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FULL PAPER

Quality assurance evaluation of spot scanning beam proton therapy with an anthropomorphic prostate phantom

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Objective: The purpose of this study was to evaluate spot scanning proton therapy with an anthropomorphic prostate phantom at the Proton Therapy Center of The University of Texas MD Anderson Cancer Center at Houston, TX (PTCH).

Methods: An anthropomorphic prostate phantom from the Radiological Physics Center (RPC), The University of Texas MD Anderson Cancer Center, Houston, TX, was used, which contained thermoluminescent dosimeters and GAFCHROMIC® EBT2 film (ISP Technologies, Wayne, NJ). The phantom was irradiated by the Hitachi synchrotron (Hitachi America, Ltd, Tarrytown, NY), and the results were compared between the treatment planning system (TPS) and RPC measurements.

Results: RPC results show that the right/left, inferior/superior and posterior/anterior aspects of the coronal/sagittal and EBT2 film measurements were within $\pm 7\%$ / ± 4 mm of the TPS. The RPC thermoluminescent dosimeter measurements of the prostate and femoral heads were within 3% of the TPS.

Conclusion: The RPC prostate phantom is a useful mechanism to evaluate spot scanning beam proton therapy within certain confidence levels.

Advances in knowledge: The RPC anthropomorphic prostate phantom could be used to establish quality assurance of spot scanning proton beam for patients with prostate cancer.

During the past decade, the use of proton beams in the treatment of cancer has increased. Passive scattering has been the most common technique for delivery of proton beams. Passive scattering uses range modulation wheels with a combination of field shaping apertures and compensators to deliver a uniform dose distribution to the target [1–4]. Until recently, the proton scanning technology has only been available at one facility, namely the Paul Scherrer Institute in Switzerland [5]. The spot-scanning beam at the Paul Scherrer Institute moves only along the longitudinal axis and is combined with a moving couch. The scanning proton beams confine the dose distribution to the target volume by depositing the dose using pencil beams of different energies to deliver the dose without using any scattering or range-modulating devices [6]. This is considered an improvement with respect to passively scattered proton beams because there are no apparatuses in the beam path to produce contamination by neutrons [7].

The principle of scanning beam is simple and is based on the fact that protons, being charged particles, are subject to Lorentz forces. That is, when subjected to an electric field,

protons are accelerated, and when subjected to a magnetic field, protons are deflected. In depth, the Bragg peaks are stacked by altering the proton energy. Through this combination of scanning and energy variation, the Bragg peak can be effectively placed anywhere within the target in three dimensions. Dose uniformity is then achieved by a treatment planning optimisation of the individual fluences of each pencil beam [8]. The Radiological Physics Center (RPC), The University of Texas MD Anderson Cancer Center, Houston, TX, has several anthropomorphic phantoms, which are used as part of the credentialing services for participation in the National Cancer Institute (NCI, at the National Institutes of Health, Bethesda, MD) sponsored clinical trials. The pelvis phantom was originally designed to be of mailable quality assurance to test intensity-modulated radiation therapy (IMRT) procedures. With this in mind, the design and materials were chosen to simulate the pelvis region of a patient with the anatomy present to create restrictions for treatment planning and delivery in typical IMRT cases. The relative stopping power of each material is used to construct the phantom to verify the tissue equivalence of the materials used. In the

Figure 1. Axial CT slice of the pelvis phantom. TLD, thermoluminescent dosimeter.

treatment of prostate cancer, the Proton Therapy Center at Houston, TX (PTCH), uses two opposing beams. Previously, RPC used a prostate phantom for passive scattering proton beam and found that by using an appropriate value of relative stopping power, the prostate phantom could be used to evaluate proton passive beam therapy. The evaluation of spot scanning is a new challenge. Therefore, the purpose of this study was to evaluate spot scanning for prostate therapy using the RPC phantom.

METHODS AND MATERIALS

The PTCH is equipped with a Proton Beam Therapy Hitachi synchrotron (Hitachi America, Ltd, Tarrytown, NY), which supplies proton beams to four treatment rooms [9]. Three of the rooms are equipped with passively scattered proton beam delivery and one is equipped with a spot scanning delivery system. The synchrotron has been configured to produce 94 different beam energies for the purposes of spot scanning. Each of the beam energies requires a different spill of the beam from the synchrotron. The maximum length of time per spill is 4.4 s. After each spill, the beam in the synchrotron is accelerated to its maximum energy and is then decelerated. The deceleration process requires approximately 1 s. The accelerating process begins again until the protons reach the required energy. The time between spills is approximately 2.1 s. Before extraction of the beam from the synchrotron, the energy of the beam is checked by measuring the revolution frequency and the orbit position. Hitachi has determined that the measurement of the beam orbit

position in the synchrotron within ± 1 mm assures the accuracy of the proton range to $<0.025 \text{ g cm}^{-2}$ [10]. The output dose of G3PB having energy of 198.3 MeV and range of 25 cm for this work was measured using a PTW Markus[®] chamber (PTW, Freiburg, Germany) with an absolute dose calibration factor. The chamber was inserted into a tightly fitted moulded plastic phantom and positioned such that the centre of the chamber was aligned with the central axis of the field.

Calculation of relative stopping power

To measure the relative stopping powers of each material (prostate, bone and outer shell) in the phantom, Equation (1) was used, where Δx is the shift in the percentage depth dose curve when the target material is placed in the path of the beam. The reference curve was taken with no phantom material placed in the beam path [4].

The relative stopping power was provided by RPC and calculated as:

$$\text{Relative stopping power} = 1 + \Delta x + \text{width of the material}, \quad (1)$$

The Δx value indicates the displacement between two scans in Equation (1). This procedure was repeated for each phantom material.

Treatment planning and delivery of the treatment

The purpose of the pelvis phantom is to provide a mechanism for quality assurance evaluation of the entire proton treatment process. With this in mind, all efforts were made to keep treatment planning as close to a patient plan as possible. The phantom was scanned using a clinical GE CT scanner (LightSpeed RT16 CT scanner; GE Healthcare Technologies, Waukesha, WI), and the Hounsfield Units (HU) of each material were measured in the treatment planning system (TPS). Both the phantom shell and imaging insert were filled with water at room temperature, and a special effort was made to minimise the capture of air bubbles within the phantom. The dosimetry insert was loaded with thermoluminescent dosimeters (TLDs) and film for imaging purposes.

GAFCHROMIC[®] EBT2 film (ISP Technologies, Wayne, NJ) was cut to fit in the phantom, with one piece of the film through the coronal plane and two smaller pieces through the sagittal plane. The CT scan of the phantom with the film-loaded dosimetry insert in place was used to check for any air gaps along the planes of the film. Extra pieces of the film were fitted in the dosimetry insert to try to eliminate these air gaps.

Table 1. Organs at risk (OARs) doses predicted by the treatment planning system

OAR	No. >15% volume receives dose that exceeds	No. >25% volume receives dose that exceeds	No. >35% volume receives dose that exceeds	No. >50% volume receives dose that exceeds
Bladder Gy _{RBE}	6.7	6.3	6.0	5.7
Rectum Gy _{RBE}	6.3	6.0	5.7	5.0

RBE, relative biological effectiveness.

Figure 2. Side view of the pelvis phantom.

The phantom was placed on the CT table, and the laser markings were drawn on the left and right lateral surfaces and on the anterior surface of the phantom for reference during treatment delivery setup. Radio-opaque markers (BBs) were placed on the laser markings to localise the position of the phantom in the TPS. The pelvis phantom was scanned twice using a CT scanner at the PTCH using the pre-set abdomen protocol at RPC. This first scan had the imaging insert loaded in the phantom, and the second scan had the dosimetry insert loaded in the phantom. The image set with the imaging insert was used for the main treatment plan, as it held the necessary anatomy. The prostate, bladder, rectum and femoral heads were all contoured separately as shown in Figure 1. The dosimetry insert was loaded with TLD and film for imaging purposes.

The images were transferred to the Eclipse™ TPS (v. 8.9.17; Varian Medical Systems, Inc., Palo Alto, CA). A treatment plan was generated with left and right lateral beams that delivered a prescription dose of 6 Gy [relative biological effectiveness (RBE)] at least 95% to planning target volume (PTV) tumour at source to axis distance 270 cm.

The RBE describes the capacity of a specific ionising radiation to produce a specific biological effect [11]. For proton therapy, the International Commission on Radiation Units and Measurements (ICRU, Bethesda, MD) Report 78 recommends use of a generic RBE value of 1.1 in the clinical setting based on *in vivo* laboratory studies. Along the plateau and the spread-out Bragg peak, the RBE does not show much variation until the distal end of the spread-out Bragg peak. At this location, the RBE might increase from 5% to 10%, which can extend the biologically effective range of the beam by 1–2 mm [12].

Constraints were applied to achieve 98% dose of total dose to the prostate (PTV) and specified dose to the normal organs as prescribed in Table 1.

GAFCHROMIC EBT2 film and two TLD capsules were placed in the prostate (PTV) and two more were placed in the femoral heads. The films were placed in the coronal and sagittal plane through the centre of the prostate, as shown in Figure 2. Alignment was performed by using laser and X-ray systems to deliver the dose to the phantom (Figure 3).

BBs were physically removed from the phantom, whereas the laser markings were left in place. The BBs would have added material to the beam path and changed the delivered treatment from the planned treatment.

Figure 3. Compression of relative stopping power between phantoms, treatment planning and literature values. ● indicates phantom value; ■, treatment planning value; ×, stopping power literature.

Figure 4. Thermoluminescent dosimeters dose calibration curve 4 (a) and GAFCHROMIC® EBT2 film (ISP Technologies, Wayne, NJ) calibration curve 4 (b). OD, optical density; TLD, thermoluminescent dosimeters.

Measuring dose curves of thermoluminescent dosimeters and EBT film

GAFCHROMIC EBT2 film were scanned with a charge-coupled device microdensitometer and a TLD was used to measure an absolute dose in specific locations. These data were analysed with a MATLAB (homemade software by RPC) program. The calibrated film dose was scaled relative to the calibrated TLD dose to provide two-dimensional profiles across the sagittal and coronal planes of the phantom. The film was then carefully scanned to minimise registration errors. The calibration curves were applied to the EBT2 film and TLD for dose measurements, as shown in Figure 4.

Data registration and analysis

After the treatment, the TLD and film were both analysed and registered to the treatment plan. The TLD was registered to the phantom plan through MATLAB-based software, a Computational Environment for Radiotherapy Research (CERR)

program (Washington University, St Louis, MO), to designated points that were measured on the CT scan set to 2-mm slice widths. The five landmarks were chosen because they were easily visible on the scan and were not in the same plane. Three of the points shown (posterior edge of the rectum, the centre of the prostate and the right edge of the prostate) were in the same centre plane, whereas the other two points moved superior and posterior in the phantom. The film was scanned with a charge-coupled device microdensitometer and also registered to the treatment plan in CERR. Dosimetry tools for the phantom were evaluated as a system to verify the treatment planning, setup and delivery to the pelvis phantom. The TLD irradiations were used as the absolute dosimeter, and the film dose was scaled to these dose points for a relative measurement. Two profiles in each plane of film were exported to Microsoft Excel™ (Microsoft Corporation, Redmond, WA) along with the corresponding profiles from the treatment plan. The average displacement between the measured dose and the calculated dose was measured for each plane [13].

Figure 5. The dose profiles along the beam path on the coronal plane. RPC, Radiological Physics Center, The University of Texas MD Anderson Cancer Center, Houston, TX; TLD, thermoluminescent dosimeters.

These data were stored in a spreadsheet that was recalled when registering the film in an in-house program, which supplements CERR. This software also included a section to use the TLD measurements and would automatically scale the film dose to these points. The pinholes in the scanned film were uploaded into CERR for registration with the TPS. The dose profiles from the film were compared with the treatment plan to check for agreement in the dose surrounding the prostate. The profiles were taken through the centre of the coronal plan from left to right and from superior to inferior. The sagittal profiles went through the centre of the film in the anterior/posterior direction and were off-centre 2 mm from superior to inferior. This was because of the sagittal film being cut in the centre to intersect with the coronal film. These selected dose profiles through the film and TPS were exported for further analysis.

RESULTS AND DISCUSSION

Stopping power comparison

The stopping powers were compared with the literature values and HU calibration curve for the Eclipse TPS. The measured stopping powers were all <4% different than the corresponding literature values. For this reason, the measured stopping powers were considered valid, as differences in material composition and density could account for the differences in the stopping powers.

The measured stopping powers for several of the materials, including the target material, were nearly 4% different from the stopping power values used in the TPS. The difference in the stopping power values for the phantom materials from the TPS could impact the comparisons of the calculated and measured doses by greatly affecting the measured dose.

Each relative stopping power was then compared with the calibration curve of the CT scanner. All of the structures were contoured so that a treatment plan could be devised as shown in the axial slice of the phantom in Figure 1. The stopping powers assigned by the TPS were not altered [14,15].

EBT2 film and thermoluminescent dosimeter calibration curve

GAFCHROMIC EBT2 film is the preferred type of film to use for phantom irradiations because it reliably gathers a large amount of information and does not need wet processing because it is not daylight sensitive [16]. It is easier to cut the film into smaller pieces that are shaped to fit the phantom. The film calibration curve was used for the calibration of the irradiated film.

The TLDs were read 14 days after irradiation to lessen the effects of fading on the dose calculations. The measured TLD were compared with the measured beam data for the use of both inserts. The CT scan of the phantom holding the imaging insert was used to create the treatment plan, and these beams and dose points were placed on the image set from the dosimetry insert. It was expected that changing the calibration curve of the TPS to account for the actual stopping powers of the materials comprising the pelvis phantom would improve the dose comparison, as it would provide a more accurate calculation by the TPS.

Treatment planning

The TPS was used to generate a plan to calculate dose using the parameters that were listed in Table 1. The dose was calculated with the beams placed on both the imaging insert and again with the beams placed on the dosimetry insert.

To have the physical dose to the target at 6 Gy, the biological dose to the phantom was equaled to 6.6 cGy_{RBE}. It is

Figure 6. Posterior/anterior profile—sagittal plane. RPC, Radiological Physics Center, The University of Texas MD Anderson Cancer Center, Houston, TX; TLD, thermoluminescent dosimeters.

Figure 7. Inferior/superior profile—coronal plane. RPC, Radiological Physics Center, The University of Texas MD Anderson Cancer Center, Houston, TX.

conventional (at RPC) to irradiate the phantom, TLD and film to a target dose of 6 Gy. Dose delivery needs to be documented to correctly estimate the dose delivered to the TLD.

Dose profile comparison

The dose profiles from the film were plotted along with the profiles taken from the TPS to compare dose profiles. The fall-off regions along the edge of the dose profiles were characterised by a linear regression from the 80–20% dose levels. The average displacement is

–4.0 mm on the left side and 4.0 mm on the right side, as shown in Figure 5.

The average of these displacements was taken as the total displacement between the profiles. The left/right profile showed a displacement that was <5 mm.

The posterior/anterior dose profile from the sagittal film is shown in Figure 6. For this plane, the displacement was 3 mm,

Figure 8. Inferior/superior profile—sagittal plane. RPC, Radiological Physics Center, The University of Texas MD Anderson Cancer Center, Houston, TX.

Figure 9. Inferior/superior comparison of sagittal and coronal plane.

with good agreement along the entire profile. Note that the data at the centre of the film is missing because of the film being cut to intersect with the coronal film.

An inferior/superior dose profile was obtained from both the coronal and the sagittal films, as presented in Figure 7 and Figure 8, respectively. The displacement for each profile is <5 mm. A 1-mm setup error because of laser alignment of the phantom could have contributed to the displacement.

The lasers at the PTCH are only calibrated with the gantry at 270° horizontally clockwise and are not normally used for patient setup. Bony anatomy is used to check the setup of the patient by an on-board X-ray imaging system. When the phantom is on the treatment table, the only anatomy that could be used for localisation would be the femoral head materials, which are two symmetrical cylinders. The concern that this would not provide the necessary landmarks to adequately position the phantom led to the use of the laser markings from the CT scan.

The inferior/superior dose comparison of both the sagittal and coronal planes is very close to each other with a maximum 2% difference (Figure 9). The average displacement is 2-mm difference between the sagittal and coronal planes.

Gamma comparison

The gamma tool provides a quantitative method for comparing the two dose distributions. In this article, we have shown the use of the tool in comparing two similar dose distributions [17]. Greater than 95% of the comparison points for the EBT2 film passed the $\pm 7\%/\pm 4$ mm criterion. The gamma map analysis for the coronal and sagittal planes is shown in Figure 10.

The sagittal gamma analysis shows that the gap in the centre is because the film was cut into two pieces. Gamma comparison of sagittal and coronal film confirmed agreement of $>95\%$ of points within a $\pm 7\%/\pm 4$ mm criterion.

Thermoluminescent dosimeter measurements

The results shown in Table 2 indicate that the left and right TLD in the prostate differed from the dose predicted by the TPS, with

Figure 10. GAFCHROMIC[®] EBT2 film (ISP Technologies, Wayne, NJ) gamma analysis map for the coronal (a) and sagittal planes (b).

Table 2. The dose comparisons of organs at risk between Radiological Physics Center (RPC), The University of Texas MD Anderson Cancer Center, Houston, TX, and treatment planning system (TPS) calculations

	Femoral head left	Femoral head right	Prostate left (PTV)	Prostate right (PTV)
RPC TLD measurements G_{RBE}	2.43	2.41	5.94	5.93
TPS calculations G_{RBE}	2.49	2.46	6.1	6.1
%Difference	2.40	2.03	2.62	2.78

PTV, planning target volume; RBE, relative biological effectiveness; TLD, thermoluminescent dosimeters.

2.62% and 2.78%, respectively. These values were well within the criterion of $\pm 7\%/\pm 4$ mm. The dose to the target was within 3% of the planned dose, and the dose to the femoral heads was within 2.5%.

The left femoral head and right femoral head differed from the treatment plan dose by 2.40% and 2.03%, respectively. These results show that the dose difference between the RPC's TLD and treatment plan for the prostate and femoral heads was within 3%.

CONCLUSIONS

As the phantom was originally designed to evaluate photon IMRT procedures, the materials chosen were not necessarily proton equivalent. Comparing the measured values to the HU-stopping power calibration curve used by the TPS, it was found that the

stopping powers for the materials were relatively 4% closer to those of actual patients. The TLDs of the prostate and femoral heads were within 3% of the RPC measurements and plan value. EBT2 film dose distribution profiles and gamma comparison were within $\pm 7\%/\pm 4$ mm. Overall, it was found that the spot scanning proton beam measurements acquired in the anthropomorphic prostate phantom demonstrated acceptable agreement ($>95\%$ of points pass $\pm 7\%/\pm 4$ mm criterion) compared with the Eclipse treatment planning predicted values.

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