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Water Equivalent Thickness Analysis of Immobilization Devices for Clinical Implementation in Proton Therapy

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Immobilization devices can impact not only the inter- and intra-fraction motion of the patient, but also the range uncertainty of the treatment beam in proton therapy. In order to limit additional range uncertainty, the water equivalent thickness (WET) of the immobilization device needs to be well known and accurately reflected in the calculations by the treatment planning system (TPS). The method presented here focusses on the use of a nozzle-mounted variable range shifter and precision-machined polystyrene blocks of known WET to evaluate commercial immobilization devices prior to clinical implementation. CT studies were also completed to evaluate the internal uniformity of the immobilization devices under study. Multiple inserts of the kVue platform (Qfix Systems, Avondale, PA) were evaluated as part of this study. The results indicate that the inserts are largely interchangeable across a given design type and that the measured WET values agree with those generated by the TPS with a maximum difference less than 1 mm. The WET of the devices, as determined by the TPS, was not impacted by CT beam hardening normally experienced during clinical use. The reproducibility of the WET method was also determined to be better than ±0.02 mm. In conclusion, the testing of immobilization prior to implementation in proton therapy is essential in order to ascertain their impact on the proton treatment and the methodology described here can also be applied to other immobilization systems.

Key words: Proton therapy; Immobilization; Range shift.

Introduction

Proton therapy relies on accurate placement of the Bragg peak (and hence the distal edge) within the patient to ensure complete dose coverage of the target and minimization of dose to surrounding normal structures (1). Many aspects of the treatment process impact the accuracy of dose delivery including imaging, immobilization, treatment planning, device manufacture, proton beam Quality Assurance (QA) and beam delivery. Careful consideration of each of these aspects is required in order to have the treatment plan accurately reflect the dose delivered to the patient during treatment.

While the Bragg peak allows for proton therapy to deliver highly conformal doses to the target with relatively few beams, the location of the distal edge is considered the most critical factor ensuring dose conformality across the entire target

Abbreviations: WET: Water Equivalent Thickness; TPS: Treatment Planning System; LLUMC: Loma Linda University Medical Center; HU: Hounsfield Units; RSP: Relative Stopping Power; JMSPTRC: James M. Slater Proton Treatment and Research Center; SD: Standard Deviation; QA: Quality Assurance.

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volume. Over- or underestimation of the proton range during the planning process can lead to either a distal portion of the target being underdosed or excess dose being delivered to normal structures past the target. While the dose calculation within the patient needs to be accurate to ensure that proton range is calculated correctly, it is important to recognize that any device placed upstream (closer to the beam source) of the patient, including immobilization devices, can modify the proton range and must be considered accurately.

Immobilization devices are a standard treatment item in external beam radiation therapy as they locate the patient and hence the target in a stable and reproducible position for imaging, simulation and treatment. In proton therapy, there is the additional requirement that the proton range modification by these immobilization devices needs to be considered accurately with CT-based treatment planning (2). Further, if separate devices (such as table tops) are used during CT imaging and treatment delivery they need to be interchangeable and any difference in proton range caused by these devices needs to be considered in the range calculation or included in the range uncertainty.

X-ray CT imaging is the basis of dose calculation in both photon and proton therapy. In proton therapy, Hounsfield units (HU) are converted to proton relative stopping power (RSP). Materials that do not lie on the CT calibration curve that converts HU to RSP will have an error associated with their assigned RSP, unless the correct RSP value is incorporated in the treatment plan. Therefore, before a device can be released for clinical treatment, it must be evaluated to ensure that it does not adversely affect the proton range accuracy. Water equivalent thickness (WET) measurements and comparison to WET values predicted by CT-based treatment planning using the CT calibration curve is essential, not only for the initial commissioning of a system, but also if any replacement devices are employed at a later date. CT evaluation of the internal structure for voids or regions of higher density is also important for quality control and to identify regions that require further WET analysis.

This contribution outlines the systematic evaluation of a commercial immobilization system and associated inserts at the James M. Slater Proton Treatment and Research Center (JMSPTRC) at Loma Linda University Medical Center (LLUMC) prior to clinical use. While the results may be representative of the specific devices tested, the same procedures can be equally applied to other immobilization systems and in other proton treatment centers.

Materials and Methods

Water equivalent thickness testing is quite often completed by measuring a proton depth dose curve in a water tank, inserting the device to be tested and re-measuring the depth dose profile. The shift in proton range can be attributed to the WET of the inserted device under study, providing an accurate value that can be used in further calculations. Unfortunately, such a methodology is technically difficult to accomplish with immobilization devices as they are often too large to be accommodated by a typical radiotherapy water tank.

A method has been developed at the JMSPTRC for measuring the WET of immobilization devices using a nozzle-mounted variable range shifter (Figure 1). The range shifter is made up of precision-machined polystyrene blocks whose WET has been determined accurately with a water tank measurement. A depth dose profile using the range shifter was measured for 150 MeV protons and 6 cm modulation with a parallel plate ionization chamber (PTW Markus). The distal edge position and shape as a function of ion chamber response and upstream WET (normalized to the center of modulation) was then recorded. From the distal edge it was possible to obtain the linear relationship between normalized dose and WET that could be used in the analysis (Figure 2).

A six-degree of freedom patient positioner (3) was then used to position the immobilization device between the range shifter and the parallel plate ionization chamber located at isocenter. The thickness of the range shifter was modified until a normalized dose of 0.5 ($\pm$0.15) was registered by the detector (*i.e.*, at 50% dose level on the distal edge) allowing the WET to be calculated from the simple linear relationship between WET and normalized dose obtained from the distal edge of the depth dose profile (Figure 2). Once the appropriate range shifter was selected multiple points (typically 10) on a given immobilization device could be tested quickly utilizing the six-degree of freedom patient positioner.

To evaluate the internal structure of each immobilization device a CT scan was completed and viewed for obvious inhomogeneities such as voids or regions of higher than nominal density. The CT image sets were then sent to the treatment planning system (TPS) for WET calculation. The WET

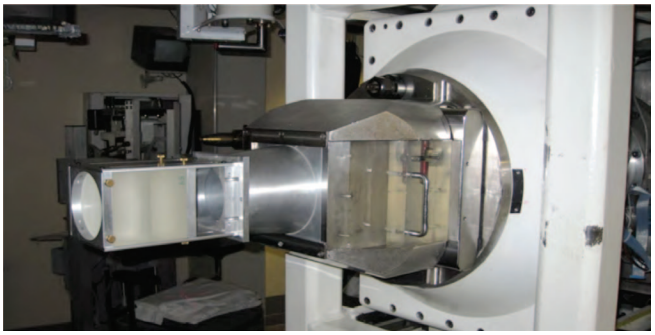

Figure 1: The variable thickness range shifter attachment.

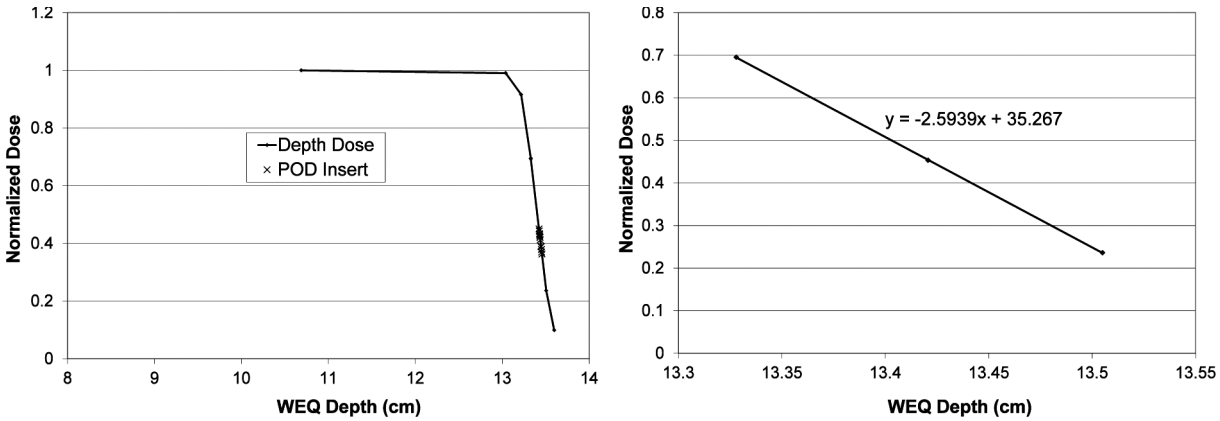

Figure 2: Depth dose profile (left); distal edge relationship used to determine WET from distal edge placement (right).

was calculated for a proton beam orthogonal to the insert by summing RSP information for each voxel along a line radiating from the radiation source and read out at specific points downstream to the device using a mouse-controlled plan explorer tool to give a total WET. CT voxels upstream to the device were excluded. WET values were averaged over a small area at the exit of the beam from the device. Air and water CT values were checked and verified as these would have an impact on calculated WET. Each device had approximately 12 points checked for completeness, typically at 10 cm intervals and along projections that were perpendicular to the surface of the immobilization device.

The immobilization devices under study here were provided by Qfix Systems, Avondale, PA and were part of their kVue immobilization system. The foundation for the kVue system is a base unit that is mounted to either a robotic patient positioner or standard treatment couch (Figure 3). This base unit consists of carbon fiber support rails that supports the insert and can be moved out of the primary beam path while the patient is on the table. The inserts, which are attached to the base unit, act as the table top and index to the base unit via a locking mechanism that triggers two locating pins in each insert. A full complement of inserts was allocated for CT and the proton treatment room, respectively, with one full spare in the event of loss or damage. All sets were evaluated for clinical implementation.

Multiple inserts are available for use with the system and four were tested as part of this clinical integration. At LLUMC, the flat and BoS inserts are utilized for QA procedures and head/neck treatments, respectively, and are available as standard inserts for the kVue system. Custom BoS overlays were also tested, which are of the same construction as the kVue inserts yet designed to be utilized as table overlays on existing treatment couches that do not utilize the kVue system.

A semicircular pod insert for abdominal/thoracic/spine treatments (Figure 3) and bite block insert for intracranial radiosurgery (Figure 4) were custom made by Qfix for proton treatments at LLUMC and were tested using the same methods described above. The bite block insert indexes and locks in place using the one-touch latch system of the kVue. A vacuum system secures the position of the stereotactic frame to the insert which is indexed via 4 metal pins. The bite block is a dental impression of the patient's upper jaw, that is attached via vacuum to the upper teeth and palate providing reproducible immobilization of the patient's head (4). This vacuum-assisted system allows for a reproducible and stable head location and immobilization while being minimally invasive and allowing quick removal in the event of an emergency. The head cushion is also indexed to the insert via replicable plastic pins to aid in the reproducibility of the setup.

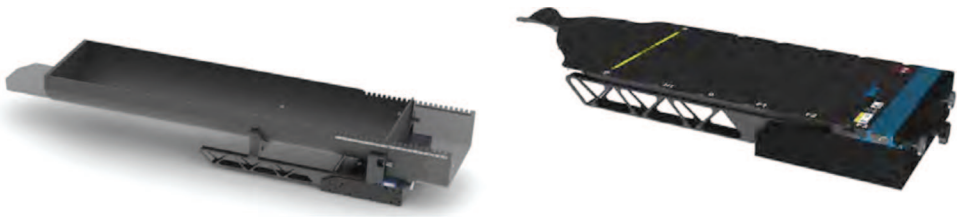

Figure 3: The kVue immobilization system base unit with the pod insert (left) and BoS insert (right).

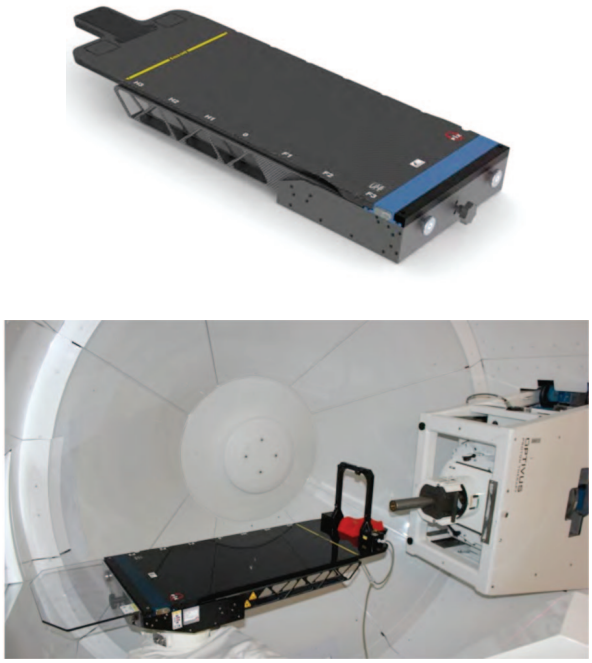

Figure 4: Bite block insert mounted on the Qfix kVue (top) and the bite block insert with indexed head cushion and vacuum stereotactic frame attached to the robotic patient positioner (bottom).

All inserts utilize a foam core construction overlaid with a carbon fiber skin to maintain strength and minimize WET. The BoS insert also features a contoured head support that does not contain a foam core, but rather is comprised entirely of carbon fiber. This head support is minimal in design to minimize edge effects and nozzle clearance issues. The WET of head support region was evaluated separately from the main foam core table to ensure accuracy of the results (Figure 5).

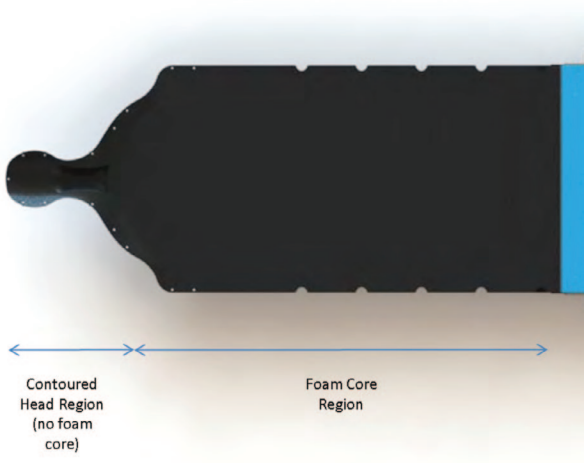

Figure 5: BoS insert with the two separate regions evaluated in this study indicated.

Results

The measured WET analysis for all tested devices is located in Table I. A total of three flat extensions, seven BoS inserts/overlays, three pod inserts, and three bite block inserts were tested. Evaluation of the BoS inserts was broken up into regions without foam core (indicating the contoured head region) and with foam core (indicating the table region of the insert) to differentiate between the two regions being tested. Multiple measurements (8-12 per device) were completed by different personnel to avoid bias. The reproducibility determined through multiple measurements of the same location was better than ±0.02 mm.

Table I
Measured kVue insert WET data. The standard deviation (SD) in this case is the standard deviation of all measurement points for a given device type.

Device	Average WET (mm)	SD of WET (mm)	Maximum variation in WET (mm)
Bite block	5.35	0.12	0.18
Flat	5.39	0.06	0.08
BoS (no foam core)	2.71	0.09	0.15
BoS body (foam core)	5.18	0.08	0.09
Pod	4.91	0.21	0.42

Table II compares the measured WET data with those generated using the clinical TPS based on CT imaging and HU-to-RSP conversion. The difference in WET between the two methods of evaluation was within 0.7 mm for all immobilization devices, with the TPS generally overestimating the WET of the immobilization device.

Table II
TPS-derived WET data for the kVue inserts.

Device	Measured WET (mm)	TPS-calculated WET (mm)	WET difference (calculated – measured) (mm)
Bite block	5.35	6.00	0.65
Flat extension	5.39	5.80	0.41
BoS (no foam core)	2.71	3.20	0.49
BoS body (foam core)	5.18	5.70	0.52
Pod	4.91	4.84	−0.07

CT hardening can impact the estimation of WET by the TPS which in turn can affect the proton range calculation. To ascertain the impact of CT beam hardening on the TPS, a pod insert was scanned with and without a cylindrical water phantom (28 cm in diameter and 38 cm in height) in

place to simulate a patient. WET was evaluated using the TPS for two oblique beam angles (115 and 245 degrees) and the results are displayed in Table III. No discernible difference as a result of beam hardening was observed (Table III).

Table III

TPS-derived WET data for the pod insert to evaluate the impact of beam hardening.

Device	Average WET (mm)	SD of WET (mm)	Maximum variation in WET (mm)
Pod	4.73	0.11	0.28
Pod with phantom	4.87	0.16	0.23

To allow for movement of the carbon fiber rails of the kVue system, the flat, BoS, and bite block inserts have a plastic rub strip permanently attached to their underside. The rub strip is 4.5 cm wide and crosses the full length of the insert. This rub strip may be in the treatment field and the WET of this design feature needs to be considered accurately by the TPS. To ascertain the impact which this plastic rub strip has on the WET, it was measured and compared to the output from the TPS (Table IV). The results suggest that the rub strip adds approximately 1.4 mm of WET to the insert, and this is accurately reflected in the TPS.

Table IV

Measured and TPS-derived WET data of the rub strip utilized on the underside of many inserts.

Device	Measured WET (mm)	TPS-derived WET (mm)
Insert	5.39	5.40
Insert + Rub strip	6.86	6.80
Additional WET	1.47	1.40

Discussion and Conclusion

The evaluation method outlined in this work provides a relatively quick and efficient technique in determining the WET of large and bulky immobilization devices prior to implementation in proton therapy. The method proved to be very reproducible with multiple measurements of the same point within 0.02 mm WET. We recommend that prior to the implementation of any immobilization device in proton therapy (including replacement devices) the WET is evaluated using the methodology described here or a similar technique to ensure that the impact they have on proton range is accurately considered and any errors accounted for in the range uncertainty.

The kVue devices tested in this work had a very uniform WET across all tested devices of a given type with standard deviations below 0.25 mm. The foam core construction did not exhibit regions of density differences that were neither visible on CT or detected by measurement. The foam core construction also exhibited a relatively low WET (approximately 5 mm) compared to their physical thickness (10-20 mm), which is a desirable feature in proton therapy to minimize the impact of the device on proton range and penumbra. Based on the test results, the devices can be used interchangeably in CT and proton treatment rooms for imaging and treatment. The test results of spare devices also demonstrated that they can be implemented in the treatment room at any time (*i.e.* in the event of a device failure) without impacting the patient treatment or a need for re-planning.

The TPS used at the JMSPTRC (Odyssey version 4.6) tended to overestimate the WET of the immobilization device by 0.1-0.65 mm. This can be attributed to errors in determining the relative stopping power for carbon fiber, which may not lie on the CT calibration curve implemented in the TPS. This error may be further exacerbated by partial averaging due to the relatively large pixel size in the CT scan. For a 50 cm CT FOV and a 512×512 reconstruction matrix, the resolution of the CT image is approximately 1 mm. This rather coarse resolution in combination with partial volume averaging effects (carbon fiber and foam core) may have contributed to the observed differences in WET. In none of the tested devices the discrepancies were greater than 1 mm, which would need to be addressed by CT recalibration, manual correction for immobilization device WET in the TPS, or even redesign or remanufacture of the immobilization device.

A rub strip present on many of the devices to allow movement of the carbon fiber rails was accurately considered by the TPS and exhibited a WET of 1.4 mm. As the rub strip is 4.5 cm wide and crosses the entire insert, it would be a disadvantage to select avoiding beam angles in upper thorax and spine treatments, however the minimal WET and accuracy of the representation by the TPS ensure minimal impact on the accuracy of the proton treatment plan.

This work describes a practical method of validating the WET of immobilization devices prior to clinical implementation in proton therapy both by measurement and using the TPS. Such validation is essential to ensure that the TPS accurately determines the proton range and that devices used in imaging have the same WET as those used in the treatment rooms. This work focused on testing Qfix kVue inserts at the JMSPRTC prior to their clinical release, but can also be used with other immobilization systems. While the results presented here can be seen as a guideline,

validation of immobilization device WET must be independently completed prior to clinical implementation to ensure that they are accurately characterized in the proton TPS as changes in manufacturing process, CT calibration and the TPS algorithm can affect these values.

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