with field size, single-layer (monoenergetic) beams were generated for square fields with sizes of $5 \times 5$, $10 \times 10$, $15 \times 15$, $20 \times 20$, $25 \times 25$, and $29 \times 29$ cm$^2$. The isocenter for these beams was located at the surface of the phantom with an extra variation for field size $10 \times 10$ cm$^2$, when the isocenter at a 10-cm depth was also evaluated. These single-layer beams have spots arranged in a uniform grid with each spot assigned the same MU value. Eleven different energies (228.5, 218.5, 211, 203.5, 188.5, 173.5, 158.5, 143.5, 128.5, 113.5, and 98.5 MeV) were sampled from the entire available range for the purpose of this evaluation. The combination of 6 field sizes and 11 different energies resulted in 66 unique beams. Point-dose measurements were made at 2 different locations along the BP: (1) at a shallow depth in the flat entrance region, and (2) at a deeper depth where the contribution to the dose from the halo would be larger. Furthermore, depth doses for the $10 \times 10$-cm$^2$ fields were also measured with a multilayer ionization chamber (MLIC) (Zebra, IBA Dosimetry) and compared with the depth doses calculated in the TPS. The point-dose measurements were considered acceptable if the percentage of difference was within ±3% of the calculated. For depth doses, the tolerance for the distal-edge position was 1 mm, and all points along the depth dose were required to be within ±3% relative difference.

For evaluation of point doses, percentage depth-doses, and lateral profiles, 3-dimensional targets corresponding to field sizes from $5 \times 5$ to $25 \times 25$ cm$^2$, with ranges from 7.5 to 32.5 cm, and widths from 0.5 to 22 cm were created in a virtual phantom in the TPS. Some of the targets corresponded to asymmetric field sizes, such as $15 \times 20$ and $10 \times 25$ cm$^2$. Each target was inversely planned to deliver a uniform dose within the SOBP region using a single beam resulting in 30 plans. Point-dose measurements were performed using the calibrated PPC05 chamber at multiple locations in the SOBP region as well in the entrance region. Additionally, for plans with field sizes smaller than $10 \times 10$ cm$^2$, percentage depth doses were obtained using the MLIC. Because of the internal electronics, the MLIC cannot be used for fields with a side $>10$ cm. The profile measurements were performed using either EDR2 film (Carestream Health, Inc, New York, New York) or a MatrixxPT (IBA Dosimetry) ion chamber array at 1 to 4 depths for each SOBP field. The following tolerances were employed for analysis: point-dose accuracy ±3% of the calculated, SOBP depth doses ±3% at any point along the curve, and range accuracy ±1 mm. For profiles, a tolerance of 1 mm was allowed for comparison of full width half maximum between TPS and measurement.

The final component of the verification process involved the evaluation of the overall accuracy of the treatment planning and delivery using realistic clinical plans. The TG-119 report by the American Association of Physicists in Medicine, which pertains to intensity-modulated radiation therapy commissioning, has provided several planning exercises for institutions commissioning their intensity-modulated radiation therapy systems [7, 8]. In the absence of any standard guidelines for proton
PBS, we adopted the TG-119 planning and delivery exercise for testing our system. The following beam arrangement was used for developing TG-119 plans: (1) a 3-field multitarget, (2) a 2-field prostate target, (3) a 2-field head and neck target, (4) a 3-field C-shape target with easy constraints, and (5) a 3-field C-shape target with difficult constraints. The plans were optimized using multifield optimization methods, that is, all beams were optimized simultaneously to achieve the desired goals. Each beam was delivered, and measurements performed at 1 to 3 depths using the MatrixxPT detector. The analyses were performed on a beam-by-beam basis and quantified using the gamma index. A tolerance of 3% and 3 mm was used with a minimum pass rate of 90% for the gamma index analysis along with a dose threshold of 10%.

Results

Spot Profile and Size Analysis

The sigma values were computed by the least-square fitting of gaussian functions to the spot profiles. The deviation between the measured and calculated sigma values in air was found to be within tolerance with a maximum deviation of 0.2 mm for a 151 MeV beam with a nominal sigma of 5.4 mm.

Depth Doses for 10 × 10-cm² Single Layers

This is a relative comparison between measured and calculated depth doses. All the depth doses met the ± 3% criteria between the measured and calculated values. The maximum deviation in range was 0.3 mm.

Point Doses for Single Layers of Different Field Sizes

All 66 point-dose measurements, performed at shallow depths (flat-entrance region) for single-layer plans (6 field sizes and 11 proton energies), were within ± 3% of that calculated by the TPS. The maximum deviation was −2.8%, seen for 5 × 5 cm² field size at 228 MeV.

The differences between calculated and measured doses for single layer plans for points at deeper depths with large halo contribution are shown for field sizes 10 × 10 and 29 × 29 cm² in Figure 4A. The maximum difference for all measurements was 3.4% for the 29 × 29 cm² field at 228.5 MeV. Figure 4B shows the dose difference as a function of field size for 2 different energies, 158.5 and 228.5 MeV.
Depth Doses Along the Central Axis for Spread-out BP Fields

The central-axis depth-dose measurements were made for the 18 beams with field sizes smaller than $10 \times 10$ cm$^2$ using the MLIC detector. The maximum range error was $\leq 1$ mm. All points in the measured depth doses were within 3% of the calculated value.

Absolute Point Doses for Spread-out BP Fields

Figure 5A through 5C summarizes the percentage of differences between the dose calculated by the TPS and measurements made on the central axis as a function of range, field area, and measurement depth. As shown, there are some point-dose values outside the tolerance of $\pm 3\%$. Specifically, the percentage of differences are larger than 3% for beams with ranges $>30$ cm, field sizes $>15 \times 15$ cm$^2$, and depth of measurements $>25$ cm. The maximum difference of 4.5% corresponds to a beam with a range of 32 cm, SOBP width of 5 cm, field size $25 \times 10$ cm$^2$, and measurement depth of 31 cm.

Lateral Dose Profiles

Profile measurements were made at 1 to 4 different depths within the SOBP region and at 5 cm depth in the entrance region. Plans were selected to cover field sizes from $5 \times 5$ to $20 \times 20$ cm$^2$, ranges from 8.5 to 32 cm, and SOBP widths from 5 to 22.
cm. Overall, > 60 profile measurements were made. The maximum deviation in full width half maximum was < 1 mm. The planned and measured profiles match well at both the shoulder and penumbra regions with a maximum deviation of < 3%.

**TG-119 Quality Assurance Plans**

The TPS was successful in finding a solution that met the given treatment-plan goals for all targets, except the C-shape PTV with difficult constraints. The structures with violations were the core (5% of the volume to receive ≤ 1000 centigray [cGy]) and C-shape PTV (95% volume to receive ≥ 5000 cGy). The quality assurance of the plans consisted of beam-by-beam delivery and verification using the 2-dimensional MatrixxPT array. The results of the gamma index analysis are given in Table 2.

**Range Shifter Implementation**

The minimum energy provided by the system is 98.5 MeV, corresponding to the range of 7.5 cm in water. Any shallow targets that require proton energies below that range will require the use of range shifters in the beam path. Two range shifters corresponding to WET of 4 cm and 7.5 cm were also validated for clinical use. This was similar to the beam verification outlined in this study, but with the addition of a range shifter in the beam path. Point-dose measurements revealed large discrepancies that were dependent of field size and air gap for the range shifters. Differences > 8% were found at shallow depths (< 3 cm), when using a range shifter of 7.5-cm WET. For this reason, additional commissioning data are required to provide accurate beam models with range shifters. A full description of this will be provided in a separate publication.

**Discussion**

The clinical implementation of the RS proton PBS system has been presented. The beam modeling for the pencil beam in RS requires the IDDCs (or BPs) in relative units. To measure those BPs with a scanning ion chamber, a reference signal is required. The positioning of the reference detector in the beam path is difficult because of the small size of the spot. One way to mitigate that issue is to get a reference signal directly out of the nozzle MU chamber.

A trend can be seen in Figure 4 in which the discrepancy between measured and calculated doses increases with field size for higher energy levels. We found that the RS planning system underestimated doses for beams that had field sizes > 15 × 15 cm² and energy > 218 MeV. The maximum differences for some points were found to be as much as 4.5%. Most of these beams are rarely used in the clinic. The higher differences for larger fields and higher energies may be due to a few reasons: (1) the measurements of the IDDCs using an 8-cm BP chamber will not account for any charge in the low-dose region that is farther than 4 cm from the central axis [9–12], and (2) the inability of the pencil-beam algorithm to accurately account for the low-dose region produced around the central spot that is called the nuclear halo. Although a second gaussian is used to model the nuclear halo, it may not be enough to model the low-dose tails that are produced farther from the central axis. As the field size increases, this effect is compounded by the addition of low-dose tails at the central axis. Because the SOBP plans are composed of many single layers with different weights, the dose differences from unmodified single layers are propagated to the complex, inversely modulated SOBP plans. The efficiency of an 8-cm BP chamber was estimated using the open

---

**Table 2. Results of the beam-by-beam gamma index (GI) for various TG119 targets.**

| Multitarget      | C-shape target—Hard | C-shape Target—Easy | Head and Neck Target | Prostate Target |
|-------------------|----------------------|----------------------|----------------------|-----------------|
|                   | GL (cm) | GI | GL (cm) | GI | GL (cm) | GI | GL (cm) | GI |
| Left Lateral, cm  | Anterior, cm (cm) GI | Anterior, cm (cm) GI | Anterior, cm (cm) GI | Left Lateral, cm (cm) GI | Left Lateral, cm (cm) GI |
| 10                | 97.6 | 8.5 | 94.6 | 8.5 | 97.4 | 10 | 100.0 | 10 |
| 15                | 94.5 | 4   | 97.8 | 4   | 97.9 | 15 | 99.8 | 15 |
| 20                | 99.5 | 15  | 94.8 | 15  | 92.8 | 19 | 99.8 | 19 |
| Vertex, cm        | Left Lateral, cm (cm) GI | Right Lateral, cm (cm) GI | Right Lateral, cm (cm) GI | Left Lateral, cm (cm) GI |
| 10                | 98.9 | 10  | 99.1 | 10  | 98.4 | 10 | 99.7 | 10 |
| 15                | 98.0 | 13.5 | 99.8 | 13.5 | 100.0 | 12.5 | 99.9 | 15 |
| 20                | 99.5 | 15  | 94.8 | 15  | 92.8 | 19 | 99.8 | 19 |
| Anterior, cm      | Right Lateral, cm (cm) GI | Right Lateral, cm (cm) GI |
| 13                | 97.1 | 10  | 99.5 | 10  | 97.5 |
| 15                | 98.5 | 13.5 | 99.2 | 13.5 | 98.5 |
| 22                | 97.4 | 15  | 95.3 | 15  | 93.3 |
source, highly validated GATE (Geant4 Applications for Tomographic Emission) code [13]. The BP corresponding to 226 MeV cm was simulated for 2 scenarios: (1) charge collected in 8-cm-diameter disc to simulate the BP chamber, and (2) charge collected in 40-cm slab to account for the low-dose tail (Figure 6). The maximum loss of charge was $8.3\%$ at 21 cm depth. Although, it is desirable to have a chamber $>8$ cm for IDDC measurement, at the time of our commissioning, no bigger chamber was available. Even though, our measurements were done with 8 cm, the validation results show that the performance of the TPS was clinically acceptable under most conditions. An 8-cm BP chamber was also used for commissioning purposes by Fracchiolla et al [14].

Commissioning of range shifters is necessary to enable the treatment of shallow targets. In the current version of RS, whenever a range shifter is added to the beam path, the range shifter and the physical air gap are considered part of the patient geometry. The dose calculations are started at the upstream surface of the range shifter. The result is a large inhomogeneity (air gap) in the beam path that is currently not handled well in RS. Discrepancies as large as 8% were seen at the shallow depths for the thicker (7.5 cm WET) range shifter. One possible solution is to commission a separate beam model from spot profiles and IDDC measurements made with the range shifter in place. The process of commissioning these additional beam models is underway and will be described in a separate manuscript.

Before the clinical release of the TPS, an independent verification of dose-MU calibration was performed by a physicist not involved in the commissioning process. Later on, calibration-check thermoluminescent dosimeters from the Imaging and Radiation Oncology Core (IROC, Houston, Texas) were irradiated, and the output was determined to be within 1%. In January 2015, a site visit was undertaken by an IROC team to credential the use of proton therapy in National Cancer Institute–funded clinical trials at SCCA-PTC. As part of the credentialing process, various anthropomorphic phantoms (proton head, proton lung, proton prostate, and proton liver) were irradiated. After the successful irradiation of phantoms, site visit, and calibration check TLD, the SCCA-PTC completed the IROC approval process and obtained the credentialing in April 2015.

The commissioning and verification methodology presented in this study can be used as a reference guide by upcoming proton therapy centers. Very often, the capabilities of a newly acquired TPS in dose-calculation accuracy and limitations are not known before the commissioning process. Our study will aid such centers and has a potential to reduce the variability of the proton PBS commissioning. This could further standardize the radiation therapy dose reporting in future multicenter trials using PBS.

### ADDITIONAL INFORMATION AND DECLARATIONS

**Conflicts of Interest:** The authors have no conflicts of interest to disclose.
References

1. Pedroni E, Bacher R, Blattmann H, Böhringer T, Coray A, Lomax A, Lin S, Munkel G, Scheib S, Schneider U, Tourovsky A. The 200-MeV proton therapy project at the Paul Scherrer Institute: conceptual design and practical realization. Med Phys. 1995;22:37–53.

2. Gillin MT, Sahoo N, Bues M, Ciangaru G, Sawakuchi G, Poenisch F, Arjomandy B, Martin C, Titt U, Suzuki K, Smith AR, Zhu XR. Commissioning of the discrete spot scanning proton beam delivery system at the University of Texas M.D. Anderson Cancer Center, Proton Therapy Center, Houston. Med Phys. 2010;37:154–63.

3. Zhu XR, Poenisch F, Lii M, Sawakuchi GO, Titt U, Bues M, Song X, Zhang X, Li Y, Ciangaru G, Li H, Taylor MB, Suzuki K, Mohan R, Gillin MT, Sahoo N. Commissioning dose computation models for spot scanning proton beams in water for a commercially available treatment planning system. Med Phys. 2013;40:041723.

4. Cameron J, Schreuder N. Smaller – lighter – cheaper: new technological concepts in proton therapy. In: Linz U, ed. Ion Beam Therapy: Fundamentals, Technology, Clinical Applications. Berlin, Germany: Springer-Verlag; 2012. pp. 673–85.

5. Shen J, Liu W, Anand A, Stoker JB, Ding X, Fatyga M, Herman MG, Bues M. Impact of range shifter material on proton pencil beam spot characteristics. Med Phys. 2015;42:1335–40.

6. International Atomic Energy Agency. Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry Based on Standards of Absorbed Dose to Water. Vienna, Austria: IAEA; 2000. Technical Report Series 398.

7. Ezzell GA, Galvin JM, Low D, Palta JR, Rosen I, Sharpe MB, Xia P, Xiao Y, Xing L, Yu CX; IMRT Subcommittee; AAPM Radiation Therapy Committee. Guidance document on delivery, treatment planning, and clinical implementation of IMRT: report of the IMRT Subcommittee of the AAPM Radiation Therapy Committee. Med Phys. 2003;30:2089–115.

8. Ezzell GA, Burmeister JW, Dogan N, LoSasso TJ, Mechalakos JG, Mihailidis D, Molineu A, Palta JR, Ramsey CR, Sailer BJ, Shi J, Xia P, Yue NJ, Xiao Y. IMRT commissioning: multiple institution planning and dosimetry comparisons, a report from AAPM Task Group 119. Med Phys. 2009;36:5359–73.

9. Li Y, Zhu RX, Sahoo N, Anand A, Zhang X. Beyond gaussians: a study of single-spot modeling for scanning proton dose calculation. Phys Med Biol. 2012;57:983–97.

10. Lin L, Kang M, Solberg TD, Ainsley CG, McDonough JE. Experimentally validated pencil beam scanning source model in TOPAS. Phys Med Biol. 2014;59:6859–73.

11. Schwaab J, Brons S, Fieres J, Parodi K. Experimental characterization of lateral profiles of scanned proton and carbon ion pencil beams for improved beam models in ion therapy treatment planning. Phys Med Biol. 2011;56:7813–27.

12. Pedroni E, Scheib S, Böhringer T, Coray A, Grossmann M, Lin S, Lomax A. Experimental characterization and physical modelling of the dose distribution of scanned proton pencil beams. Phys Med Biol. 2005;50:5461–61.

13. Jan S, Santin G, Strul D, Staelens S, Assie K, Aute M, Avner S, Barbier R, Bardies M, Bloomfield PM, Brasse D, Breton V, Bruyndoncckx P, Buvat I, Chatziioannou AF, Choi Y, Chung YH, Comtat C, Donnarieix D, Furrer L, Glick SJ, Groiselle CJ, Guez D, Honore PF, Kehoas-Cavata S, Kirov AS, Kohli V, Koole M, Krieger M, van der Laan DJ, Lamare F, Largeron G, Lartizien C, Lazaro D, Maas MC, Maigne L, Mayet F, Melot F, Merheb C, Pennacchio E, Perez J, Pietrzyk U, Rannou FR, Rey M, Schaart DR, Schmidtlen CR, Simon L, Song TY, Vieira JM, Visvikis D, Van de Walle R, Wieers E, Morel C. GATE: a simulation toolkit for PET and SPECT. Phys Med Biol. 2004;49:4543–61.

14. Fracchiolla F, Lorentini S, Widesott L, Schwarz M. Characterization and validation of a Monte Carlo code for independent dose calculation in proton therapy treatments with pencil beam scanning. Phys Med Biol. 2015;60:8601–19.