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STEREOTACTIC IMAGE-GUIDED INTENSITY MODULATED RADIOTHERAPY USING THE HI-ART II HELICAL TOMOTHERAPY SYSTEM

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Abstract—The highly integrated adaptive radiation therapy (HI-ART II) helical tomotherapy unit is a new radiotherapy machine designed to achieve highly precise and accurate treatments at all body sites. The precision and accuracy of the HI-ART II is similar to that provided by stereotactic radiosurgery systems, hence the historical distinction between external beam radiotherapy and stereotactic procedures based on differing precision requirements is removed for this device. The objectives of this work are: (1) to describe stereotactic helical tomotherapy processes (SRS, SBRT); (2) to show that the precision and accuracy of the HI-ART meet the requirements defined for SRS and SBRT; and (3) to describe the clinical implementation of a stereotactic image-guided intensity modulated radiation therapy (IG-IMRT) system that incorporates optical motion management. © 2008 American Association of Medical Dosimetrists.

Key Words: **Helical tomotherapy, Intensity modulated radiation therapy, Image-guided radiation therapy, Stereotactic radiosurgery, Stereotactic radiation therapy, Stereotactic body radiation therapy, IMRT, IGRT, MVCT.**

INTRODUCTION

The HI-ART II helical tomotherapy unit (TomoTherapy, Inc., Madison, WI) is a new radiotherapy treatment system designed to efficiently perform image-guided intensity modulated radiation therapy (IG-IMRT). The concept of helical tomotherapy was introduced by Mackie et al.[1] in the early 1990s, based on his work carried out in the late 1980s. Numerous features of current advanced radiotherapy practice were initially presented in that seminal publication including the integration on a single platform of (1) inverse treatment planning, (2) intensity modulated delivery, (3) onboard computed tomography (CT) imaging for daily target localization with the patient in the treatment position, and (4) adaptive planning tools based on dose reconstruction using daily CT localization images. Over the next decade, helical tomotherapy research progressed to the point where a clinical prototype called HI-ART (highly integrated adaptive radiation therapy) was developed. Subsequent commercialization of a second-generation design dubbed HI-ART II (TomoTherapy, Inc., Madison, WI) ensued with FDA 510K approval achieved in 2002. Currently, there are approximately 150 clinical sites around the world treating patients using the HI-ART II.

External beam procedures have been classified based on accuracy criteria, with conventional radiotherapy techniques estimated accuracy to be in the range of 5 to 7 mm, and stereotactic methods to be in the range of 2 to 2.4 mm.[2] This latter estimate is based on uncertainties in fixation hardware (1.0 mm), isocenter alignment (1.0 mm), CT image resolution (1.7 mm), and tissue motion (1.0 mm). C-arm–type linacs were conceived in an era where 2-mm mechanical accuracy was considered state-of-the-art because this was significantly smaller than the positional uncertainty inherent in the treatment simulation and planning methods of the time, as well as setup and intrafraction motion errors at the time of treatment. While 3 to 5 mm has been considered clinically acceptable for fractionated external beam treatments at 1.8 to 2.0 Gy per fraction, greater accuracy is required for single fraction treatments of 15 to 20 Gy, owing to the significant collateral damage that would result to normal tissue adjacent to the target volume. This is due to a sigmoidal dose-volume response for normal tissues, where the normal tissue complication rate increases dramatically at high-dose levels with small increases in the volume irradiated.[3] If one considers that a 2-mm positional uncertainty in targeting dose to a 2-cm spherical tumor can be accounted for by adding a 2-mm margin to the tumor, this small margin will result in a 44% increase in the irradiated volume, most of which is normal tissue. Consequently, tertiary hardware was developed specifically for linac-based stereotactic procedures to reduce the mechanical uncertainty to less than 1 mm comparable to that of the Gamma Knife.[4,5]

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The multileaf collimator (MLC) was introduced to external beam radiotherapy as a replacement for custom cerrobend and lead blocks and the 2-mm uncertainty specification was applied to MLC leaf positioning. This was considered clinically acceptable for conventional radiotherapy because treatment portals were typically designed with a generous margin of 1 cm or greater around the clinical target volume. The advent of IMRT forced the radiotherapy community to reconsider the precision and accuracy requirements of the MLC because leaf-positioning errors of 2 mm can produce dose errors of greater than 5%. In addition, mini-MLCs have been developed with very small leaf widths (< 5 mm) to improve leaf resolution and to allow fixed beam 3D conformal and IMRT techniques to be applied to linac-based stereotactic procedures. Now, submillimeter leaf positioning uncertainty is desirable to reduce local dose errors levels of less than 5%.

Subsequent to IMRT's clinical acceptance is the recent development of the CT image-guided radiotherapy (IGRT) concept utilizing CT imaging systems integrated into the treatment unit gantry for the purpose of localizing soft tissue anatomy at the time of treatment setup. CT imaging requires a high degree of mechanical accuracy during the revolution of the source and detector to minimize image artifacts during the image reconstruction process. Consequently, the development of CT IGRT has forced a tighter specification on the uncertainty of the C-arm type gantry isocenter, with a 1-mm isocenter specification now the standard for new C-arm type linacs outfitted with cone-beam CT imagers.

Despite this improvement, the exact position of the source and detectors during the gantry rotation/image acquisition process must be characterized in the image reconstruction software model to minimize reconstruction artifacts in images with pixel resolutions less than 1 mm. For comparison, the isocenter specification of the HI-ART II ring gantry is 0.2 mm, and no additional characterization of the source-detector geometry is required for routine image reconstruction.

The new generation IGRT-capable treatment units are now mechanically accurate enough to carry out SRS procedures because their isocenters meet the 1-mm specification defined in AAPM Task Group Report 54.[2] The addition of CT image guidance to the IMRT process suggests the possibility of reducing positional uncertainty further. This, combined with IMRT's improved dose conformation capability, improves the potential for reducing normal tissue complications from high-dose procedures. With this motivation in mind we will present an overview of our development efforts to extend the HI-ART II to image-guided intensity-modulated intracranial and extracranial stereotactic procedures.

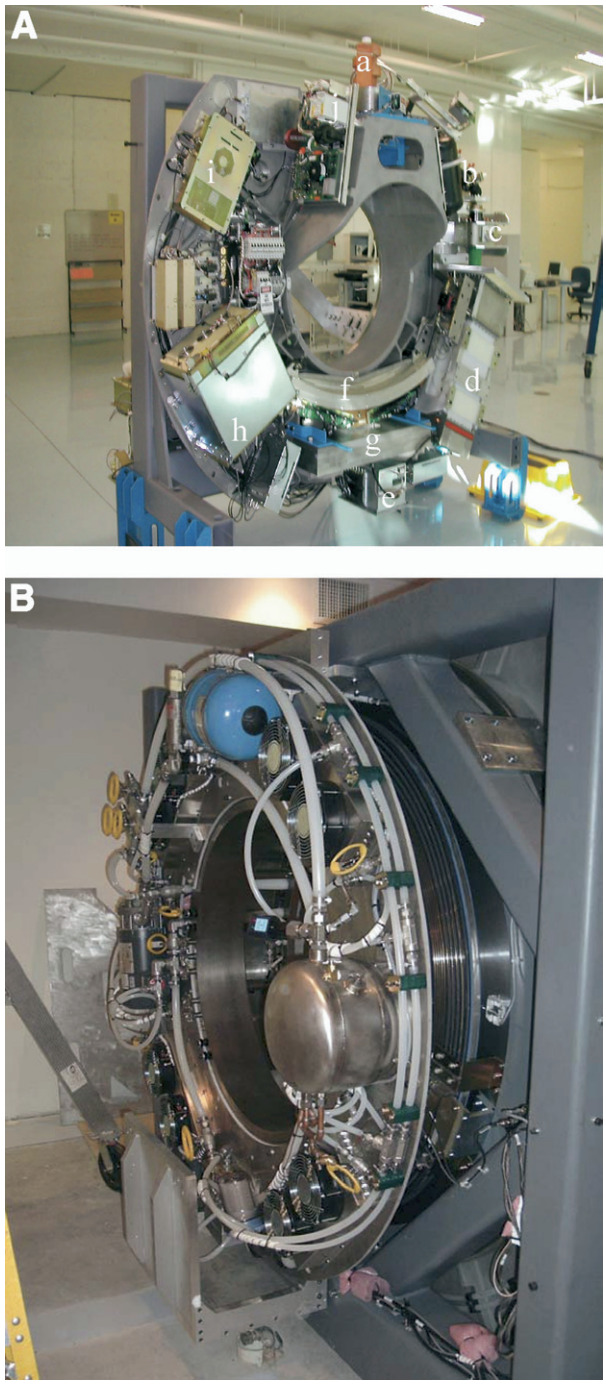

Fig. 1. (A) Front side of gantry showing various subsystems including (a) linac, (b) circulator, (c) magnetron, (d) pulse forming network, (e) image data acquisition system, (f) CT detector, (g) beam stop, (h) high voltage power supply, (i) control computer, and (j) gun. Image courtesy of TomoTherapy, Inc. (B) Backside of gantry showing cooling system.

THE HI-ART II DESIGN

Figure 1 shows the HI-ART II with gantry covers removed. The major subsystems of the treatment unit are: (1) the x-ray linac, (2) the CT imaging system, (3) the cooling system, and (4) the treatment couch. The

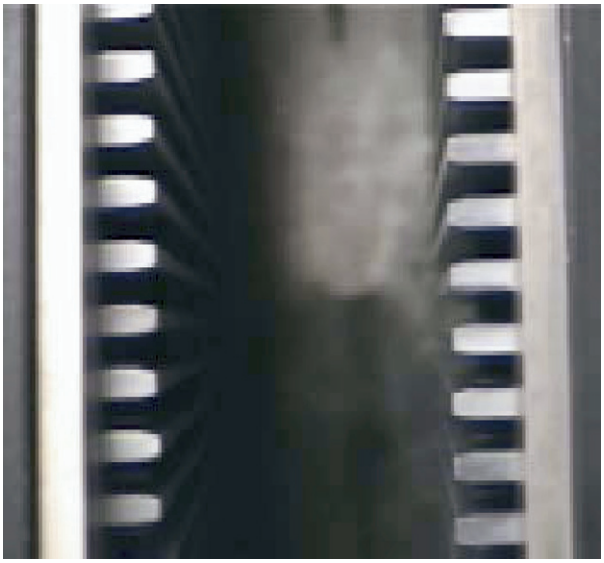

Fig. 2. View looking up into the HI-ART II binary multileaf collimator with covers removed showing the interdigitating leaves. The leaves are made of tungsten and are 10-cm thick projecting to 0.625 cm at the gantry rotation axis. Image courtesy of TomoTherapy, Inc.

HI-ART II design is based on a ring gantry to achieve high mechanical stability required for accurate, artifact-free CT image reconstruction. Its isocenter specification of 0.2 mm is a factor of 5 to 10 smaller than that of C-arm type gantries (1–2-mm-diameter sphere) and is smaller than the pixel size of reconstructed MVCT images.

Intensity modulation is achieved using a binary multileaf collimator (bMLC). Referring to Fig. 2, the bMLC consists of 64 leaves that cover a 40-cm diameter circular region of modulation at a source-axis distance of 85 cm. Hence, the leaf resolution at the isocenter is 0.625 mm. Solid jaws define commissioned fanbeam widths of 10, 18, 25, and 50 mm at isocenter on the clinical unit used in this work. Leakage characteristics of the jaws and bMLC are < 0.01 % and 0.03 %, respectively. The 80% to 20% penumbra width of 5 mm corresponds to a gradient of 12%/mm. This gradient corresponds to a dosimetric uncertainty of 2.4% at the edge of and irradiated target due to 0.2-mm mechanical flex of the gantry.

The treatment couch is a conventional helical CT couch design that uses a "cobra" motion when the table is translated vertically, that is, the couch moves up and in towards the gantry during vertical motion. Couch position accuracy is less than 1-mm longitudinally and approximately 0.5 to 1-mm vertically, with digital readouts (0.1-mm precision) available on touch screen pads located on the gantry. Lateral motion is performed using manual adjustment of screw knobs at the head and foot of the couch, with an uncertainty of 0.5 mm. A carbon fiber couch top (260-cm long by 53-cm wide by 2.2-cm thick) provides rigid patient support and minimal attenuation of the treatment and MVCT x-ray beams. The maximum longitudinal translation of the couch top is 170 cm. The "modulatable" treatment volume is a 40-cm diameter cylinder of 135-cm length. Couch flex is approximately 0.2 mm over a translation of 3 cm in the region of the head of the table when fully loaded with the weight of a patient.

The treatment unit operator's workstation combines the functions of CT imaging, image registration, and treatment delivery as indicated by the tabbed panes labeled "Scan," "Register," and "Treat" in the screen image of Fig. 3. The operator defines the volume of slices to be imaged under the Scan tab and initiates the imaging procedure that takes 10 seconds per slice to acquire and reconstruct. A 5- to 10-cm long volume can be imaged in approximately 1.5 to 3 minutes depending on the pitch selection. Next, the Registration tab is selected and the operator automatically registers the localization MVCT images with kVCT CT-simulation images based on bony and/or soft-tissue anatomy, which takes 10 to 20 seconds. Manual registration is then invoked, allowing the operator to visually correct the image registration. Several methods of analyzing the registered images are available, including direct MVCT to kVCT image comparison using a checkerboard display tool, and overlay of anatomical or isodose contours on the kVCT images. All daily images and final registration offsets are saved to the patient database record prior to proceeding to treatment delivery. While 6 degrees-of-freedom are available (x-y-z translation, and pitch, yaw, and roll rotational motions), the majority of patient corrections are handled by translational adjustments of the couch top. The HI-ART II can automatically adjust longitudinal (y) and vertical (z) motions, and gantry offset (roll), with lateral correction obtained manually using screw adjustments at the head and foot of the table. Pitch and yaw adjustments must be handled using a tertiary positioning device with angle readouts.

Treatment planning and delivery

Treatment planning is carried out on a PC workstation that is networked to a computational cluster consisting of 16 dual-9processor nodes, RAID hard drives, and an SQL data server. The data server contains the common database for treatment planning and delivery; that is, there are no separate databases for treatment planning, treatment localization imaging, and treatment delivery record-and-verification. Each patient has a single comprehensive record in the database that integrates treatment plan data (including planning CT, contours, and dose-volume constraints) with data generated during each treatment delivery (including daily MVCT images and record and verification data).

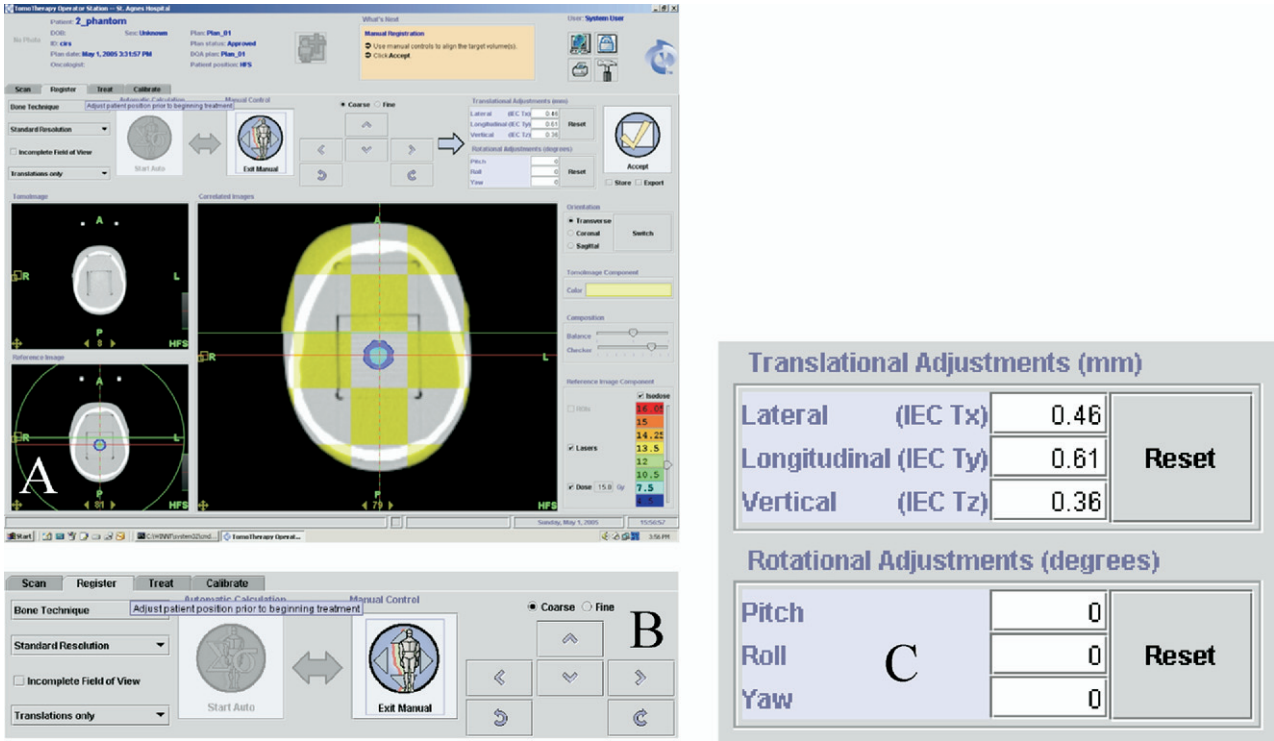

Fig. 3. (A) Screen shot of the treatment unit operator's workstation. The workstation is primarily used for image acquisition, image registration, and treatment delivery whose functions are separated into tabbed windows labeled "Scan," "Register," and "Treat." (B) The portion of the registration panel showing the automatic and manual registration modes. (C) The result of an automatic image registration operation is shown. The agreement in the x, y, and z directions is 0.46, 0.61, and 0.36 mm, respectively.

Figure 4A shows a screen shot of the HI-ART II treatment planning workstation. The planning process consists of 3 steps that are denoted by the tabbed panes labeled "ROIs," "Optimization," and "Fractionation." The 2 additional steps for treatment plan quality assurance are implemented in the "Delivery QA Setup" and "Delivery QA Analysis" panels. The function of the "ROIs" panel is to review the CT images with structure overlays, assign precedence to overlapping structures, and to align the positioning lasers with the skin fiducials. Contour editing tools are available in this panel to modify existing contours. The HI-ART II v2.1 software does not support contour creation, only editing of existing contours. Contoured structures must be created outside of the planning system, typically using an existing 3D treatment planning system, then imported into the HI-ART II planning system as DICOM objects along with the patient's CT images. The only additional structures needed for treatment planning aside from those required for plan optimization are fiducial marks on the skin designating the setup position of the lasers, and a couch structure used by the HI-ART II software to automatically replace the diagnostic couch with the HI-ART II couch in the patient's CT image set.

Most of the effort in creating a treatment plan is carried out in the "Optimization" panel, shown in Fig. 4A. Here, the operator defines the dose-volume prescriptions for one or more targets, and the dose-volume constraints for the avoidance structures that are used in the optimization process. Each target structure is assigned a 3-point dose-volume histogram (DVH) consisting of (1) a minimum dose point, (2) a maximum dose point, and (3) intermediate dose-volume point. The avoidance structures are assigned a 2-point DVH consisting of (1) a maximum dose point, and (2) an intermediate dose-volume point. A set of dose-volume constraints can be saved for reuse on similar cases in the future to save time in setting up the optimization. In addition, the operator must also select a small number of parameters associated with the dose calculation and optimization procedures: the type of dose model, the field width, the dose grid resolution, the helical pitch (the distance that the couch translates per gantry rotation expressed as a fraction of the field width), and the modulation factor (the ratio of the peak intensity to the average intensity; range 1–3).

Three dose calculation models are available. The simplest, fastest, and least accurate method is to compute TERMA (total energy released per unit mass). This method is useful for preliminary calculations when one wants to verify that the dose constraints and ROI precedence values are reasonable and consistent. The second method, called "Full Scatter," performs a full convolution superposition calculation at each iteration and is useful in the initial stages of the opti-

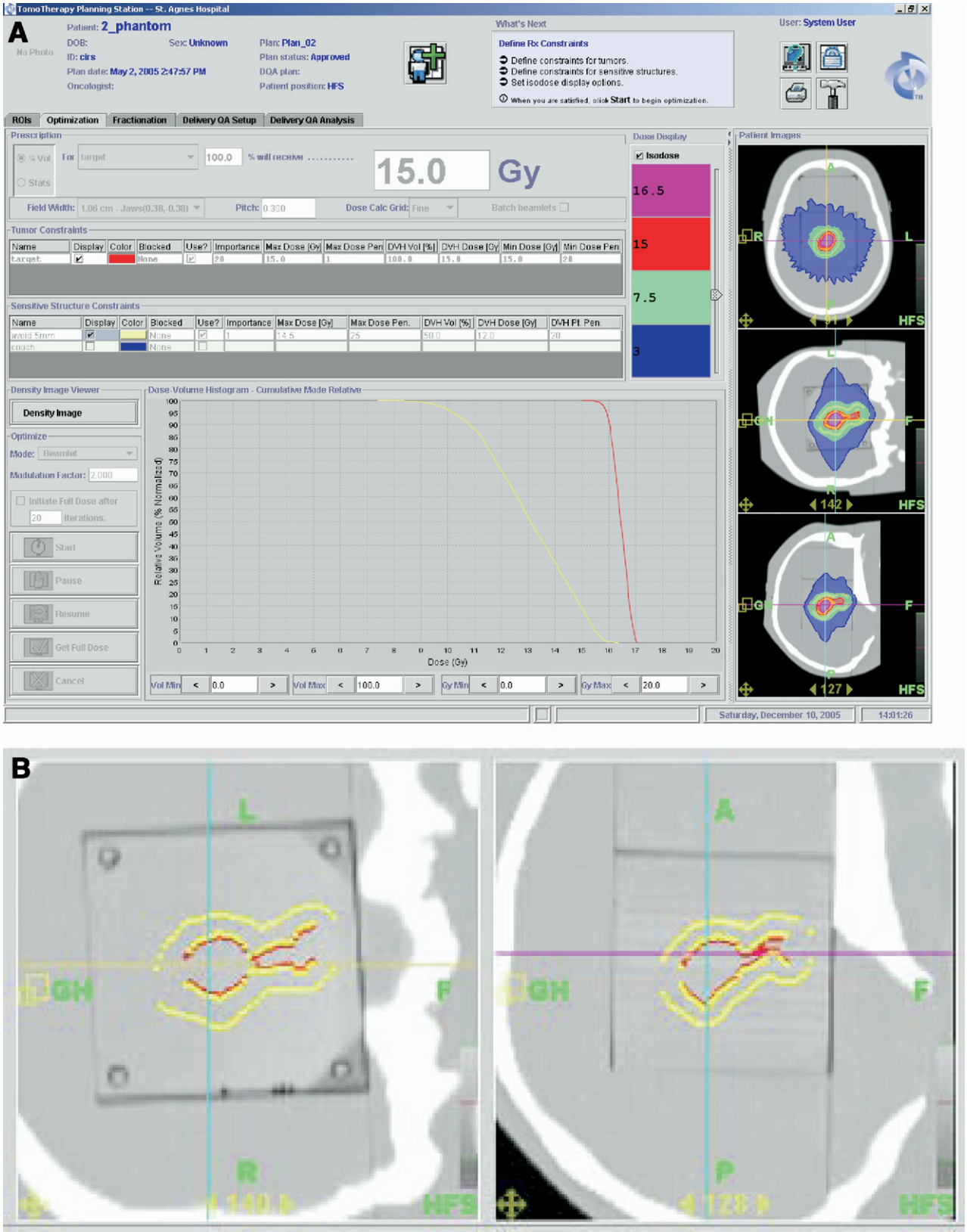

Fig. 4. (A) Screen shot of the optimization panel showing the dose-volume constraint table, DVH, and isodose distributions in the 3 principal planes. (B) Coronal and sagittal views of an irregular target volume defined in a SRS head phantom. The target is surrounded by a 10-mm wide dose-constraint structure ("ring") intended to improve conformation of dose to the target.

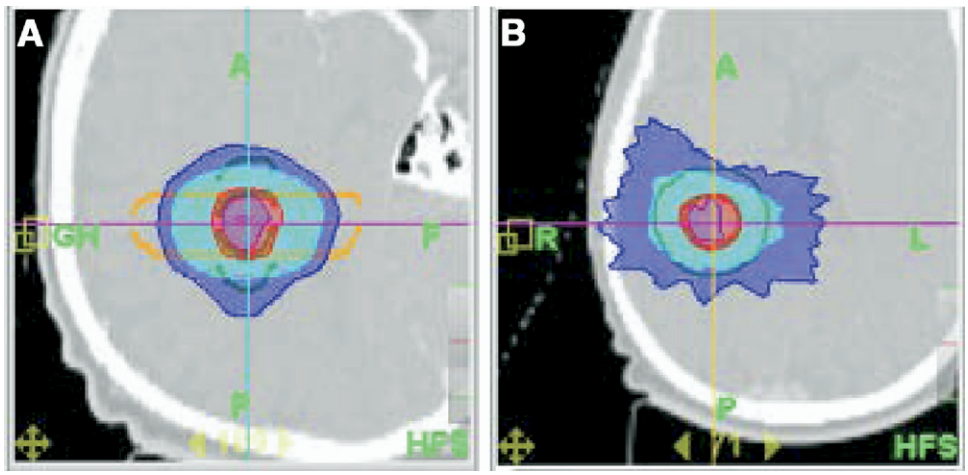

Fig. 5. The "donut" and "caps" strategy for dose constraints is useful when the field width exceeds the size of the target. In this case, the field width was 25 mm and the target width was approximately 16 mm. The 2 constraint structures and dose distribution are shown for an example 15-Gy SRS treatment. (A) Sagittal view. (B) Axial view.

mization to estimate DVH constraint parameters. The third method, called "Beamlet," is used to precompute 3D dose distributions for each MLC leaf that projects onto the target volume. This is the most common model used for planning as it allows rapid evaluation of dose during each optimization iteration.

Each full rotation is modeled as 51 static beam directions equally distributed over 360°. The number of rotations required to cover a target length L using a field width of W and pitch P is L/(WP), typically in the range of 10 to 20 rotations for small targets and pitch values. For example, a 3-cm target treated with a 1-cm field width and pitch of 0.2 requires 15 rotations.

All beamlets intersecting the target volume from each discrete beam direction are computed as independent 3D dose distributions using a multiprocessor computation cluster consisting of 32 CPUs. The number of beamlets can be very large even for small target volumes: the example given above will to a first approximation require 765 (*e.g.*, 15×51) 3D dose computations to initiate the optimization, hence the use of multiprocessing. The Beamlet model ignores some small perturbations in x-ray fluence when adjacent MLC leaves are opened sequentially vs. simultaneously.[6] For this reason, the final leaf opening patterns are analyzed and small corrections made to leaf opening times, which are then used to perform the final dose calculation using the Full Scatter dose model.

Dose can be computed at 1 of 3 spatial resolutions: FINE (1–2 mm, 1.4 mm typical), NORMAL (2–4 mm, 2.2 mm typical), or COARSE (4–8mm, rarely used). The difference in computation time between the different resolutions is roughly a factor of 10. For example, the pencil-beam dose distributions for a 2-cm-diameter spherical target in a CT volume defined by 160 slices scanned at 1-mm slice spacing will take approximately 10 minutes using the NORMAL calculation grid, but this increases to over 2 hours using a FINE calculation grid, which is the more appropriate resolution to use for a small target volume. This is not a major issue for treatments using non-invasive fixation (SRS or SBRT) because the planning can be completed prior to the day of treatment. If invasive fixation is used, it is preferable to complete the treatment within 4 to 6 hours of head ring placement for the sake of patient comfort, consequently the long computation time can be an issue if the plan needs to be modified and recomputed. Note that once the beamlets are computed, the optimization process proceeds at a fast pace, where a single iteration takes 3 to 4 seconds to complete and a useful plan is obtained in 5 minutes to 1 hour depending on the complexity of structures.

A common strategy for increasing the conformation of absorbed dose to the target is to add a margin of 5 to 10 mm around the target as a separate dose-volume constraint structure, or "ring," as shown in Fig. 4B. The maximum dose of the "ring" is set to be slightly below the minimum dose of the target, and 50% of the volume receives 50% to 80% of the target minimum dose to ensure isodose lines constrict to the shape of the target. The optimized dose resulting from this simple strategy is shown in Fig. 4A for a complex intracranial target. A more complex strategy, based on the fact that the helical delivery is composed of 2 motions (*i.e.*, gantry rotation and table translation), is to create separate constraint structures to independently manage the dose conformation in the plane of rotation and perpendicular to it using a "donut" and "caps" (Fig. 5). This strategy is useful when the target size is smaller than the smallest available field width, although it results in a broader penumbra in the direction of table motion than would exist using a smaller field width, as illustrated in the example of Fig. 4A, where a 10-mm field width was used.

The HI-ART II uses simultaneous couch translation and gantry rotation to achieve a helical delivery. Gantry rotation speed range is 1 to 6 RPM with CT imaging performed at 6 RPM and most conventional (1.8–2.0 Gy per fraction) treatments carried out at 1 to 3 RPM. The 1-RPM lower limit places a restriction on the amount of dose that can be delivered in a single rotation. To first approximation, the maximum dose deliverable at 1 RPM is effectively about 80% to 90% of the nominal dose rate of the unit (850–1000 cGy/min), depending on the size of irradiated cross-section. As a consequence, a 15- to 20-Gy treatment fraction must be subdivided into 2 or more equal treatments of 7.5 Gy or less for the gantry rotation speed to be greater than 1 RPM. For example, in our clinic, a 60-Gy (20 Gy/f x 3f) stereotactic lung treatment is delivered as 12 identical 5-Gy treatments, with 4 treatments delivered sequentially on the same day in a 1-hour time slot. MVCT localization imaging is performed before each 5-Gy treatment, allowing us to adapt the patient/target position prior initiating the next 5-Gy treatment. Additionally, the lower dose per fraction has the added advantage that a 5-Gy treatment can be verified using the popular Kodak ERD2 dosimetry film without saturating the optical density of the film. Alternatively, radiochromic film can be used to verify one or more of the treatment segments without concern for optical density (OD) saturation and without the need for a developer.

Treatment plan documentation consists of (1) screen printouts of the treatment planning panels including isodose in axial, coronal, and sagittal directions, and (2) a multiple page plan report that includes: the patient name and ID number, plan parameters (field width, modulation factor, pitch), final DVHs, current dose, a page of dose-volume statistics, and a page of fractionation data that includes number of gantry rotations and period, couch travel and speed, monitor units, and absorbed dose per fraction. Treatment delivery printouts include the time of exposure and dose delivered. This data is useful in the event of an incomplete treatment as it allows one to estimate the length of the target volume that was irradiated. While treatment interruptions are a rare event, the system will automatically generate a completion procedure when these occur.

Megavoltage CT localization – precision and accuracy

HI-ART II utilizes megavoltage CT imaging for target localization, a process called TomoImage Verification Registration CT, or VRCT. The same linac source used for treatment is used to produce a low-intensity, 3.5-MV (nominal) energy x-ray beam for imaging. Helical CT imaging acquisition is carried out at 1 of 3 predefined, user-selectable, pitch settings of 1 (FINE), 1.6 (NORMAL), or 2.4 (COARSE). The VRCT system produces 512 × 512 CT images having a pixel dimension of 0.78 mm and a slice thickness of 4 mm defined by the primary jaws, at a dose of 1 to 2 cGy per procedure. Image acquisition is 2 slices per 10 second rotation corresponding to the maximum gantry rotation speed of 6 RPM. Meeks *et al.*[7] investigated the image characteristics of the TomoImage system and reported a high-contrast resolution of 1.2 to 1.4 mm and low-contrast resolution of 4%, sufficient to distinguish prostate from surrounding muscle.

Megavoltage CT imaging has the advantage of suppressing image artifacts that otherwise arise in kVCT imaging due to photoelectric attenuation amplification related to differences in atomic number. Compton attenuation, which is independent of atomic number, dominates in the megavoltage energy range resulting in CT numbers that are linear with electron density. Consequently, high atomic number implants and fillings are relatively artifact free (Fig. 6). In the presence of significant artifacts, it is desirable to use the MVCT images as a primary dataset for dose computation because the false CT numbers will distort the inverse planning results. The main limitation of the MVCT images is the poorer low-contrast resolution that can make target definition more difficult than kVCT images. Although the presence of metal artifacts in stereotactic treatment volumes is typically rare, for those situations that present themselves, MVCT is a viable alternative to kVCT imaging.

In our clinic, MVCT localization imaging is performed before each 5- to 7-Gy SRS/SBRT treatment delivery segment, resulting in a total of 3 to 5 imaging procedures during a daily treatment session. Each MVCT localization image acquisition takes approximately 3 to 4 minutes to acquire images covering a 10-cm length using a FINE pitch setting. The patient is first set up in the immobilization system on the treatment couch and marks on the patient's skin and immobilization system are then aligned with the localization lasers by couch movement. The laser-based setup typically localizes an intracranial target to within 5 mm and an extracranial target in the thorax to within 1 to 2 mm of the final position determined by the MVCT localization images. The volume of images to be acquired is defined by the therapist on a sagittal "scout" view of the patient rendered from the original plan CT image set. Once images are acquired, the Image Registration tab is selected and automatic registration performed using bony anatomy in the MVCT and kVCT image sets. Alternatively, one can register the images using bone and soft-tissue anatomy, which is sometimes useful for lung SBRT. The therapist will then perform manual adjustments of the registered images based on soft-tissue anatomy in the important regions defined by the radiation oncologist. The registration moves can be made on axial, coronal, and sagittal views of the registered image sets. The comparison is further enhanced by overlaying the anatomical structures or an isodose colorwash (Fig. 7).

The registration can be carried out using 3 (x-y-z translation), 4 (translation plus roll via gantry rotation),

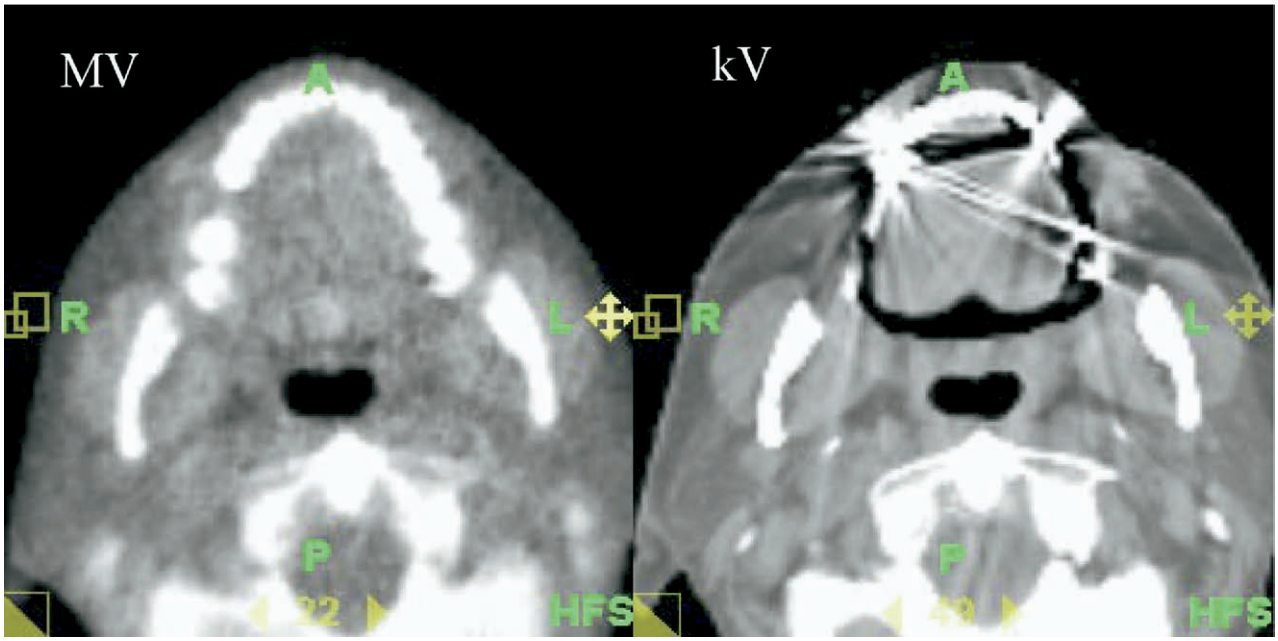

Fig. 6. Comparison of megavoltage CT vs. kilovoltage CT. Image artifacts due to high Z tooth fillings are eliminated in the MVCT image at the cost of lower soft-tissue contrast.

or a full 6-degrees-of-motion (x-y-z translations, roll, pitch, and yaw). The offsets determined can then be applied to the patient setup. Veritical (z) and longitudinal (y) translations are motorized through the use of the treatment couch. The gantry motion can make the roll adjustment automatically. The lateral adjustment (x) is performed manually using hand cranks on the couch top. Automated pitch and yaw adjustments are not currently provided by the HI-ART II but would have to be incorporated into an independent couch-top adapter.

The accuracy of the MVCT localization process was established by simulating an SRS delivery using a SRS head phantom (CIRS, Inc, Virginia Beach, VA) in an invasive head ring rigidly attached to the table (Fig. 8). The setup was imaged on the CT simulator and a tomotherapy plan developed for the HI-ART II using a small 1.5-cm target in the center of the phantom. The target was centered on the film plane of a dosimetry insert. The phantom setup was then moved to the HI-ART II couch top for imaging and delivery. The Image

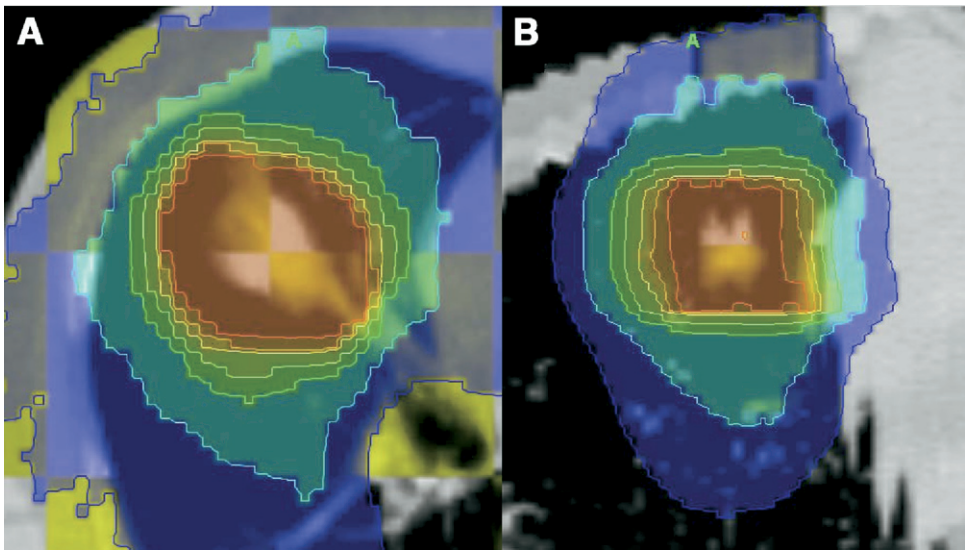

Fig. 7. Lung SBRT localization result showing MVCT (yellow checkerboard) and isodose overlays on the grayscale CT simulation image used for planning. (A) axial plane. (B) sagittal plane.

Fig. 8. SRS head phantom setup for testing localization accuracy of dose to a small target. Inset photo shows the internal film dosimetry block.

Registration procedure was performed to determine offsets to align the phantom with the plan. Automatic registration of bony anatomy was performed using the translation degrees-of-freedom setting. The offsets were made to the setup and the phantom re-imaged. The total offset vector was tabulated and the process repeated 5 times. The range of values obtained was 0.5 to 1.1 mm.

Next, the plan was delivered to the phantom after radiochromic film was inserted in the film block. Following the treatment delivery, the film was removed from the phantom and digitized using a 16-bit scanner (Vidar Dosimetry Pro, Vidar, Inc., Herndon, VA). The digitized image was then imported into the tomotherapy planning system dosimetry QA analysis tool and registered with the computed dose distribution. Figure 9 presents a comparison of computed and measured dose profiles in the lateral and longitudinal directions of the coronal plane. These results indicate overall accuracy of the HI-ART II image localization and treatment delivery process is approximately 1 to 2 mm, which meets the 2- to 2.4-mm overall accuracy specification for SRS defined in Task Group 54.

Motion management

Accurate IG-IMRT is based on the comparison of two 3D digital models of the patient defined by volumetric CT datasets acquired at different points in time. A kVCT image set is acquired at the time of simulation and acts as the baseline model of the patient against which daily MVCT volumetric image sets are compared during the Image Registration step of the tomotherapy process. The implied assumption when using the MVCT dataset as a model of the patient setup for the treatment is that the patient position and shape remain static during the 10 to 15 minutes required to image and treat a 5-Gy treatment segment. Currently, there is no means built into the HI-ART II system to provide feedback on patient motion, and because the accuracy requirement for stereotactic procedures is so stringent it is necessary to provide (1) rigid immobilization, and (2) a real-time system to monitor patient motion during the imaging and treatment process for these procedures.

In our practice, we have adapted commercially available equipment for HI-ART II intracranial and extracranial stereotactic procedures (Figs. 10 and 11). For intracranial SRS procedures, using invasive and noninvasive fixation, a commercially available optically-guided SRS system (Linac Scalpel and Radiocameras Treatment Guidance System (TGS), ZMED/Varian Medical Systems, Inc., Holliston, MA) has been combined with 3 custom couch-top adapters (Integrated Medical Technologies, Troy, NY) for use on the HI-ART II helical tomotherapy unit. The camera couch-top adaptor allows the Polaris IR camera (Northern Digital, Inc., Waterloo, Ontario, Canada) to be attached to the couch top so that the camera moves with the table to maintain a fixed geometry with the patient in accordance with the Radiocameras software model (Fig. 10A). An optical

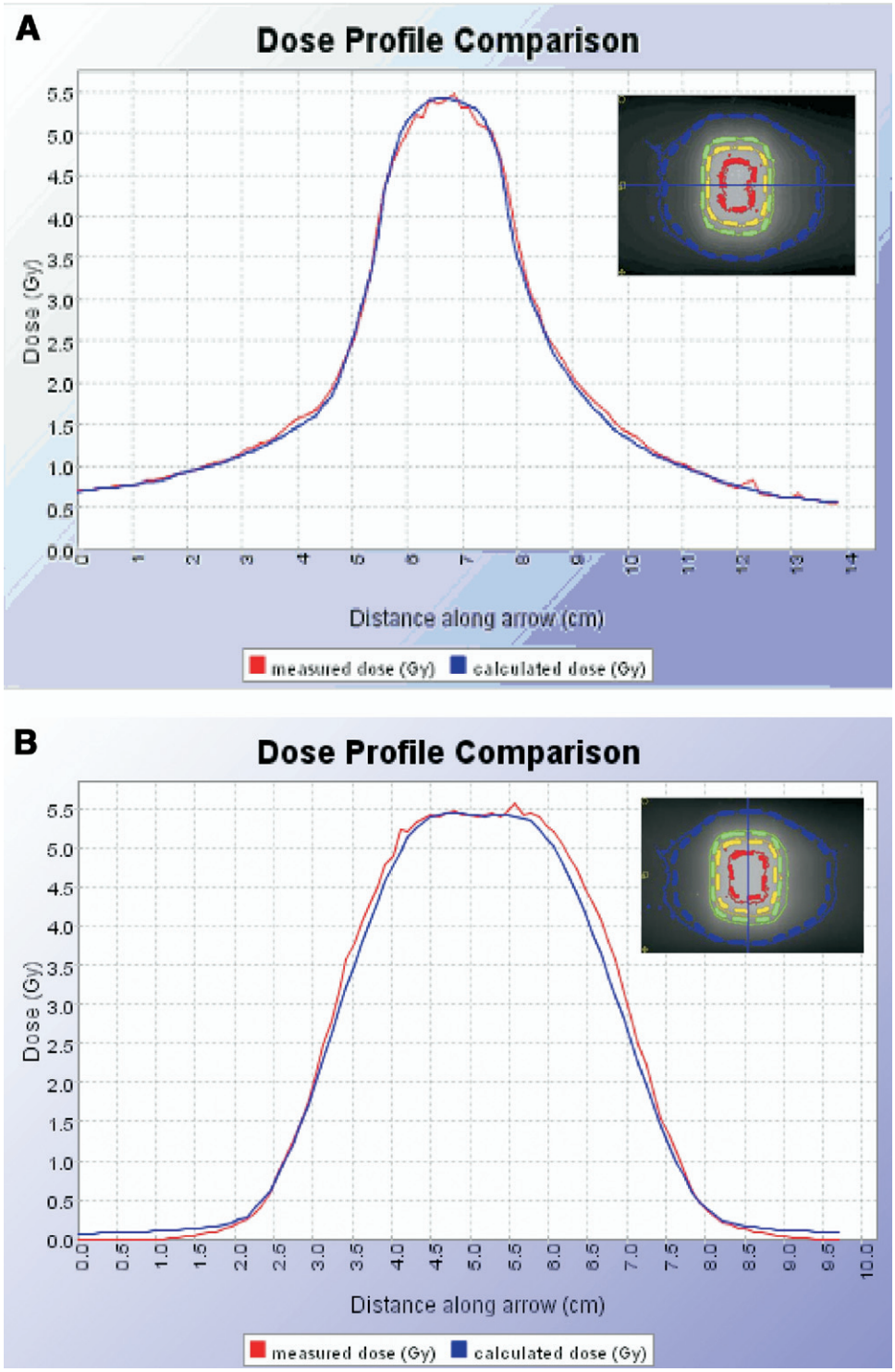

Fig. 9. SRS/SBRT dose targeting measurements illustrating the high accuracy of the overall process of MVCT localization and treatment delivery. (A) Coronal – lateral direction. (B) Coronal – longitudinal direction.

calibration phantom adaptor facilitates the calibration of the IR guidance system to the HIART II virtual isocenter (Fig. 10B). Once calibrated, the optical calibration phantom is removed from its adaptor and the treatment couch adaptor is abutted to it to place it in the treatment position (Fig. 10C). The patient is then placed on the table and the head ring screwed to the table adapter for the Tomotherapy SRS procedure. Noninvasive SRS fixation is achieved using a thermoplastic mask system that is secured to the couch top with a table clamp integrated to the carbon fiber baseplate (Orfit Industries America, Uniondale, NY). Motion monitoring is performed by

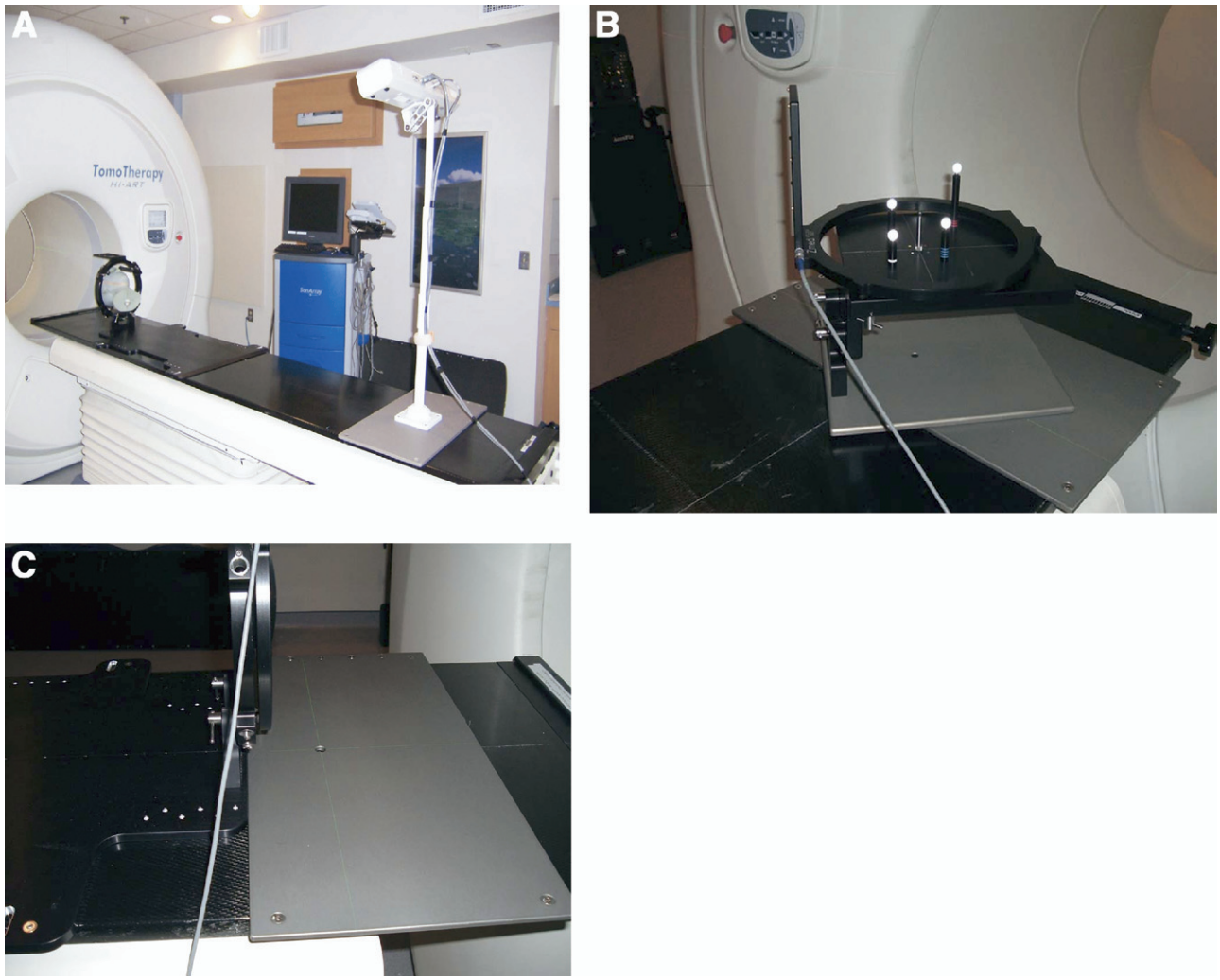

Fig. 10. The Zmed Radiocameras Treatment Guidance System and invasive fixation hardware were adapted for use on the HI-ART II couch top. (A) SRS treatment setup using Zmed invasive fixation and infrared emitter fiducial array attached to the custom couch-top adapter. The Polaris camera is attached to a separate couch-top adapter that allows the camera to be easily removed when not used. (B) Calibration setup showing the Radiocamera calibration phantom with infrared emitter fiducial array attached for functional verification. (C) The couchtop adapter is aligned with the calibration baseplate following camera calibration procedure. The camera baseplate is then removed for the treatment.

tracking an infrared reflector array that is attached to a custom mouthpiece using the Radiocameras system.

Motion monitoring for either type of intracranial SRS fixation system is initiated at the time of the MVCT imaging procedure by zeroing the Radiocameras readouts when the patient is inside the HI-ART II gantry bore at the starting position of the imaging procedure. Typical couch sag as measured by the Radiocameras system is 0.2 to 0.3 mm over 3 to 5 cm of couch motion, which is comparable to the NDI Polaris camera's stated RMS accuracy of 0.35 mm in the useable field of view defined by a cylindrical region 1-m tall and 1-m diameter located approximately 1 m from the camera. A display of the Radiocamera system's position readouts is located at the operator's station outside of the treatment room to allow real-time monitoring of the patient. Our action level is to interrupt treatment and reposition the patient in the event the displacement vector exceeds an RMS deviation of 1 mm. In this situation, the HI-ART II software creates a completion procedure that is initiated after a second localization MVCT scan is performed and the readouts re-zeroed.

Extracranial immobilization equipment consists of the Medical Intelligence BodyFix RT Immobilization System and a custom-made abdominal compression belt (XSqueezeMe, Integrated Medical Technologies) that attaches to the BodyFix carbon fiber baseplate (Fig. 11). The patient is placed in a supine position with arms above the head in a BodyFix BlueBAG whole body cushion. The patient is covered with a plastic sheet and a vacuum pulled under the sheet to restrain the patient from moving. Next, the abdominal compression belt is attached to the BodyFix baseplate and Velcro straps adjusted to compress the diaphragm the desired amount

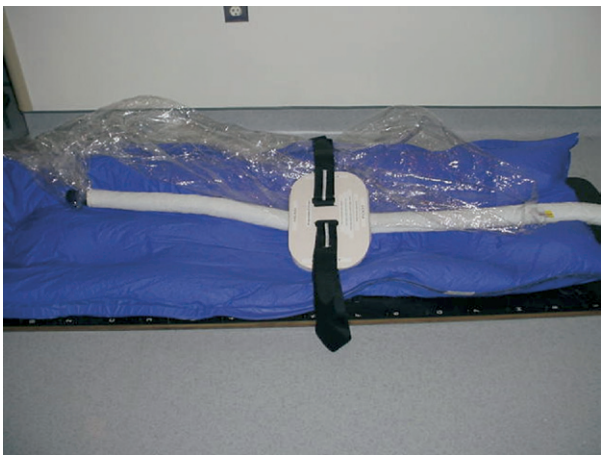

Fig. 11. SBRT immobilization equipment includes the BodyFix immobilization system augmented with an abdominal compression belt.

using rulers attached to the straps as a guide. The patient is then imaged to localize the target volume.

The extracranial immobilization system is used exclusively for lung SBRT treatments. Our practice is to deliver 3 fractions of 20 Gy over a 1.5- to 2-week period following the guidelines of RTOG Protocol 0236.[8] The patient is immobilized, as described above on the couch top of an RF simulator. The amount of target motion with full immobilization and abdominal compression in place is estimated under fluoroscopy and used to define a treatment margin on the CT simulation images. Margins typically range from 1 to 2 cm using this estimation technique. The patient and immobilization equipment are then moved to a large-bore CT simulator (Philips Ac-QSim/VoxelQ, Philips Medical Systems, N.A., Bothell, WA) and the treatment volume imaged at 3-mm slice resolution under conditions of shallow breathing. The target volume is outlined on the VoxelQ workstation and the position of setup lasers defined on the skin surface. The images are transferred to the planning system, where the margins are applied to the target to create a PTV, and additional constraint structures defined for inverse planning. The immobilization and simulation processes take 1 hour to perform. Generation of the lung SBRT inverse plan takes 30 minutes to 2 hours to complete on the tomotherapy planning system. An example planning result is shown in Fig. 12, illustrating the high conformance of dose to the target, and low dose to uninvolved lung. Figure 7 shows the result of the image registration of MVCT localization images (yellow checker board) with the CT simulation images (grayscale) along with isodose distribution overlays.

DISCUSSION

This presentation has described our initial developments for using the HI-ART II Helical tomotherapy system for intracranial and extracranial stereotactic IG-IMRT. Our work has focused on using existing technologies for realizing clinical treatment capability with certain limitations that are described below.

Dose computation time is long for stereotactic applications—approximately 2 hours—owing to the use of a FINE computation grid that is applied isotro-

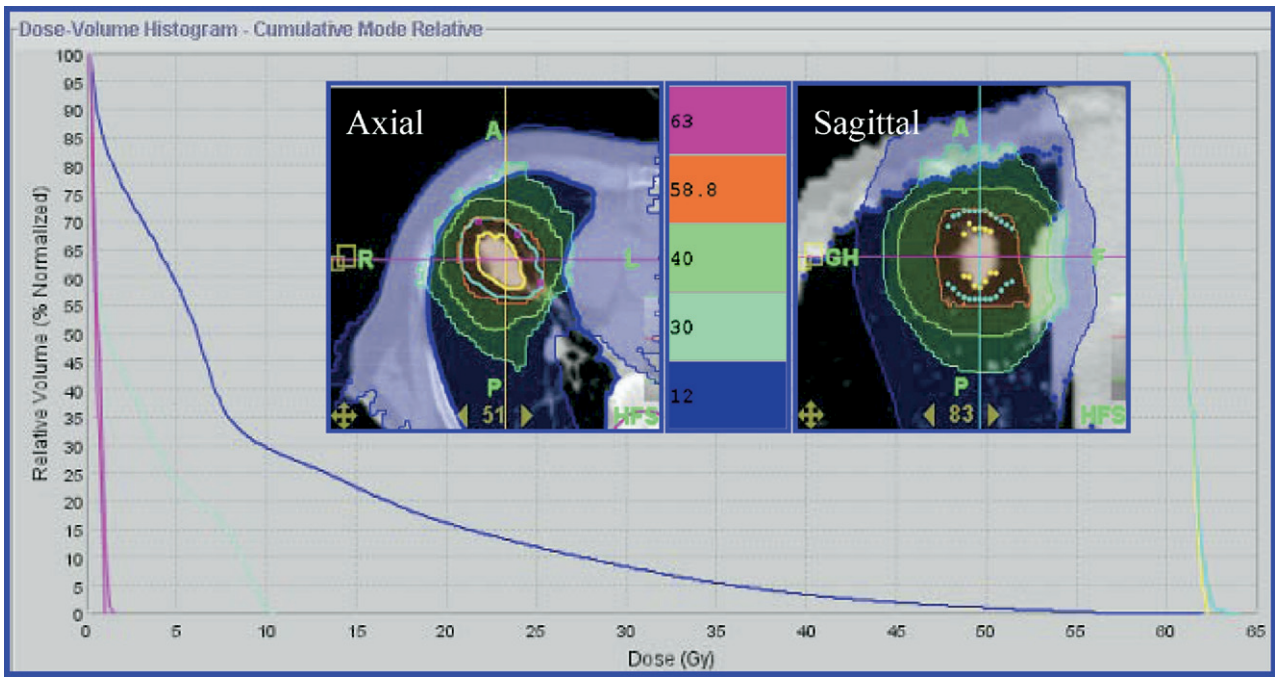

Fig. 12. Helical tomotherapy lung SBRT optimization result.

pically over the complete CT dataset volume. Although this is generally not a major issue for noninvasive SRS, because preparation of the plan is done 1 to 2 days ahead of the treatment date, it is nevertheless an issue when invasive head fixation is used where it is desirable to complete the imaging, planning, and treatment delivery within 4 to 6 hours of head ring placement to alleviate patient discomfort.

Reduction of computation time could be achieved by adding more processors to the computation cluster – a brute force hardware solution that would require a significant financial investment to reduce the computation time to less than 1 hour. An alternative approach used in many computationally-intensive modeling scenarios is to use a variable grid size, wherein a fine resolution is used in the target region plus some margin, and a coarser resolution for the remaining volume. Given that the target volumes in stereotactic procedures are small, a coarse grid would cover most of the computation volume, consequently it is expected that the dose computation time would be reduced significantly from several hours to less than 30 minutes using the existing 32 CPU computation cluster.

By convention, intracranial SRS treatments are carried out using noncoplanar arc arrangements to restrict the dose to nontarget regions to be as low as possible. The HI-ART II is currently limited to coplanar delivery consequently the dose to nontarget regions is higher than that achieved using noncoplanar arcs with circular collimators, especially for small isolated spherical targets (Fig. 13).

Despite this limitation, the HI-ART II provides excellent dose conformation to the target regardless of complexity and it allows simultaneous treatment of multiple targets. Consequently, we triage complex SRS cases (large irregular targets) to the HI-ART II and treat simpler cases using the noncoplanar SRS system.

Manual treatment interruptions during an intracranial SRS treatment due to patient motion exceeding the 1-mm action level can extend the treatment by 10 to 15 minutes if the patient is to be relocalized using the MVCT prior to initiating the treatment completion. A more efficient approach will require gating the beam output using patient motion feedback from the optical guidance camera.

The major limitation of the SBRT method we use is that it is inherently a "3D method" that does not account for real-time target motion due to breathing. This is handled by adding a margin to the target—this increases the volume of nontarget lung irradiated and the potential for treatment complications such as radiation pneumonitis. Much work is ongoing in the radiotherapy field to develop 4D planning and delivery models to improve the accuracy of targeting the dose delivery to a moving target. This is to be achieved through synchronization of beam output and MLC leaf motion to a 4D model of the patient that is obtained using multislice CT technology.[9]

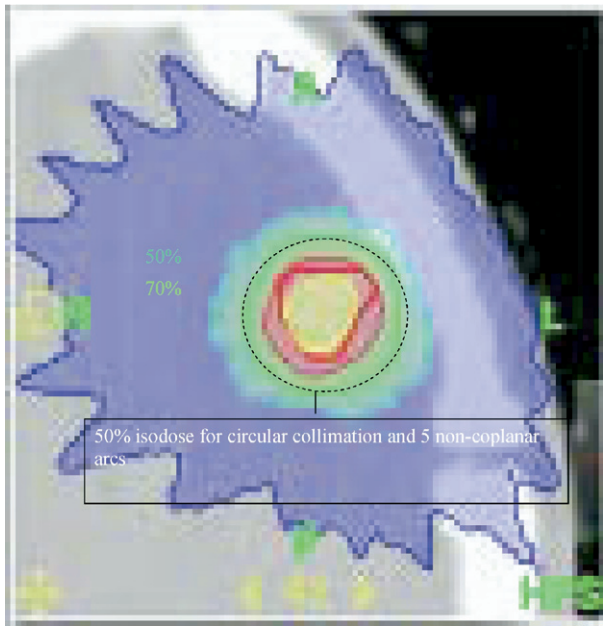

Fig. 13. Low-dose comparison of a Tomotherapy coplanar SRS, a conventional SRS treatment using circular collimation, and 5 noncoplanar arcs. The 50% isodose line (---) of the conventional SRS treatment corresponds to the 70% isodose line of the coplanar Tomotherapy SRS simulation.

The level of integration needed is significant to achieve this but the clinical advantages will merit the effort.

CONCLUSIONS

We have described the overall design and process of the HI-ART II helical tomotherapy system and demonstrated that its accuracy for localizing dose to a small target is within the accepted specification of 2 to 2.4 mm for SRS treatments using image-guided IMRT. In addition, we have described our efforts at adapting existing tools for managing patient motion to the HI-ART platform to allow SRS and SBRT treatments to be carried out accurately. The HIART II currently lacks a treatment delivery model that can handle target motion and noncoplanar delivery. Nevertheless, it is very useful for complex SRS cases, and for routine SBRT using currently accepted immobilization and 3D planning techniques. The presence of integrated CT imaging on IMRT-capable treatment units such as the HI-ART II provides an exciting opportunity to significantly improve the accuracy of targeting high doses to a small tumors with a potential reduction in normal tissue morbidity.

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