Imaging Resolver Localization for Whole Body Stereotaxy Using TomoTherapy

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Background/Aims: Assessment of the system accuracy is important to characterize in the implementation of stereotactic radiosurgery/radiotherapy (SRS/SRT). The accuracy of an integrated stereotactic radiotherapy (SRT) system utilizing the TomoTherapy Hi-Art system and the Medical Instrumentation and Diagnostics Corporation (MIDCO) BodyLoc Whole Body Stereotactic Localizer was evaluated for the purpose of delivering conformal radiotherapy with non-invasive fixation for hypo-fractionated treatment regimens.

Methods: Measurements of setup accuracy for image guided radiation therapy (IGRT) clinical positioning of prostate, head and neck and brain treatments utilizing the MVCT image registration capability of the TomoTherapy system were individually assessed and compared to similar published data. Using Monte Carlo simulations, phantom positioning and phantom target studies, the BodyLoc's imaging resolver was evaluated for its accuracy in stereotactic localization, patient positioning and dosimetric accuracy. Setup positioning accuracy for clinical cases utilizing different combinations of mask and posterior supports was evaluated using image guidance to establish an acceptable non-invasive fixation method.

Results: Analysis of the TomoTherapy system clinical positioning data showed the mean three-dimensional positioning displacements for image guided intensity modulated radiation therapy (IGRT) setups of the prostate, head and neck and brain treatments to be ±9.8 mm, ±5.5 mm and ±3.2 mm respectively. This compared favorably with published data for prostate and head and neck sites. A combination of a reinforced aquaplast mask with a mouth piece type bite block along with a customizable posterior mold (Accuform) resulted in fixation reducing the mean setup variation to ±1.4 mm which is comparable to values of inaccuracy demonstrated by Galloway, Maciunas and Latimer [5] and is slightly less than the voxel length of the reconstructed MVCT. The BodyLoc system's imaging resolver was evaluated for accuracy at known QA marker levels within the system. The calculation accuracy was confirmed at the 100 mm 300 mm, 500 mm, 700 mm and 900 mm QA marker Z ordinate levels within the frame to be within ±0.5 mm. The combined system dosimetric accuracy was measured with film and, through profile analysis , was shown to be ±0.6 mm.

Conclusion: The combination of the BodyLoc system's high-resolution imaging resolver for stereotactic localization and immobilization along with the TomoTherapy's MVCT image-guidance and helical treatment delivery, results in positioning accuracy acceptable for SRT and select SRS cases. This result was shown to be less than the length of the MVCT voxel (sub-voxel accuracy) despite significant partial volume effects in the longitudinal dimension. The dosimetric accuracy of the combined delivery system is within the values recommended in the ACR Practice Guidelines of ±1 mm for intracranial treatments and ±2 mm for extracranial applications. The integrated SRS/SRT system consisting of the Tomotherapy HI ART, Philips AcQSim/Pinnacle treatment planning system and the MIDCO BodyLoc system has been combined to be a fully functional system.

Introduction

The premise of stereotactic radiotherapy is to be able to accurately determine the internal location of a target volume within a patient by referencing an external 3-D coordinate system and precisely delivering an accurate dose to a closely defined volume. SRT treatments deliver hypo-fractionated regimens with respect to conventional fractionation schemes. The dose conformality and steep dose gradient required for tumor eradication and simultaneous sparing of adjacent normal tissue requires semi-rigid immobilization to reduce displacement of the treatment volume from the intended treatment position. During a stereotactic procedure, an imaging system is used to localize the target point

with respect to an external stereotactic apparatus to establish a reference coordinate system which is used for treatment set-up [8].

Treatments of this type require a stereotactic localizer, high resolution multi-modality imaging for tumor localization and motion suppression during radiation delivery in order to assure safe and effective outcomes. In this study, the TomoTherapy Hi-Art system, the ADAC Pinnacle 3 (Phillips Medical Systems, Bothell, WA) treatment planning system (TPS) and MIDCO BodyLoc Whole Body Stereotactic Localizer are integrated into a fully functional stereotactic delivery system. Published positioning accuracy is compared to that of the BodyLocWhole Body Stereotactic Localizer as measured with image guidance of the Tomotherapy HI ART system for delivering conformal radiotherapy with non-invasive fixation.

Materials and Methods
System Components
The TomoTherapy Hi-Art treatment machine is a modern linear accelerator that delivers intensity-modulated radiation therapy (IMRT) through a helical delivery to treat tumors. The TomoTherapy treatment unit has a 6 MV in-line linear acclerator that is mounted to a slip-ring gantry that continually rotates around the patient during treatments, delivering IMRT at all 360°. As the gantry rotates, the couch slowly moves longitudinally through the gantry creating a spiral radiation delivery. The TomoTherapy treatment unit has an 85 cm source to axis distance (SAD) and produces a fan beam with a width of 40 cm and a length of 1.0, 2.5 or 5 cm. TomoTherapy's binary multi-leaf collimator is composed of 64 individual leafs of 0.6 cm width which are pneumatically driven in a binary fashion for intensity-modulation.   The TomoTherapy system is capable of delivering intracranial and extracranial stereotactic radiotherapy with the use of a stereotactic frame as well as conventional fractionated radiotherapy.

The TomoTherapy treatment system uses image-guidance to assure accurate and precise set-up and delivery. The helical geometry of the TomoTherapy treatment unit easily incorporates spiral MVCT scans into the treatment process. MVCT scans are acquired and registered to the planning kVCT prior to treatments. Registration determines any translational or rotational adjustments. The appropriate shifts are applied as a final step prior to treatment.

The TomoTherapy system requires external systems to supplement its functionality. Creation of contours or structures for treatment planning is not included within the current toolset. However, the system is capable of importing and editing structures that have been created on another treatment planning system. In addition to the creation of regions of interest (ROI's), the Philips AcQsim3/Pinnacle treatment planning system provides multi-modality image fusion capabilities. Its Syntegra module has three different algorithms for the auto-registration of image sets from different modalities. These include "local correlation", "cross correlation", and "normalized mutual information". The system is also capable of manual manipulations for all translation and rotational adjustments, allowing the clinician to make final adjustments if necessary. Dose visualization on MRI is inferred in the absence of display capabilties within

Tomotherapy. Additionally, the high pixel resolution display capabilities of the Pinnacle system allow stereotactic localization at its resolution avoiding the reduction to 256 x 256 pixels which occurs upon import into Tomotherapy. Pinnacle's DICOM RT export capabilities allow transfer of contours created in Pinnacle into the TomoTherapy system.

The Tomotherapy system utilizes a 5.5 mm - 6 mm slice thickness during MVCT acquisition. The pitch is modified for voxel reconstruction on its "course", "normal" and "fine" settings. On the fine setting, voxel length is 1.5 mm – 2 mm. This results in significant partial volume effect in the longitudinal dimension for larger objects on the MVCT especially at high and low density tissue interfaces. This can present challenges when registering the MVCT with the kVCT.

The MIDCO BodyLoc Whole Body Stereotactic Localizer (MIDCO, San Diego) has been integrated into the stereotactic system, providing stereotactic localization, improved immobilization and to assist targeting accuracy especially in the cephalad- caudad (Z) dimension. The BodyLoc system employs a unique imaging resolver which extends from its base to its apex over 1 meter in length. Unlike "N" localizers which are limited in their length, the imaging resolver consists of a pair of sine wave fiducials coupled with a linear fiducial enabling stereotactic localization in the Z dimension beyond that of "N" localizer dependent systems. Because the two sinusoidal fiducials are out of phase by 90 degrees, the positioning of the three fiducials establishes a unique Z coordinate for each CT slice in the transverse plane. Additional pairs of linear fiducials establish the anterior-posterior (Y) and left-right (X) coordinates (Figure1). Each fiducial line is made of a non-ferromagnetic fiber optic material that has a high contrast on both radiographic and CT images. The BodyLoc software uses the mathematical algorithm to calculate all (X, Y, Z) stereotactic coordinates which identify the target point uniquely in 3-D frame space [6].

Figure 1 – Bodyloc Fiducial Array

The BodyLoc system has a cross bar with x-axis and y-axis scales for target localization within the frame's geometry of its "Body" section (Figure 2). Within the "Head" section it employs a targeting box for target localization (Figure 3). The system also has sets of

QA fiducial markers (Figure 3) at Z = 100 mm, 300 mm, 500 mm, 700 mm and 900 mm that are used to verify the accuracy of stereotactic coordinate determination in the Z-axis [7].
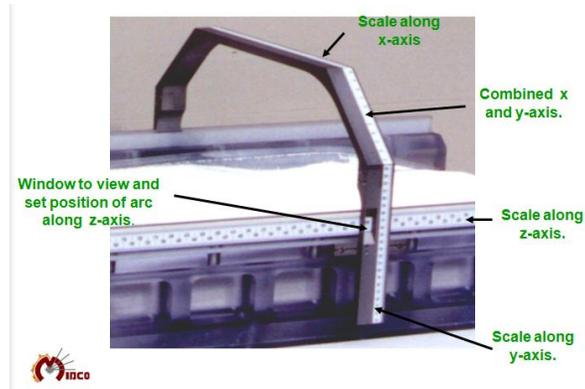

Figure 2 – BodyLoc Moveable Arc used for stereotactic target coordinate setup in the body section
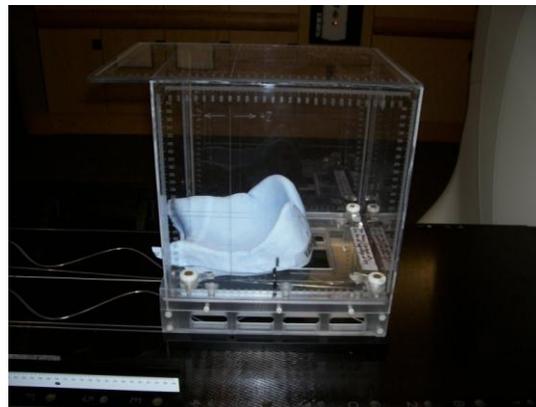

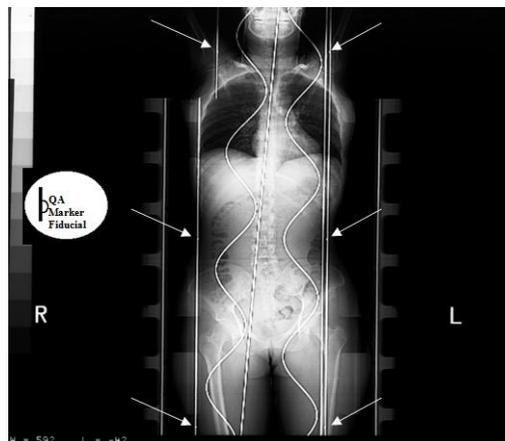Figure 3 – BodyLoc target box for stereotactic target coordinate setup in the head section

Figure 4 – QA markers in the base are placed at known Z locations

Accuracy of Stereotactic Localization Algorithm

Monte Carlo simulations were used to evaluate the BodyLoc's imaging resolver for its accuracy in determination of a stereotactic reference coordinate system. Four series of simulated measurements were made during the Monte Carlo simulations. In the first, z-axis locations were incremented over a range of 250 mm (2π radians), at intervals of 6.25 mm. In the subsequent three series, the ranges were 500 mm, 250 mm, and 250 mm respectively, with intervals of 6.25 mm, 3.125 mm and 1.00 mm. These tests simulated clinical use, wherein 5 mm and 3 mm axial can slices are commonly used. In addition, 1.00 mm increments in the z-direction were tested to simulate 1.00 mm axial scan slices. The latter constituted an extreme test, since 1 mm slices in body scanning is rarely employed.

The BodyLoc resolver system is designed to achieve resolution in the z-axis equal to that of the x-axis ($\Delta X = \Delta Z$). The z-axis resolution that can be achieved is dependent upon the resolution of the x-axis (pixel resolution) and not that of the imaging study voxel length (slice thickness). If the x-axis resolution has a value of DX, the resultant calculated value in the z-axis is DZ, then the ratio of DZ/DX = 1. Monte Carlo results are shown in Table 1.

Table 1. Monte Carlo Simulation Results

Z Interval (Slice Thickness)	DZ/DX
1.000 mm	0.996
3.125 mm	0.997
6.250 mm	0.996

Accuracy in Patient Positioning

A clinical positioning study was performed in order to evaluate the accuracy in patient positioning during IMRT setups on TomoTherapy for prostate, head and neck and brain treatments. These results were compared to previously published data. Patient positioning accuracy on TomoTherapy was measured during Image Guided IMRT treatments. Vac-Lok bags were used for leg immobilization of prostate patient. For the head and neck and brain, paients were immobilized using Med-Tec S Type head and neck masks. MVCT scans were acquired before treatment to verify patient positioning. Offsets obtained from registration of the original planning kVCT and the MVCT were recorded for all three sites (see figure 5). The patient positioning accuracy was then determined by calculating the mean three-dimensional positioning displacement by the following formula:

$$\text{3D Displacement Vector} = (x^2 + y^2 + z^2)^{1/2}$$

The results from the patient positioning accuracy study were then compared to results from published papers [3, 4, 5]. The work of Galloway et. al . was used to establish an expectation value for intracranial stereotactic radiosurgery treatments. It was of interest

to improve upon the accuracy of the S-Type fixation system with utilization of the BodyLoc system.
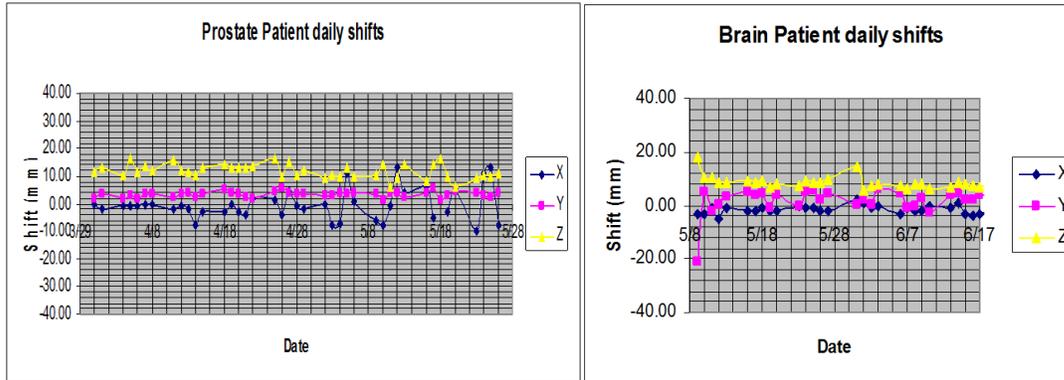

Figure 5 – Examples of translational adjustments for IGRT patients on Tomotherapy

Table 2. Comparison of Positioning Accuracy

Site	Conventional Published Data	Grossmont IGRT Data
Prostate	± 5 to 15 mm[3]	± 9.8 mm
Head and Neck	± 6.97 mm[4]	± 5.5 mm
Brain	± 1.5 to 2.5 mm[5]	±3.2 mm

To analyze the combined setup accuracy of the Bodyloc and TomoTherapy to consistently position patients, reproducibility analysis was performed on a series of phantom setup trials. A fine resolution MVCT was performed on an anthropomorphic head phantom fixated with a reinforced thermoplastic mask, attached to the BodyLoc stereotactic frame. The phantom was positioned using stereotactic target coordinates of the BodyLoc. Resultant translational adjustments during registration of the MVCT and kVCT images were then analyzed for MVCT's acquired in fine resolution and auto-registered using the "full image" algorithm on the Tomotherapy operator station. The algorithm provides displacements for six degrees of freedom, three translational (to hundredths of a millimeter) and three rotational (to hundredths of a degree). The image fusion result was then visually inspected to ensure proper alignment. These values are taken as the composite setup accuracy for the combined system. Table 3 shows the results of 15 trials.

Table 3. The results of Phantom Positioning Reproducibility for 15 Trials

Average ΔX	0.2 mm
Average ΔY	1.0 mm
Average ΔZ	0.3 mm
Average Vector Displacement	1.1 mm
Max Vector Displacement	2.8 mm

The reinforced aquapast mask system coupled with a mouth piece type bite block to reduce any rotational movements was clinically implemented. Improvement in longitudinal immobilization was demonstrated in utilization of an "Accuform" (see figure 5) formable mold for posterior support when compared to use of a "Timo" head holder as shown in Table 4.
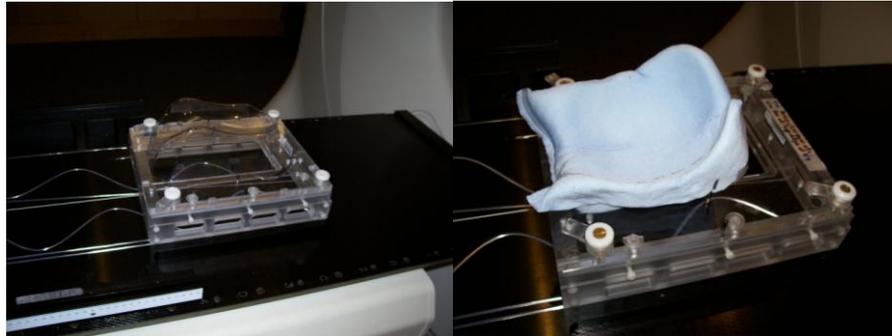

Figure 5 – Timo (left) and Accuform (right) formable mold used for posterior support

Table 4. Non-Invasive Intracranial Positioning Accuracy

	Reinforced Aquaplast with Timo	Reinforced Aquaplast with AccuForm
ΔX	-0.4 mm	-0.8 mm
ΔY	-0.2 mm	-0.9 mm
ΔZ	-3.9 mm	+0.8 mm
Average Displacement	3.9 mm	1.4 mm

For extracranial sites in the thorax and abdomen, a Vac-Lok bag is used for posterior support and coupled with a thermoplastic mold for anterior fixation. Respiratory suppression is accomplished during mold formation using manual compression of the diaphragm. Initial scans are taken and translational adjustments are made. A verification scan is completed prior to treatment and intra-fraction if necessary. Initial displacement is consistent with positioning accuracy expected for thoracic or abdominal treatment sites, however, subsequent verification scans demonstrate, immobilization satisfactorily constrains the patient throughout the treatment. Results of translational adjustments representing positioning accuracy and immobilization are shown in Table 5.

Table 5. Non-Invasive Extracranial Positioning Accuracy and Immobilization

	Thermoplastic mold with Vac-Lok Initial Scan	Thermoplastic mold with Vac-Lok Verification Scan
ΔX	-1.5 mm	-0.8 mm
ΔY	-4.4 mm	+0.2 mm
ΔZ	-2.9 mm	-0.5 mm
Average Displacement	5.4 mm	1.0 mm

Verification of System Mechanical and Dosimetric Accuracy

The American College of Radiology has recommended that "treatment delivery should be accurate to within ±1 mm" for intracranial SRS treatments and that "radiation delivery equipment should have mechanical tolerances for radiation delivery of ±2 mm [9]. The Gammaknife, Cyberknife and Novalis radiosurgery treatment units all have established methods for verifying these parameters. Figure 7 shows test methods for each system respectively. Each of these tests compare the coincidence of the center of the radiation field with the mechanical isocenter for each of the translational dimensions.

Gamma Knife Pin-prick   Cyberknife E2E

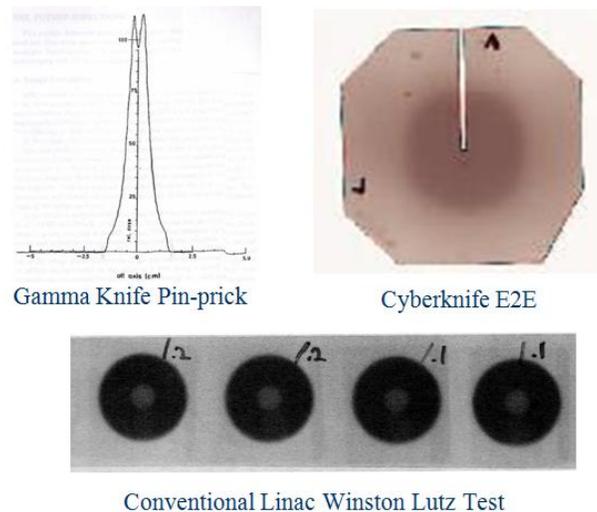Conventional Linac Winston Lutz Test

Figure 7 – Methods to verify accuracy of dose delivery

In the absence of an analogous method for Tomotherapy, it was necessary to devise an equivalent means for verifying this essential parameter. To this end, MIDCO developed and manufactured an acrylic hexagonal shaped phantom called the HexaPhant®. The HexaPhant was designed with a film cassette holder that has six brass pins and accommodates an 85 mm x 85 mm piece of film. An ion chamber holder can be positioned in place of the film cassette. The HexaPhant has two test probes that have 8 mm MR compatible gelatin balls and two probes that contain five 2 mm tungsten balls spaced 3 mm apart that are radiologically identifiable [11]. The HexaPhant can be mounted to the BodyLoc frame so that the film cassette or ion chamber can be oriented in either the sagittal or coronal plane. The location of the center pin within the film cassette is designed to coincide with the stereotactic target coordinate of a 5 mm cylindrical irradiated volume. MD-55 Radiochromic film was then loaded into the BodyLoc film cassette (see Figure 8) and punctured with the six pins. The film was irradiated with the treatment plan. The Delivery Quality Assurance (DQA) module of the TomoTherapy Planning system was used to analyze the dose profiles on the exposed film. Profile analysis demonstrated the Hexaphant Accuracy Test (HAT) resulted in a vector displacement of 0.6 mm (Table 6) which is within the ACR recommended values for either intracranial or extracranial applications.
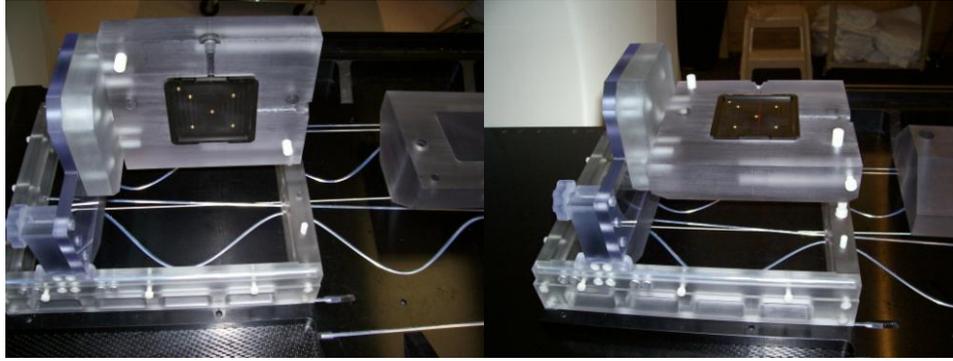
Figure 8 – HexaPhant shown with film cassette oriented in sagittal and coronal planes

Table 6. HAT - System Delivery Accuracy

	Calculated Position	Measured Position	Displacement
X-direction	42.5 mm	43.0 mm	0.5 ± 0.1 mm
Y-direction	15.4 mm	15.7 mm	0.3 ± 0.1 mm
Z- direction	34.1 mm	34.3 mm	0.2 ± 0.1 mm
Total Displacement			0.6 ± 0.2 mm

Dose Conformality

Dose conformality was evaluated for a series of cylindrical, spherical and crescent shaped target volumes of varying size. Dose distributions were generated using Tomotherapy. Conformality indexes were calculated and plotted versus target volume. Conformality Index values for Gamma Knife can range from 1.2 – 1.8. Figure 9 shows results for Tomotherapy simulations and patient results.
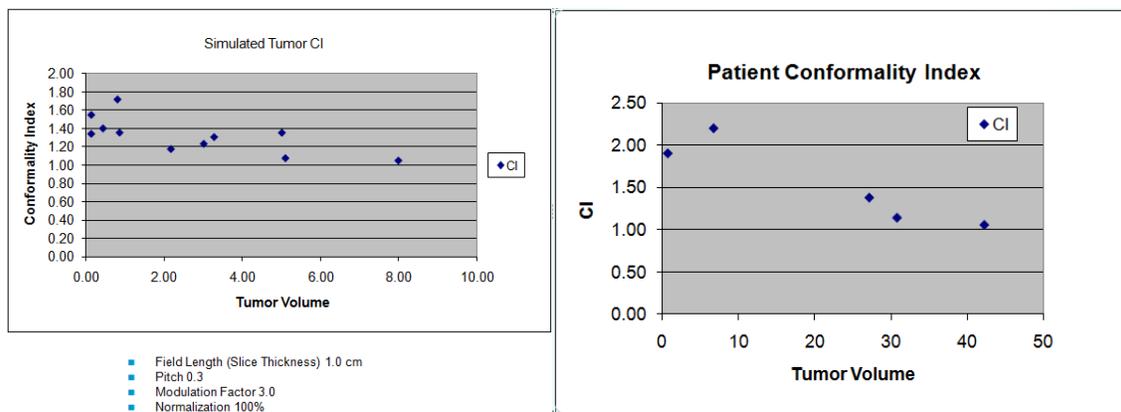

Figure 9 – Calculated Conformality Indexes for simulation target volumes and clinical patients

Results

Results of the TomoTherapy system clinical positioning study show the mean three-dimensional positioning displacements for IGRT setup for prostate, head and neck and brain treatments to be ±9.8 mm, ±5.5 mm, and ±3.2 mm respectively (see Table 2). These results compare favorably with conventional published data of ± 5 to 15 mm and,

± 6.97 mm for the prostate and head and neck sites.   For the brain, use of the Bodyloc for Stereotactic Localization and targeting coupled with a reinforced thermoplastic mask, mouth piece bite block and Accuform for immobilization result in positioning accuracy comparable to values (1.5 mm- 2.5 mm) for known stereotactic headframes quoted by Galloway et. al. which is also consistent with the reconstructed voxel length of the Tomotherapy MVCT on its "fine" acquisition setting.

The results of the Monte Carlo tests are shown in Table 1. In addition, inspection of the data for each test reveals that there were no wide deviations at any given location, indicating that the resolver is consistently accurate for each incremental change along z-direction. These results show that BodyLoc localization algorithms compare favorably with the desired value of DZ/DX = 1. The results of a 2 mm slice thickness evaluation for QA Markers in the BodyLoc (at Z = 100, 300, 500, 700, 900 mm) show that all values are within ± 0.5 mm.

By comparing the centers of the calculated dose profiles and the measured dose profiles from the film based HAT results, the coincidence of the planned and delivered center of the irradiated target volume was verified. HAT profile analysis results on the TomoTherapy treatment unit are shown in Figure 10 for sagittal and the coronal dose profiles.

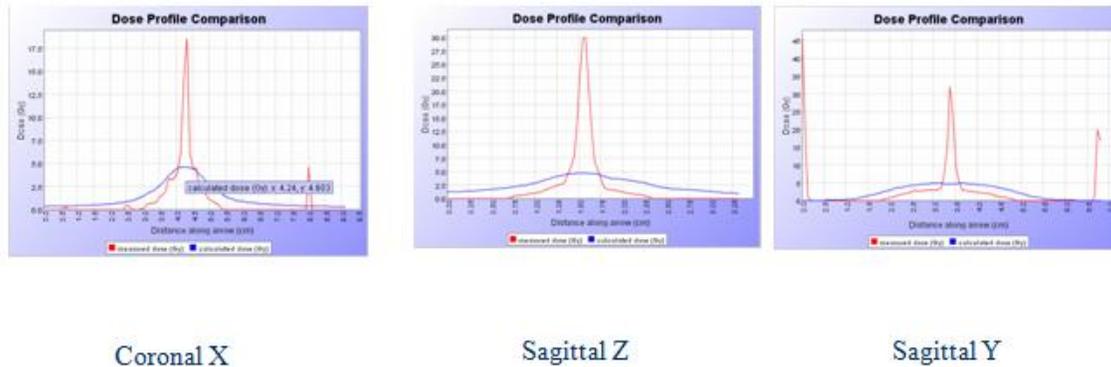Coronal X   Sagittal Z   Sagittal Y

Figure 10 – Resultant profiles from the HAT

HAT profile analysis in the sagittal plane showed that the discrepancy between the two centers along the longitudinal (Y) direction was approximately 0.3 mm and the discrepancy along the vertical (Z) direction was approximately 0.2 mm. The results in the coronal plane showed that the discrepancy between the two centers along the lateral (X) direction was approximately 0.5 mm. The overall system accuracy was found by calculating the vector sum of the X, Y and Z displacements (see Table 6):

$$R = [(0.5)^2 + (0.3)^2 + (0.2)^2]^{1/2} = 0.6 \ mm$$

The total discrepancy from the calculated radiation isocenter to the measured radiation isocenter was approximately 0.6 mm. This value fell well within the 2 mm tolerance that is recommended in the ACR Guidelines. This value is comparable to other stereotactic machines such as the Leskell Gamma Knife, with typical discrepancies between two centers along X, Y, and Z directions of approximately 0.25 mm [10].

CONCLUSIONS
The combination of the MIDCO BodyLoc Whole Body Stereotactic Localizer and the TomoTherapy MVCT image registration improves target localization and patient positioning over conventional methods. The non-invasive intracranial patient positioning accuracy is ±1.4 mm which is slightly less than ±1 voxel length. Typically, voxel lengths for diagnostic imaging studies (kVCT, MRI) for stereotactic work may be as fine as 0.5 mm. Using the BodyLoc system allows finer resolutions of structural dimensions than using the TomoTherapy system alone for stereotactic localization. Therefore, the combination of the high-resolution stereotactic image resolver fiducial system and immobilization of the BodyLoc with TomoTherapy MVCT image guidance results in sub-voxel length mean vector positioning accuracy.

A method (HAT) has also been developed for assessing the system radiation delivery accuracy. The HAT results satisfy the ACR dose delivery accuracy recommendations for both intracranial and extracranial treatments. The TomoTherapy Hi-Art, MIDCO BodyLoc and the Philips AcQSim/Pinnacle treatment planning system have been successfully combined into an integrated SRS/SRT system.

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