

Use of Electromagnetic Technology for Four-Dimensional Radiotherapy Localisation and Realtime Tumour Tracking

a report by

James M Balter¹, J Nelson Wright², Edward Vertatschitsch², Lisa Levine², Lynn Purdy², Patrick Kupelian³, Twyla Willoughby³, Mack Roach⁴, Jean Pouliot⁴, Howard Sandler¹ and Dale Litzenberg¹

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Conformal Radiotherapy and Target Motion

The past decade has seen a quiet revolution in the technology and procedures underlying radiotherapy. Improvements in imaging technology have combined with both three-dimensional conformal radiotherapy (3-D CRT) and intensity-modulated radiation therapy (IMRT) techniques to permit very precise planning and delivery of treatment. Such precision has permitted a number of treatment paradigms to flourish. The incidence of radiation-induced complications from treatment has been reduced, leading to the practice of increasing radiation doses in some tumour sites with potential improvements in tumour control, and in other sites to reduced morbidity from radiotherapy. A growing area of interest, spurred in part by this revolution in precision, involves the delivery of large doses of radiation in a few sessions to certain types of tumours. Such hypofractionation has been tested for intracranial applications as well as accelerated partial breast irradiation and in thoracic and intrahepatic tumours. Concomitant with an increase in precision of treatment delivery, very high precision positioning of the patient for treatment is required to maintain potential improvements. The process of radiotherapy treatment requires that a patient be posed and positioned in a reproducible way multiple times over a period ranging from weeks to months. Such accuracy is difficult to achieve. The pursuit of rapid, reliable positioning methods has thus been a major factor driving technological innovation in radiotherapy in recent years.

Positioning Accuracy

The problem of positioning accuracy can be broken down into two major elements – immobilisation and localisation. Immobilisation can be considered the process of constraining patient and target motion while treatment is delivered. Localisation describes the processes that ensure the tumour position at treatment matches that intended at the time the treatment was initially planned. A plethora of technology has emerged to aid immobilisation and localisation. A slowly evolving methodology of

radiograph-based localisation has recently given way to an explosion of new in-room imaging technology (computed tomography (CT), ultrasound, video). These evolving methodologies improve the ability to visualise the location of soft tissue structures in the body. Their limitation, however, is that they require time to acquire and process the significant volume of information needed to image, analyse and act in order to improve target position. Some target sites are not completely amenable to the long-term (10- to 30-minute) immobilisation that would permit in-room imaging to work effectively. Physiological motions exist on timeframes of seconds (breathing) to minutes (e.g. prostate movement) that would cause the relative position of tumours to deviate from where they were estimated to be on pre-treatment imaging models. Furthermore, such motions generally involve shape and position changes of adjacent organs and tissues, leading to complex deformations of the patient in the region to be treated. Accurately targeting a tumour in the presence of such changes requires use of advanced alignment technology that is not yet mature.

Fiducial-based Target Localisation with X-ray Images

An alternative method of targeting has arisen in parallel with improved imaging. Implanted fiducial markers can identify the target position using 2-D X-ray images. Typically, such markers have been made of metal of sufficient density as to be visualised on megavoltage radiographs. With recent improvements due to the availability of kilovoltage X-ray imaging in treatment rooms, such markers can be visualised fluoroscopically, providing tumour-based positioning and position monitoring during treatment. The cost of such procedures is a significant investment in imaging equipment, as well as potentially high radiation doses to the skin from extended fluoroscopic procedures.

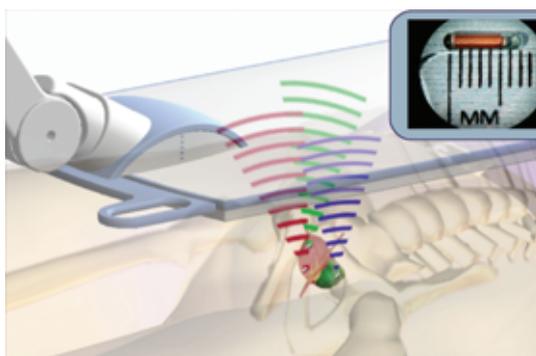
Fiducial-based Target Localisation and Tracking with AC Electromagnetics

An investigational system is under development that provides the temporal resolution of implanted fiducials without the related complexity and risks of

1. The University of Michigan
2. Calypso Medical Technologies
3. MD Anderson Cancer Center Orlando
4. The University of California

James M Balter is an Associate Professor in the Radiation Oncology Department of the University of Michigan. He has spent the past 15 years studying methods to efficiently implement precision radiotherapy, and supporting clinical trials to maximise the advantage of precision in radiation dose escalation and morbidity reduction. He has published over 40 manuscripts and 10 book chapters on topics of image alignment, patient positioning strategies and characterisation of internal organ movement.

Figure 1: Rendering of the Calypso® 4D Localization System and implantable Beacon® transponder



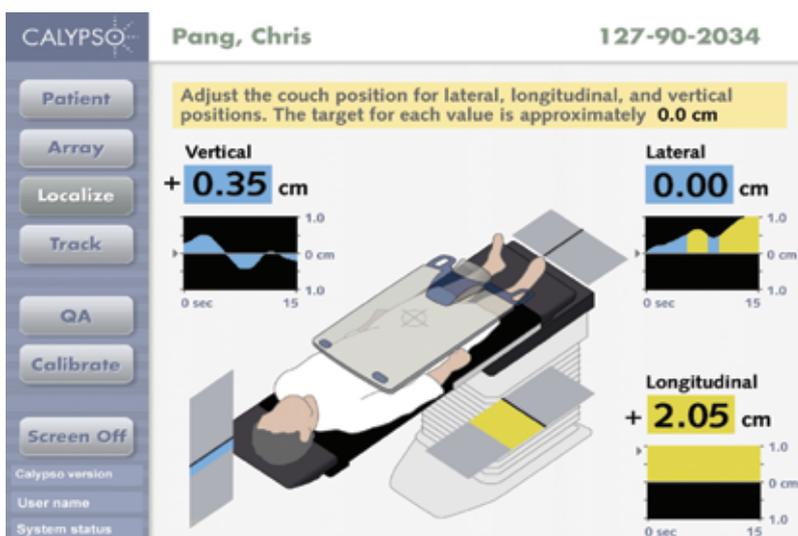
Three Beacon transponders are implanted in the prostate. The array induces the transponder, which returns a resonant signal. Each transponder responds at a unique frequency. The inset is a picture of a transponder.

Figure 2: A Patient Being Positioned Using the Calypso System



The array is in place over the patient.

Figure 3: Current Interface for Patient Positioning



X-ray-based targeting approaches. This system uses AC electromagnetic fields to precisely and accurately locate tumours and track implanted transponders in

realtime. This technology has been developed for body-wide application, with the first clinical study focused on realtime prostate radiation therapy localisation and tracking.

The markers are passive and require no external leads, thus making them suitable for permanent implantation. They have been successfully implanted under internal review board-approved protocols at three hospitals – MD Anderson Cancer Center Orlando, The University of Michigan Hospital and The University of California, San Francisco. Implantation for prostate localisation is performed transrectally under ultrasound guidance. Typically, three transponders are implanted at the base and left and right mid-gland regions.

Transponder locations are related to the tumour (target) position during the treatment planning process. A dosimetrist identifies the treatment isocentre, and determines the relative positions of the transponders relative to isocentre for input into the localisation and tracking system.

When treatment starts, the system can be used to rapidly localise the patient through an objective interface, providing guidance in registering the tumour target efficiently and accurately in realtime to machine isocentre. Transponder positions are determined using an array that hovers over the patient on an articulated arm. The array location is tied to the treatment coordinates via infrared cameras mounted to the ceiling of the treatment room. The system is designed to stay in place during treatment, being sufficiently thin that megavoltage treatment beams can pass through with minimal attenuation or scatter effects. *Figure 1* shows a rendering of the principle of operation. The inset shows a transponder. *Figure 2* shows a patient being positioned using this system during a review board-approved protocol for system evaluation.

The accuracy of this system for localisation and tracking has been tested extensively under benchtop conditions.¹ For the typical range of positions (+/-8cm from the centre in the plane of the array and up to 27cm away), sub-millimeter accuracy is maintained. Further measurements, inside a treatment room with a linear accelerator in operation, demonstrate that this accuracy is maintained during machine motion and irradiation.

Realtime Target Tracking

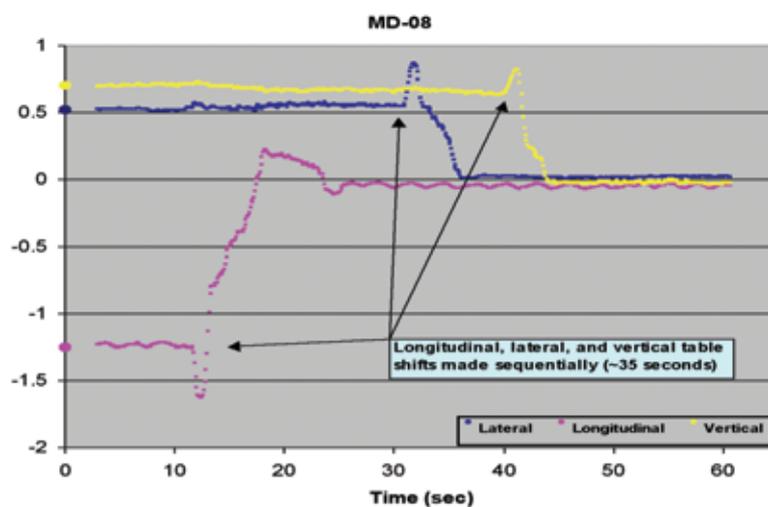
Realtime data on target location, motion, translation and rotation are collected and stored in the system's data base. Transponder coordinates are read out at a rate of 10Hz. At this speed, a realtime interface can be

1. Balter J M, Wright J N, Newell L J, Friemel B, Dimmer S, Cheng Y, Wong J, Vertatschitsch E, Mate T P, "Accuracy of a wireless localization system for radiotherapy", *Int. J. Radiat. Oncol. Biol. Phys.* (2005);61 (3): pp. 933–937.

used for interactive feedback of patient position. Figure 3 shows the current interface for positioning. Rapid feedback provides for fast positioning, even for an initial user. Figure 4 shows the positioning process for a patient performed by a technologist using the interface for the first time. The patient's position is adjusted interactively based on feedback from the interface, first about the longitudinal, then the lateral and finally vertical axes. It can be seen that positioning about all axes is complete within 50 seconds of placing the array over the patient (35 seconds after starting to adjust position) – a time significantly faster than that possible with other image-guided localisation procedures.

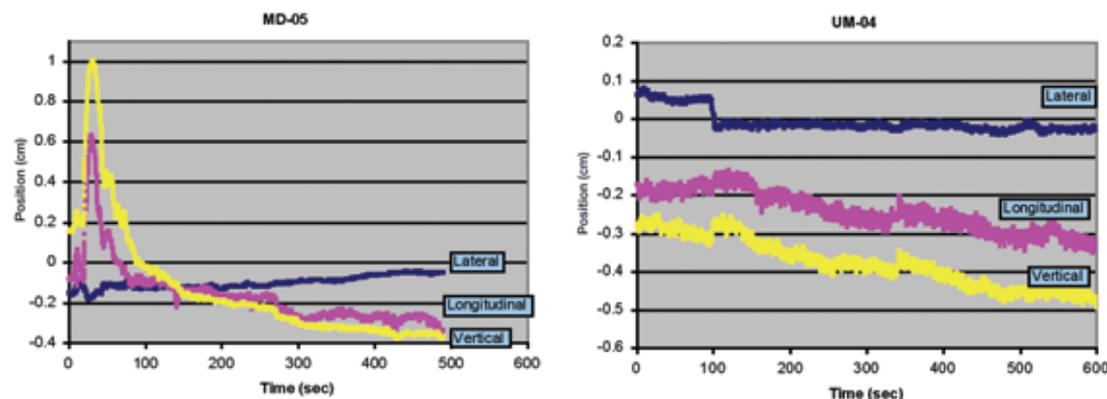
Intra-treatment monitoring of prostate position also becomes feasible with this technology. The short-term time trend in prostate movement is poorly understood to date. Methods to improve knowledge of prostate movement during treatment delivery and to manage this motion to maintain treatment accuracy are

Figure 4: Traces of the Distance of the Average Coordinate of Implanted Beacons Relative to Isocentre about the Three Major Axes During the Initial Positioning Process



The longitudinal position is adjusted first, followed by lateral and vertical position adjustments.

Figure 5a and 5b: Ten-minute Observations of the Position of the Centre Location (average coordinate) of Three Implanted Beacon Transponders in the Prostate Using the Calypso System



essential to a complete programme of precision radiotherapy. Initial results of sample monitoring of prostate position using this system (under review board-approved protocols) show surprising drifts in position over times matching delivery of a single fraction of radiotherapy and occasional large movements. Figure 5 shows an example time trace from a 10-minute observation of prostate position. Both slow drifts as well as large-scale transient movements of greater than 8mm have been observed in patients from these protocols. Future use of target motion data may include simple interlocks to prevent accidental irradiation of excess rectal wall when the prostate is transiently out of position, as well as analysis of target motion to create patient-specific predictive algorithms to determine target margins as input to the treatment planning process.

It is further expected that the realtime 4-D target tracking could signal when a significant long-term geometric change has occurred (deformation, bias in position relative to external landmarks). Once the

target geometry is analysed the appropriate plan adaptation may be employed. Examples of adaptations may include changing immobilisation and modifying treatment plan parameters (beam arrangement, margins).

Summary

The initial investigational studies clearly indicate the value of rapid feedback for initial positioning as well as realtime intrafraction treatment monitoring. The value of electromagnetic localisation to aid in these procedures is established, and it is expected that this technology will play a critical role in the expanding arena of high-dose, high-precision adaptive radiotherapy. As this technology establishes itself in prostate applications, the potential of electromagnetic localisation and tracking will be explored in other body sites, such as the lungs, where significant uncertainty currently exists due to breathing-induced motion of the tumour and surrounding radiosensitive normal tissues. ■