

Immobilization Considerations for Proton Radiation Therapy

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Proton therapy is rapidly developing as a mainstream modality for external beam radiation therapy. This development is largely due to the ability of protons to deposit much of their energy in a region known as the Bragg peak, minimizing the number of treatment fields and hence integral dose delivered to the patient. Immobilization in radiation therapy is a key component in the treatment process allowing for precise delivery of dose to the target volume and this is certainly true in proton therapy. In proton therapy immobilization needs to not only immobilize the patient, placing them in a stable and reproducible position for each treatment, but its impact on the depth dose distribution and range uncertainty must also be considered. The impact of immobilization on range is not a primary factor in X-ray radiation therapy, but it is a governing factor in proton therapy. This contribution describes the immobilization considerations in proton therapy which have been developed at Loma Linda over twenty plus years of clinical operation as a hospital based proton center.

Key words: Proton therapy; Immobilization.

Introduction

Proton radiation therapy has the potential to deliver highly conformal dose distributions to the target volume with fewer beams than conventional X-ray therapy (1). This is achieved through the use of the Bragg peak, a high-dose region at the end of the proton track. By varying the initial proton energy the Bragg peak can be placed at a specified depth within the patient, localizing dose to the target volume and sparing tissue distal to that volume. As with other forms of external-beam radiation therapy, effective immobilization of the patient and target is necessary in order to realize the full treatment potential.

Immobilization itself is not a new concept to radiation therapy. It has been used over the years in photon and electron therapy to place the patient in a reproducible and stable position for treatment. The use of both external and internal immobilization impacts the treatment team's ability to locate a specific target with the treatment beam and stabilize its position for the duration of treatment. That is true for any form of external-beam therapy, including proton therapy. However, unlike photon therapy, in proton therapy the third dimension of depth is critical in

Abbreviations: ABC: Active Breathing Controls; AP: Anterior-posterior; DIBH: Deep Inspiration Breath Hold; HU: Hounsfield Units; IS: Inferior-superior; JMSPTRC: James M Slater Proton Treatment and Research Center; LLUMC: Loma Linda University Medical Center; LR: Left-right; RSP: Relative Proton Stopping Power; SOBP: Spread-out Bragg Peak; TPS: Treatment Planning System; WET: Water Equivalent Thickness.

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beam delivery. Changes in patient contour or target position along the beam axis can impact the position of the distal edge of the Bragg peak relative to the tumor. Distal edge placement can also be modified by any device placed upstream of the patient, including immobilization devices. It is imperative that such devices be considered accurately by the treatment planning system (TPS) and their water equivalent thickness (WET) known accurately and verified using measured proton data.

Immobilization considerations for proton therapy are not simply limited to how well the TPS considers proton transport through the device. Other considerations for proton therapy include:

- Part to part variability
- Time stability
- Edge effects
- CT uncertainty
- Target motion relative to anatomy
- External immobilization
- Internal immobilization

As more proton therapy centers come on-line, a good understanding of immobilization devices is essential, as is an understanding of how these devices will impact the proton dose profile. Multi-modality centers also need to consider the functionality of current immobilization systems and whether these devices are suited to proton therapy. Site-wide solutions also need to be considered that will meet the need of both the

conventional and proton treatment modalities, allowing for multi-modality treatments.

This paper discusses several aspects of proton therapy immobilization. A central objective is to make the reader aware of important considerations pertaining to the use of immobilization and the impact this can have on the proton dose distribution.

Utilizing the Bragg Peak for Treatment

The use of fast protons as a clinical tool was first suggested by Wilson in 1946 (2) and was first employed clinically in 1954 (3). The advantage of protons derives from a high-dose region known as the Bragg peak. This high-dose region can be placed anywhere within the patient by varying the incident proton energy. There is also no primary proton exit dose (Figure 1).

Proton delivery techniques can be categorized as passive or active in the delivery of a uniform dose to the treatment volume. Both rely on accurate placement of the Bragg peak and hence the distal edge within the patient. Passive techniques, which have been most commonly used in the clinical setting (4, 5) spread the beam laterally using a combination of high-Z (*i.e.*, lead) and Lexan foils (6). The combination of two materials, one of low and the other of high atomic number, produces a flat beam of constant flux and a constant range. The beam is then modulated in depth using a rotating plastic wheel (2, 7) that effectively allows for the superposition of multiple Bragg

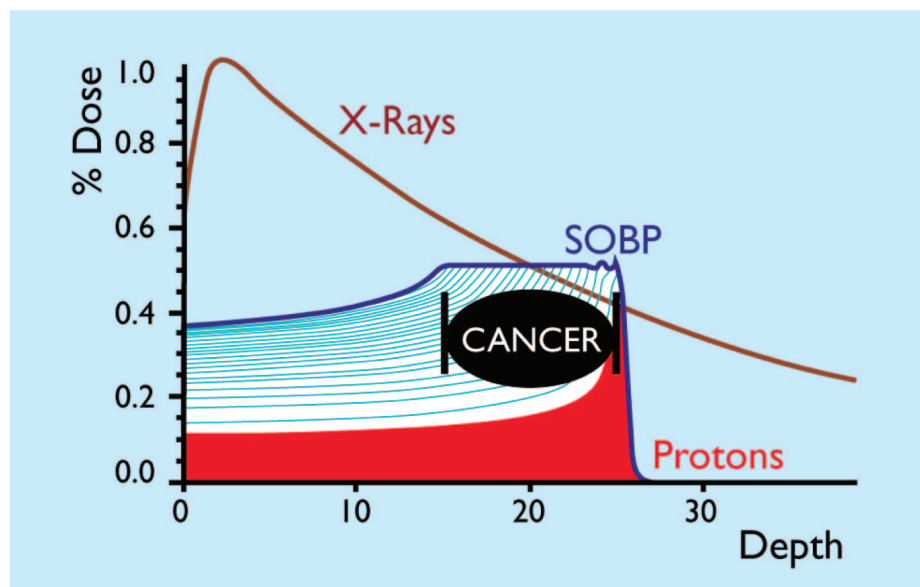


Figure 1: Comparison of the X-ray depth dose curve with the spread-out Bragg peak (SOBP) used in proton beam delivery for clinical treatment (3).

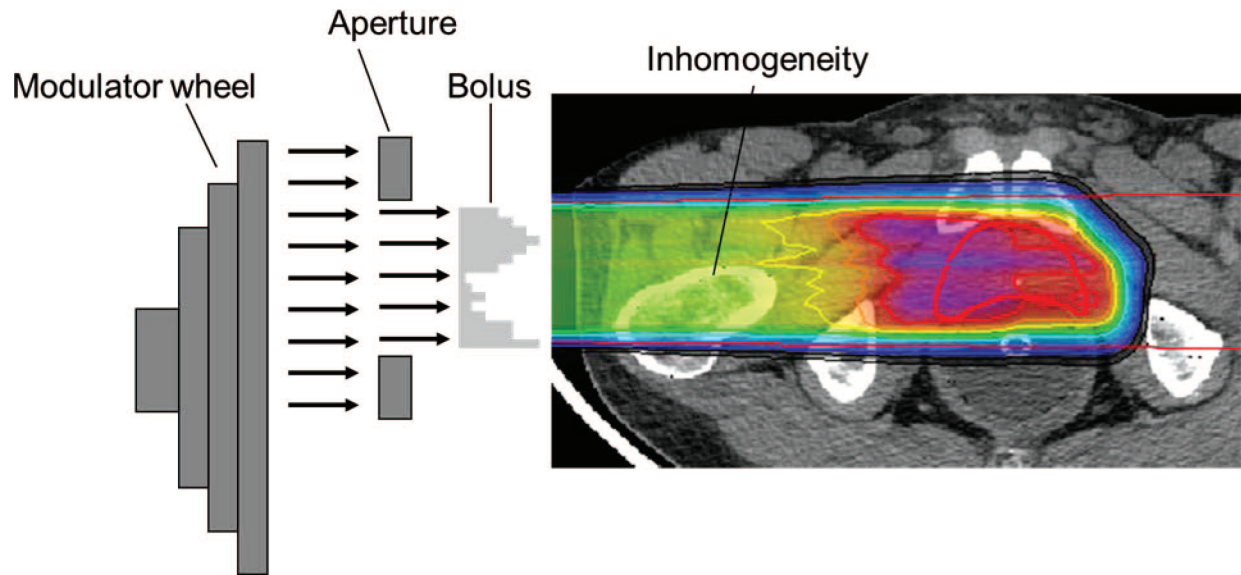


Figure 2: Schematic of a single passive proton treatment beam and associated treatment devices. Colors (red to blue) indicate decreasing dose.

peaks of varying intensity (Figure 1) to create a region of uniform high dose called the Spread-Out Bragg Peak (SOBP), (8) the width of which is customized to the target volume. The beam is then collimated by brass or Cerrobend® apertures and its penetration depth is varied by means of a wax or Lexan bolus (Figure 2). Active proton beam delivery techniques (9-12), employ a magnetically guided proton pencil beam in combination with dynamic changes of beam energy and beam intensity during treatment to paint a monoenergetic Bragg peak in three dimensions over the target volume. Active beam delivery methods allow for larger and more complex volumes to be treated with a single field, yet introduce a time dependent delivery of dose to the target, making localization and immobilization of this target all the more critical.

In employing the proton beam for treatment, placement of the Bragg peak is key to successful delivery of a conformal radiation dose to the target volume. In proton therapy the water-equivalent depth of the target determines the energy of the protons used and also the range shift or bolus employed. The water equivalent depth is calculated by the TPS, considering all upstream (closer to the incident beam) structures including bone. This calculation determines where the distal edge of the proton beam is located in the patient and produces the bolus (or selects the proton energy in the case of active beam scanning) accordingly. Uncertainty in the range of the proton beam, which can be exacerbated by material heterogeneity, organ deformation and internal motion, can negatively impact the delivered dose distribution and is the subject of ongoing study and improvements. While many groups are actively investigating image guidance and new imaging techniques, any shifts of the target relative to internal structures, such as ribs, pelvis, or other bony landmarks,

during or between treatments can result in errors in placing the distal edge. An often overlooked area of importance is immobilization. Good therapeutic immobilization allows the physician to not only locate the target and minimize inter- and intra-fraction motion, but also to reproducibly define the patient's external contour, allowing for reproducible proton range estimations from imaging through to treatment delivery on a daily basis. In proton therapy, attention also needs to be paid to minimize.

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In proton therapy, attention also needs to be paid to minimize the proton WET of the immobilization devices in order to reduce the effect on proton beam penumbra and range uncertainty. The WET of any immobilization device also needs to be accurately considered by the TPS to ensure that the proton range calculation is accurate. The many aspects to creating and employing immobilization for proton therapy applications must be carefully considered, to achieve successful dose delivery to the target.

CT 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 relative proton stopping power (RSP) using a bi-linear relationship. This relationship is fit to maximize the accuracy of anatomical materials imaged during the CT scanning process. Materials such as those used in the construction of immobilization devices that do not lie on the CT calibration curve (that converts HU to RSP) will have an error associated with their assigned RSP, impacting the proton range calculation. Additionally, inhomogeneities in the table top and other immobilization devices can contribute to errors in proton range. 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.

A methodology for experimental WET testing is described below. This or a similar method should be used to evaluate device WET and compare the finding with that generated by the TPS. If the discrepancy in WET is large (*i.e.* >1 mm) corrections must be investigated. One option is to exclude the table top from the external contour (and thus exclude this from the range calculation of the TPS) and have the TPS insert a table top of the appropriate WET. This is often the favored option over changing the CT calibration curve, which can impact the imaging of human anatomy. Another option, albeit time-consuming and prone to error, is to have the dosimetrist contour and correct the table top to the appropriate WET value. A final, more drastic option is to select immobilization devices that are made of a material better characterized by the CT calibration curve. This is a costly option that is becoming less necessary as commercial proton immobilization systems contain design attributes (such as foam core construction) which limits the impact of immobilization device material on range uncertainty.

Experimental WET Testing

Experimental testing of WET is a key component of evaluating an immobilization device prior to clinical release. WET testing involves measuring the shift in proton range passing through the device under test and comparing the result to that of water. The outcome is then compared with data collected from the TPS to evaluate the performance of the TPS in determining the proton range shift after traversing such devices. WET testing is 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, which are often too large to be accommodated by a typical radiotherapy water tank.

A method has been developed at the James M Slater Proton Treatment and Research Center (JMSPTRC) for measuring the WET of immobilization devices using a nozzle-mounted variable range shifter (13). In conjunction with a six-degree-of-freedom patient positioner (14) this methodology allows for the WET of immobilization devices, including table overlays, to be evaluated and compared to treatment planning data. This method was used in the evaluation of the kVue platform (Qfix Systems, Avondale, PA) prior to clinical release at JMSPTRC and proved to be very reproducible, with multiple measurements of the same point within 0.02 mm WET. The devices tested as part of this clinical implementation exhibited a very uniform WET across all tested devices of a given type, with standard deviations below 0.25 mm. The foam core construction also exhibited a relatively low WET (approximately 5 mm) compared to the 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.

The evaluation method outlined in Wroe *et al.* (13) provides a relatively quick and efficient technique in determining the WET of large and bulky immobilization devices prior to implementation in proton therapy. While the results presented in Wroe *et al.* (13) can be seen as a guideline, validation of immobilization devices' WET must be independently completed prior to clinical implementation to ensure that they are accurately characterized in the proton TPS; changes in manufacturing process, CT calibration and the TPS algorithm can affect these values.

Target Motion Relative to Anatomy and Internal Immobilization

Motion of the target relative to internal (such as ribs, pelvis, or other bony landmarks) or external (including immobilization devices and table tops) structures during treatment can result in errors in distal edge placement. This also limits the effectiveness of target tracking in proton therapy because, while the target location may be compensated for, the impact of motion on the proton range from shifts in the target relative to upstream structures is not considered. Tracked motion can thus result in the target lying in the treatment field, yet errors in range from changes in upstream structures (due to motion) can impact target coverage or dose to normal tissue beyond the target. Hence, in proton therapy immobilization of the structure is the best approach to ensure that the treatment is delivered as planned.

For cases where respiratory motion may impact target placement and shape (such as for lung, liver and pancreas

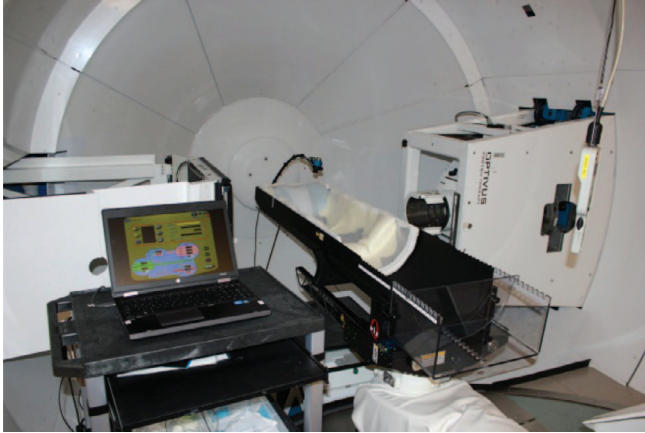


Figure 3: The SDX system set for treatment at the JMSPTRC.

treatments), we have implemented at the JMSPTRC a spirometric device from Q-Fix Systems. This system provides real-time feedback to both the patient and treating therapist on lung volume, ensuring that the patient has a reproducible deep inspiration breath hold (DIBH) during imaging and treatment. To aid in the portability of the system we have installed wireless network access points in each of the imaging and treatment rooms, while the SDX and control computer are housed on a cart with standalone UPS power. When set up for patient treatment, (Figure 3) the main SDX spirometric unit is located at the head of the treatment couch and patients view their respiratory cycles via video goggles. These systems are connected via two cables to the cart, which powers the unit and acts as an informational hub for the SDX system. The lack of additional, cables either for power or communication in the control room, means that setup is quick and easy; further, the treatment room is less cluttered, with fewer trip hazards. Therapists in the control area can use a real-time remote desktop application and the wireless network to view the system and control beam delivery to coincide with patient breath hold, while all information is kept on a secure and redundant server.

Many systems provide similar functionality, either through the use of belts that measure chest expansion, or active breathing controls (ABC), which regulate airflow to the patient. In the case of belt systems, the belt location needs to be such that it is outside the treatment field to minimize proton range uncertainty, which can limit the effectiveness of such a system. ABC systems control airflow to the patient and hence produce a reproducible DIBH; however, these systems are sometimes not tolerated well by patients who are sensitive to having their respiration controlled by an outside source.

In prostate treatments, inter- and intra-fraction motion can be minimized by asking the patient to maintain a modestly

full bladder during imaging and treatment, and by placing an endo-rectal balloon (Figure 4). Multiple centers have evaluated the use of endo-rectal balloons recently (15, 16) with the results demonstrating the ability of this immobilization device to provide reproducible and effective immobilization of the prostate for treatment. The data produced by Wang *et al.* (16) suggest that the use of an endo-rectal balloon can reduce the necessary symmetrical internal margin for prostate treatment by 40%. This data also suggests that the endo-rectal balloon is most effective at reducing prostate motion in the anterior/posterior (AP) and inferior/superior (IS) directions which is significant in proton therapy as it allows for localization of the target relative to upstream bony anatomy, hence reducing range uncertainty caused by target motion. Additionally, the endo-rectal balloon also creates a region of water equivalent homogeneity in a structure that is relatively heterogeneous in its composition aiding in the minimization of proton range uncertainty near the target structure. Finally the use of an endo-rectal balloon in prostate treatment results in the displacement of a large portion of the rectum posteriorly away from the target organ and hence away from the treatment radiation field limiting the integral dose to this relatively sensitive normal structure.

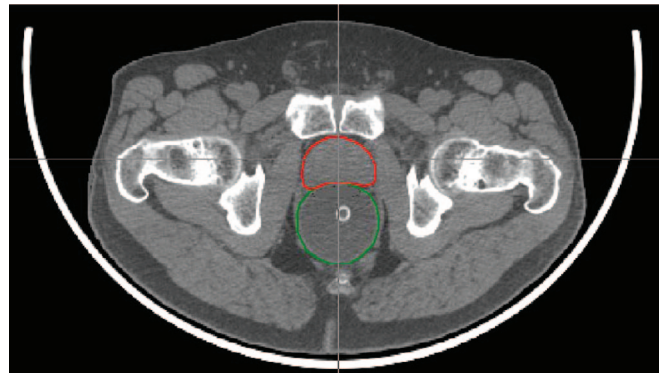


Figure 4: A proton treatment planning CT showing a water-filled endo-rectal balloon (green) to limit inter- and intra-fraction prostate (red) motion.

The Patient Contour and External Immobilization

External immobilization is a well-understood component in external-beam radiotherapy to achieve a reproducible and stable patient setup with minimal inter- and intra-fraction motion. This is certainly also the case for proton therapy, where good immobilization allows for the Bragg peak to be used to the fullest extent. Additionally, in proton therapy the water-equivalent depth of the target must be maintained throughout the entire treatment course. This can pose challenges in obese patients, where shifting adipose tissue (both inter and intra-fraction shifts) can compromise

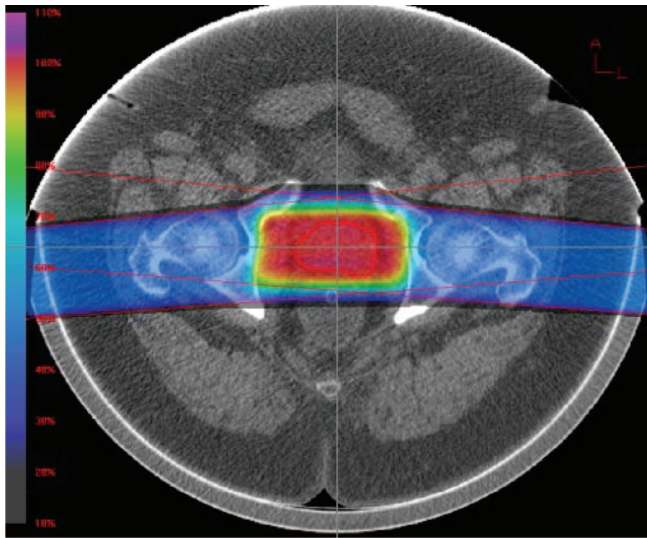


Figure 5: A proton treatment plan of an obese patient with the external contour maintained through the use of pod immobilization.

the water-equivalent depth of the target and lead to under-irradiation of the target and/or over-irradiation of structures beyond the distal edge.

In obesity situations it is important to not only adequately immobilize the patient, but also to maintain the integrity and stability of the external contour. At the JMSPRTC this is achieved through pod immobilization (Figure 5). For all patients with thoracic and abdominal targets (including those in and around the spine) a custom mold is made with expansion foam inside a pod shell, allowing full-body immobilization. In obese patients the pod also acts to create a reproducible posterior patient contour that allows for a repeatable WET to the target, and in turn minimizes range uncertainty. This repeatable patient contour allows for minimal range uncertainty in beams using these angles.

Part-to-Part Variability

In proton therapy it is important that any immobilization device or table top that the patient is imaged with be of the same size, shape and composition as those used in the treatment room. Variation in these parameters between devices located in the treatment and imaging rooms separately can negatively impact the range uncertainty. In an ideal case the immobilization device used for imaging purposes will travel with the patient to the treatment room, negating part-to-part variability; this is certainly the case with devices such as face masks and alpha cradles. Loma Linda expanded on this idea in having a patient-specific pod used for imaging and treatment for all abdominal and thoracic target locations (Figure 6). As the patient was scanned and then treated in the same device, any part-to-part variability (*i.e.*, from pod to pod) was negated. Additionally, as the treatment beams traversed the pod only (opposed lateral treatment technique) and not a table top, variation in table top composition or dimension from room to room would not impact range uncertainty. The difficulty with having all immobilization devices as patient-specific as this, however, is the space needed to store the devices.

More typically, immobilization devices, including table tops, head cushions *etc.*, are becoming treatment-room specific. In such a situation it is imperative that the devices be interchangeable so as not to compromise patient position or introduce additional range uncertainty. Evaluations of device interchangeability need to include analysis of the external dimensions and contours of the device, but also need to look at the internal composition of the device. Such analyses can be completed using CT imaging to detect regions of heterogeneity from the manufacturing process, and can also be used in conjunction with the TPS to evaluate the WET of the device. Such image sets also provide a valuable baseline for re-evaluation of devices over the length of their service life to determine

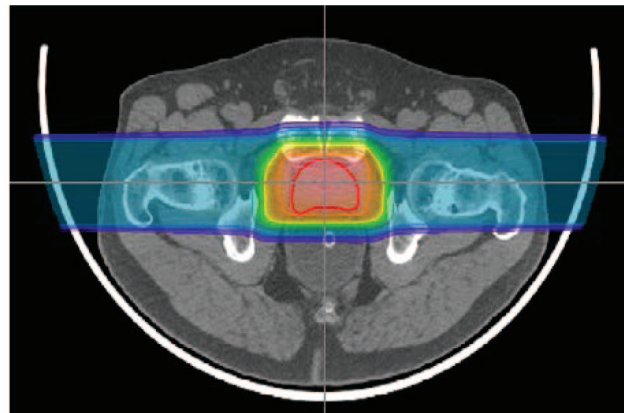


Figure 6: Patient situated in the pod immobilization device awaiting treatment (left); treatment plan of a proton prostate treatment treated with opposing lateral fields (right).

changes in internal composition as a result of wear and tear or damaging events. Experimentally measured WET can also form part of this evaluation in the initial phases to evaluate the performance of the TPS in detecting subtle shifts in proton range with device composition.

Edge Effects

Edge effects refer to passing the proton beam across the edge of an immobilization structure or along a boundary. The range shifts caused by these edges are correctly considered by the TPS in production of the range compensator; however, small shifts in patient position relative to this edge causes a mismatch between the range compensator and upstream WET, and can impact the distal edge placement in the patient. If we take Figure 7 as an example, the two red arrows indicate beams that would be impacted by edge effects either from the beam partially passing through the mask frame or parallel to the boundary formed by the side edge of a silverman head holder. If the patient shifts relative to this boundary, either randomly (*i.e.*, from play in the aquaplast mask) or systematically (for example, from weight gain/loss), the beam will be aligned to the patient anatomy, causing a mismatch between the range compensator and the upstream immobilization device. The thicker the edge being traversed, the greater the mismatch that potentially could impact target coverage.

To limit edge effects, planning guidelines can be constructed to ensure that treatment beams do not pass through immobilization device edges and considers such errors within margins of setup uncertainty. Examples of such beam selections are displayed by the green arrows in Figure 7. Because of the Bragg peak advantage in proton therapy, limiting beam-angle selection generally does not impact target coverage or normal tissue avoidance, however improvements are being made in immobilization device construction that reduce

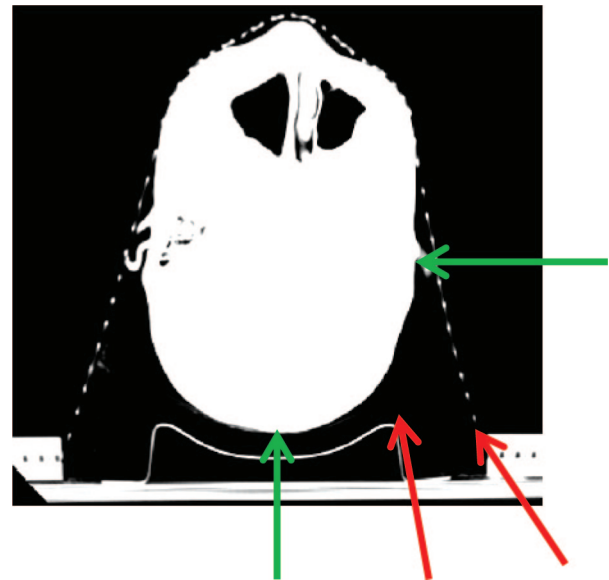


Figure 7: Examples of beam angles that can be impacted by edge effects (red arrows) and those that are not (green arrows).

edge effects and improve treatment angle options available to radiation oncologists. These improvements focus around making device edges as thin as possible or beveling the edges such that small patient shifts along such edges have minimal impact on range uncertainty. Carbon fiber technology and foam core construction additionally allow for very thin (WET and not necessarily physical thickness) table tops including head and neck supports (often combined with frameless aquaplast mask designs) and pods to be created, which allow for an almost infinite number of beam angle options for the physician (Figure 8). These new table tops are finding their way into the marketplace as proton-specific devices but can be readily applied to X-ray and IMRT therapies.

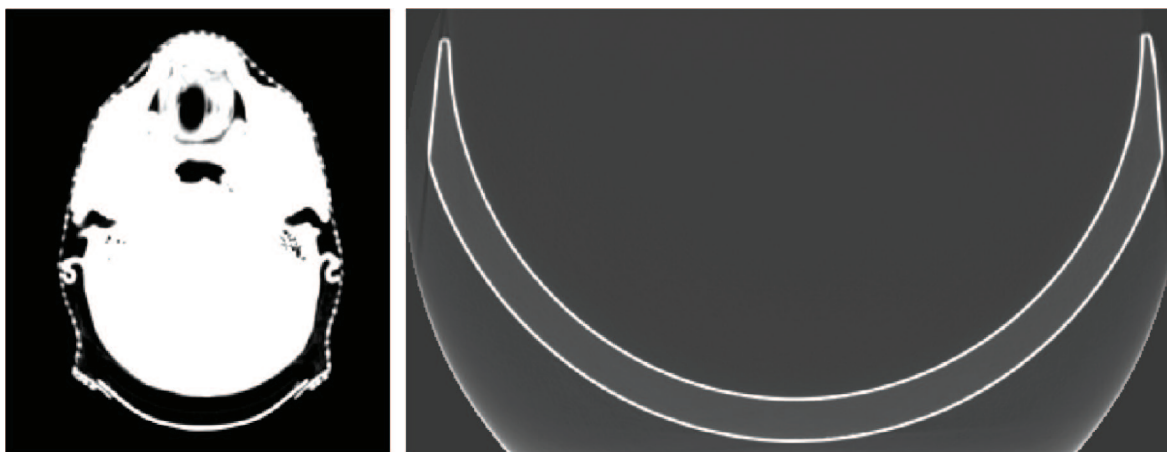


Figure 8: Example of a contoured head/neck support with as frameless mask design (left) and bevelled pod edges (right) to reduce range uncertainty from edge effects.

Device Non-uniformity

Device non-uniformity refers to low/high density regions that negatively impact the homogeneity of the immobilization device. These are of concern in proton therapy as while the inhomogeneity may be considered correctly by the TPS and the bolus (or beam energy in the case of beam scanning), any shift of the patient relative to this inhomogeneity can negatively impact the range uncertainty and, hence, the dose delivered to the target. Hence, the goal of immobilization device manufacture in proton therapy is to create devices that are as homogeneous as possible, to minimize range uncertainty.

In the past, table tops with honeycomb core structures could exhibit inhomogeneities due to the glue filling the core structure (producing regions of high density), while solid structures built from the layup of fibres and resin could exhibit air gaps (or regions of low density). With the development of foam core technology and carbon fibre overlay, the manufacture of homogeneous and low density table tops is becoming industry standard. However, customizable immobilization devices, such as vacuum bags, can exhibit inhomogeneities (*i.e.*, folds) the extent of which is determined by the experience of the staff member conducting the immobilization and the complexity of the treatment site

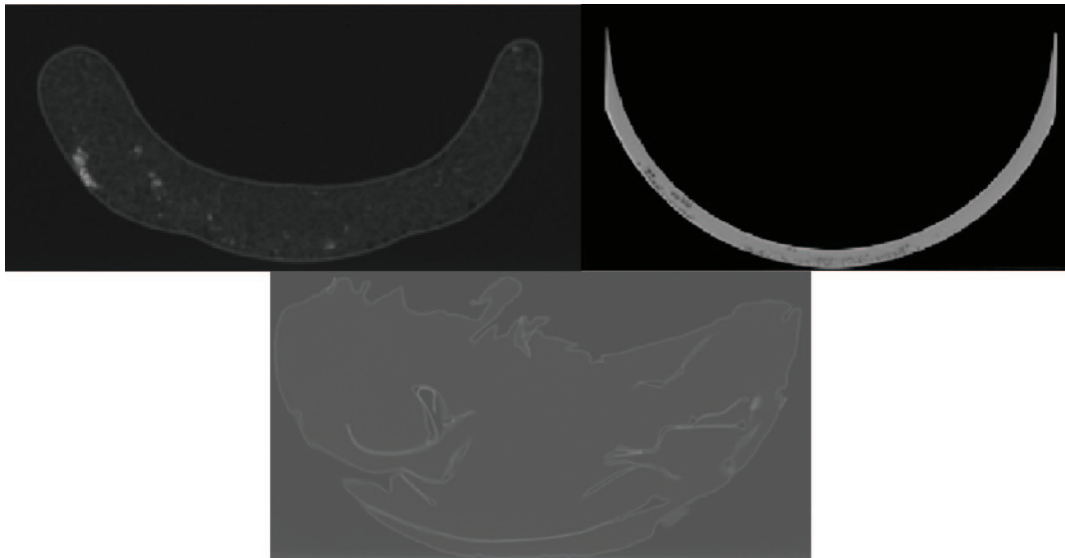


Figure 9: Examples of immobilization devices that exhibit inhomogeneity, including customized head/neck pillow (top left), pod prototype produced from fibre layup construction (top right) and a vacuum bag (bottom).

being immobilized. While a single fold in a vacuum bag produces a small range shift, multiple folds can measurably impact range uncertainty; immobilization devices such as these should not be used in areas that the proton beam will traverse (although they may be used to immobilize non-treat-through parts of the patient's body). Other options such as expansion foam can be considered for the immobilization of treat-through areas due to the low density and minimal impact on proton range.

Time Stability

Custom devices are a significant part of immobilization in radiation therapy, allowing the immobilization device to be formed to the specific anatomy of the patient. Typically a chemical reaction or external stimulus (such as heat) allows the device to become malleable for a period of time, after which the device becomes stable and rigid for imaging and treatment. While such devices certainly aid in providing a custom

immobilization platform, care needs to be taken to ensure that a given device does not change its physical properties after imaging. Changes in shape and rigidity post imaging can obviously impact the level of immobilization afforded to the patient on a daily basis. More specifically to proton therapy, changes to the density of the immobilization device can impact the proton range calculation and hence the delivered dose profile.

One such customizable device that was evaluated for proton treatment at the JMSPTRC was the Qfix MoldCare cushion. The cushion is composed of a soft fabric bag containing expanded polystyrene beads coated in a moisture-cured resin. When activated with water, the pillow can be formed to the desired contour and, in a matter of minutes, becomes completely rigid. The form of the cushion remains static over several weeks and does not degrade with regular use. However, upon CT imaging of the cushion for treatment planning it was clear that inhomogeneities were present (Figure 10). CT imaging of a number of cushions at a number of time

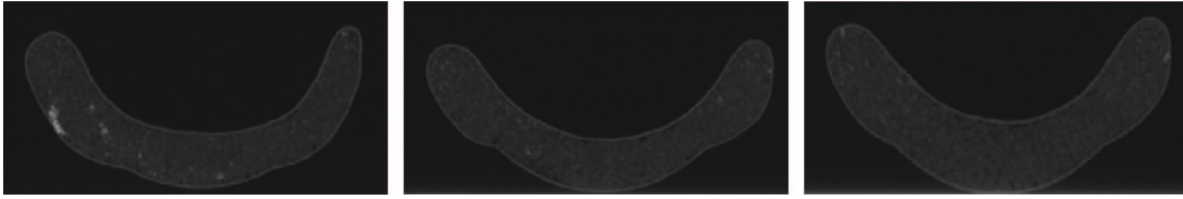


Figure 10: CT images of the MoldCare cushion system 0, 6 and 24 hours (left to right) after activation. Note that changes in shape are not a result of the curing process, but rather from imaging different positions in the cushion.

intervals over a 48 hours period confirmed that this was not limited to a single cushion or a single batch of cushions, nor was the inhomogeneity static over a period of time. It is hypothesised that the water used in the activation of the resin had not completely dried at the time of CT scanning, resulting in relatively high density regions ($HU \sim 1000$) surrounded by low density foam ($HU \sim 200-300$). Over a period of time (12-24 hours) this inhomogeneity disappeared as the cushion dried completely. This period may be decreased through the use of drying agents or dehumidifying devices.

The presence of small regions of higher density during the planning phase but not present during treatment will impact the depth dose distribution in proton therapy, contributing to the range uncertainty. Evaluation of cushions upon the onset of initial rigidity using the Odyssey treatment planning system demonstrated 1-2 mm range shift when the beam traversed the high-moisture-content inhomogeneity compared to cushions evaluated 24 hours or more later. In order to reduce range uncertainty in the proton dose calculation, it would be acceptable to immobilize the patient and then wait 24 hours until completing the treatment planning CT, as after this time the cushion's internal composition is static. If waiting is not a feasible option (because of anaesthesia or patient scheduling), it would also be possible to correct the inhomogeneities within the planning system manually as they will not be present during treatment. This task, however, is time-consuming and laborious.

This example highlights that when deploying new customizable immobilization systems in the clinic it is important to thoroughly evaluate not only the external structure and ruggedness but also the internal structure, as inhomogeneities can negatively impact the range uncertainty in proton therapy.

Site-wide Immobilization

Proton therapy, while being an excellent modality for cancer treatment, is part of a larger suite of cancer treatment options available to the physician. Allowing proton therapy to be available along with 3D conformal therapy, IMRT and brachytherapy provides the physician the greatest flexibility in providing the best possible treatment options to the patient. Immobilization should be designed to support the transfer of

patients between modalities, maintaining patient position across multiple modalities with a single treatment planning scan. While this scenario provides greatest efficiency in treatment planning and delivery, it also reduces imaging dose to the patient, which may be higher if treatment planning CTs need to be repeated for different setups on different treatment machines or modalities.

Site-wide immobilization also reduces the demands on staff, especially therapists, allowing them to become proficient with an immobilization system that is constantly in use. Further, it reduces demands on training and in-services that results from maintaining multiple modality-specific immobilization devices. Maintaining a site-wide immobilization system also lessens the financial burden on the facility; although the initial outlay for a site-wide solution may be high, in the long term cost savings will be significant in comparison to maintaining multiple systems that are machine- or modality-specific.

From the experiences at the JMSPRTC we have concluded as a general rule that, while not all conventional X-ray immobilization is adaptable to use in protons, almost all proton immobilization is able to be applied to X-ray therapy. However, as a caveat, each institution needs to evaluate its immobilization needs and equipment available, as this may impact decisions for site-wide solutions. It should be remembered that while financial, administrative, and education considerations need to be made, the ultimate deciding factor should be the immobilization system's ability to provide adequate immobilization to the patient and its ability to provide to the physician the greatest flexibility in deciding the appropriate treatment course for the patient.

Conclusion

Immobilization is an often overlooked, yet key aspect in radiation therapy, allowing for accurate, stable and reproducible positioning of the patient on a daily basis. Without these three components of positioning, delivery of dose to a given target while minimizing dose to surrounding critical structures becomes almost impossible. In proton therapy there is the added consideration of the impact which upstream immobilization devices have on range uncertainty and accurate placement of the distal edge within the patient. While this

increases the complexity of immobilization in proton therapy, with careful consideration of all aspects that have been discussed herein it is possible to employ effective immobilization as part of the treatment program to utilize the Bragg peak to maximum effect.

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