FEASIBILITY OF REAL-TIME MOTION MANAGEMENT
ON THE RADIXACT™ SYSTEM

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Abstract

In this study, we adapted the motion tracking technology from the CyberKnife® Treatment Delivery System to a system capable of delivering helical tomotherapy treatments and performed motion correction using the jaws and binary multileaf collimator (MLC). To enable motion modeling and tracking, a kV flat-panel imaging system was added to an existing gantry, mounted perpendicular to the MV treatment beamline, and an optical camera was mounted above the foot of the couch. Flat-panel images were acquired every few seconds to determine internal target positions and the target positions were correlated with breathing amplitudes detected continuously by the camera view of external markers. Jaw positions and MLC leaf patterns were updated continuously to follow the target motion. Film measurements were taken of deliveries, with and without motion management enabled, and compared against the planned (no-motion) dose. With motion correction enabled, dose delivered to a respiratory motion target closely matched the planned dose. For a target with non-periodic motion (e.g., prostate-like motion), dose delivered with motion correction enabled was substantially improved compared to delivery when no motion correction was used.

Introduction

Targets move during radiotherapy treatment for many reasons, including bodily processes, such as respiration and digestion. It is clinically beneficial to account for this motion, to ensure that the target receives the prescribed dose, as well as to minimize toxicity associated with irradiation of surrounding healthy tissue. Accounting for motion is particularly important when higher doses of radiation are delivered in fewer sessions than conventional radiotherapy, such as for stereotactic body radiation therapy (SBRT).

Various pre-treatment and in-treatment approaches have been used to manage target motion. Pre-treatment alternatives include expanding planning target volume (PTV) margins, immobilizing the patient or target, or both. Immobilization techniques include the use of deep inspiration breath-hold, abdominal compression, bladder and bowel preparation and other similar methods of physically preventing motion. But these methods are generally inconvenient and negatively impact patient comfort. Margin expansion for respiratory motion is usually done through the definition of an internal target volume (ITV) that covers the target throughout its entire range of motion. Whether using an ITV for respiratory motion, or simply expanding PTV margins for other motion-related setup uncertainty, the resulting target volumes can be large and include additional healthy tissue. Furthermore, it has been shown that target motion can change significantly, from day to day and even during treatment, which means that an ITV defined during treatment planning may not accurately cover the target range of motion during treatment delivery.

In-treatment techniques focus on adjusting the treatment delivery to the patient, rather than forcing patient anatomy to stay in the planned path of the treatment beam. This requires technology to track the target position and hardware capable of changing the planned treatment delivery in real time to correct for the motion. For conventional radiotherapy systems, this usually means stopping treatment delivery when a motion larger than a specified threshold is detected, repositioning the couch, acquiring additional images to verify the patient’s position and then resuming treatment delivery.

In the case of targets that move with respiration, some conventional radiotherapy systems gate the treatment delivery based on the patient’s respiratory cycle, i.e., these systems turn the radiation on only when the target is in the path of the treatment beam. Respiratory gating is time consuming, because the radiation is turned off for most of the respiratory cycle; the duty cycle is typically less than 30%. Wider gating windows – the portion of the respiratory cycle during which radiation is turned on – means faster treatment, but also reduces the precision of delivery and results in more normal tissue being irradiated.
The most advanced technique goes further and re-targets the treatment beam in real-time to follow the moving target. The treatment beam moves as the target gradually drifts (common for intracranial and spine targets), unpredictably shifts (common for prostate and gynecological targets) or moves with respiration (common for abdominal and thoracic targets). This technique maintains the delivery accuracy throughout treatment delivery and enables planning with minimal PTV margin expansion. For targets that move with respiration, real-time re-targeting enables PTV margins similar to those used with very short gating windows, but without increasing delivery times (a 100% duty cycle). The CyberKnife System is the only radiotherapy device that can maintain sub-millimeter accuracy throughout treatment delivery with fully integrated image guidance, automatic motion tracking, and real-time robotic beam re-targeting to correct for motion. To track motion during delivery it uses an orthogonal imaging system with diagnostic kV sources fixed to the ceiling and flat-panel detectors located in the floor, along with an optical camera positioned above the couch. The system also includes a suite of proprietary tracking algorithms specifically designed for particular clinical applications. Translational and rotational motion of soft tissue targets, like the prostate, can be tracked using implanted fiducial markers. Xsight® Lung Tracking can track lung targets without implanted fiducial markers, eliminating the risk of pneumothorax due to marker implantation. The sub-millimeter accuracy of these and other tracking algorithms on the CyberKnife System has been demonstrated and reported in the literature.

In addition, targets that move with respiration, such as lung and liver, are tracked with the Synchrony® Respiratory Motion Tracking System. This system dynamically aligns the treatment beam to the moving target and synchronizes the treatment delivery to the patient's normal breathing, without compression and/or breath holding. A robotic arm moves the treatment beam based on a correlation between the target position, determined from periodic kV image acquisitions, and the breathing amplitude continuously monitored with external optical markers. This respiratory correlation model is built before each treatment and periodically updated during treatment delivery with additional kV image acquisitions to adjust to the patient's gradually changing respiratory pattern. Synchrony Respiratory Motion Tracking is the most advanced respiratory motion management system, and is unique to the CyberKnife System. Its sub-millimeter accuracy has been demonstrated and reported.

Accuray Incorporated has unique expertise in image-guidance technologies, anatomical site-specific tracking algorithms and robotic beam delivery correction. It is our intention to transfer the currently approved and proven effective technology and expertise from the CyberKnife System to the Radixact™ Treatment Delivery System. This white paper describes experimental work that has been done to evaluate the feasibility of this technology transfer.

**Experimental Methods and Results**

Helical tomotherapy treatment delivery provides precise treatments with conformal dose distributions, but the system's continuous motion makes this modality incompatible with some forms of motion management. For example, the continuously rotating gantry is unlikely to be at the correct angle to synchronize dose delivery with a narrow window of breathing phases, as required for gated delivery.

However, real-time re-targeting, similar to that performed by the CyberKnife System, is compatible with helical delivery modalities. As the couch progressively moves into the gantry and the linear accelerator continuously rotates around the patient, the jaw positions could be modified to compensate for superior-inferior target motion (Figure 1) and the binary MLC leaf patterns could be modified to compensate for anterior-posterior and mediolateral motions (Figure 2).
Before the system can correct for motion, it must first be able to detect the position of the target. To track internal target motion like the CyberKnife System, we mounted kV flat-panel imaging hardware onto a gantry capable of helical tomotherapy deliveries, as shown in Figure 3. A kV tube and detector were mounted at 90 degrees offset from the MV treatment beam-line. In addition, an optical camera was installed above the foot of the couch, looking into the bore.

An in-house robotic phantom was used to simulate realistic target motion. The phantom consists of three linear actuators supporting an acrylic cylinder, in which can be placed a film and ion chamber to acquire dosimetric measurements. Gold fiducial markers – visible in kV images – were implanted inside the acrylic cylinder and light-emitting diode (LED) markers visible to the optical camera were attached to the moving stage of the robotic platform.
The experimental system acquires periodic kV images to track the gold fiducials, then correlates the fiducial positions with breathing amplitudes continuously monitored by the optical camera following the external LED markers. These sequential monoscopic kV images are acquired as the gantry rotates to build an initial correlation model. The model is updated by acquiring additional images throughout the subsequent treatment delivery. The impact of MV scatter on kV flat-panel images was negligible, so kV images can be acquired without interrupting the treatment delivery. Jaw positions and MLC leaf patterns are updated continuously in real-time, re-shaping (effectively re-pointing) the treatment beam to follow the target motion. Jaw and leaf adjustments are made every 10 ms with only a few tens of milliseconds end-to-end latency.

Respiratory Motion Experiment

To test the system’s efficacy in correcting for respiratory motion, we delivered a helical tomotherapy treatment plan to a small moving target. A small target was chosen since dose delivery uncertainties resulting from motion are more noticeable in the dose profiles measured for smaller targets. The treatment plan was prepared to cover at least 95% of a 1 cm target volume with 2.5 Gy, which resulted in a dose distribution just over 2 cm wide at the half-max isodose line. The treatment duration was 126 seconds.

To simulate respiratory motion, the phantom was programmed to move linearly in all three axes using the motion trace in Figure 4, which has a maximum amplitude of approximately 15 mm. This motion trace corresponds to a typical respiratory breathing pattern recorded during treatment delivery by the Synchrony® Respiratory Tracking system.

Superior-Inferior dose profiles were measured through the center of the target using EBT3 radiochromic film and compared against the same plan in three different scenarios: with no phantom motion, with phantom motion without correction and with phantom motion with correction. Results are shown in Figure 5.

We observe that when no motion correction was applied (orange line), the dose profile is blurred and shifted, and the peak drops by 19% compared to the reference with no phantom motion (blue line). When motion correction is enabled (green line), the dose profile closely matches the reference, demonstrating the experimental system’s ability to correct for respiratory motion.
Prostate Motion Experiment

We also evaluated the system’s ability to correct for non-respiratory motion, such as the gradual drift and unpredictable shifts that can occur in prostate treatments. The robotic phantom was programmed to reproduce a real prostate motion trace previously acquired with the Calypso® system (Figure 6). The range of motion was +8 mm to -5 mm with intermittent excursions up to 14 mm.

![Figure 6. Prostate motion trace acquired from a real patient using Calypso, left-right motion (blue), superior-inferior motion (orange) and up-down motion (green).](image)

In the case of non-periodic motion, there is no need to use the external camera. The system used only the sequential monoscopic kV images, acquired as the gantry rotated, to track the positions of the gold fiducials. The system acquired two kV images per rotation, 90 degrees apart, with a gantry rotation period of 12 seconds. Jaw positions and MLC leaf patterns were automatically adjusted to account for detected target motion after each image acquisition.

A typical hypo-fractionated prostate helical treatment was delivered. The treatment plan was prepared to cover at least 95% of a 5.5 cm diameter volume with 5.0 Gy, which resulted in a dose distribution approximately 6.5 cm wide at half-max. The treatment plan used TomoEDGE™ and the 2.5 cm field. The treatment duration was 340 seconds. The superior-inferior dose profiles were measured through the center of the target using EDR2 film, and compared against the same plan in three different scenarios: with no phantom motion, with phantom motion without correction and with phantom motion with correction.

![Superior-Inferior Dose Profiles](chart)

Film measurements are shown in Figure 7. We observe that when no motion correction is applied (orange line), the dose profile significantly changes compared to the reference with no phantom motion (blue line). The dose profile central region is hotter by up to 16%, and both superior and inferior ends are shifted toward the middle by 0.5 cm and 0.3 cm, respectively. When motion correction is enabled (green line), the dose profile more closely matches the reference, demonstrating the system’s ability to correct for a typical prostate motion with gradual drift and intermittent excursions.

![Figure 7. Prostate motion experiment film measurement results. Superior-inferior dose profiles measured through the center of the target, with no motion (blue), motion but no correction (orange) and motion with correction (green).](image)

The limiting factor in this case is the frequency of kV image acquisition. Unlike respiratory motion tracking, where the optical camera provides a continuous motion signal, new target position information is only available from the
periodic kV images. Motion that occurs between acquisitions (alternately at 3 second and 9 second intervals) is not corrected for, and results in some residual delivery inaccuracy. More frequent imaging would further improve the motion corrected delivery accuracy.

Discussion and Conclusion

This experimental work describes a possible adaptation of tracking and motion compensation technology from the CyberKnife System to the Radixact System, including experimental results demonstrating the feasibility of this approach. This could benefit many clinical indications, taking advantage of Accuray's proprietary tracking algorithms to position the target pre-treatment, and automatically adapt the treatment during delivery to account for gradual drifts, unpredictable shifts, and respiratory motion. As the adaptation is real-time, the beam-on time for a motion-corrected treatment does not take additional time compared to a non-motion-corrected treatment. This would mean faster motion corrected treatment delivery compared to gated treatment delivery.

References

Important Safety Information:

Most side effects of radiotherapy, including radiotherapy delivered with Accuray systems, are mild and temporary, often involving fatigue, nausea, and skin irritation. Side effects can be severe, however, leading to pain, alterations in normal body functions (for example, urinary or salivary function), deterioration of quality of life, permanent injury, and even death. Side effects can occur during or shortly after radiation treatment or in the months and years following radiation. The nature and severity of side effects depend on many factors, including the size and location of the treated tumor, the treatment technique (for example, the radiation dose), and the patient’s general medical condition, to name a few. For more details about the side effects of your radiation therapy, and to see if treatment with an Accuray product is right for you, ask your doctor.

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