Dose and Position Quality Assurance Using the RADPOS System for 4D Radiotherapy with CyberKnife

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Abstract— **The CyberKnife system consists of a compact LINAC mounted on a mobile robotic arm and the Synchrony Respiratory Motion Tracking System. This complex radiotherapy system needs independent performance verification to assure safe treatments. In this work, we use the RADPOS 4D dosimetry system to verify CyberKnife's motion tracking and delivered dose. RADPOS motion measurements are compared with internal metal fiducial and external LED marker log files. Dose measurements are compared with film and treatment planning system (TPS) calculations. RADPOS and EBT3 Gaf-Chromic films were calibrated in Solid Water (5 cm depth, 80 cm source-detector distance, 60 mm cone, Exradin ion chamber, Fluke electrometer). A CT-based treatment plan was created for a Solid Water breast phantom containing fiducials and RADPOS. Dose calculations were performed using Multi-Plan TPS, Monte Carlo (MC) and ray tracing (RT) algorithms. Before treatment, film was inserted inside the breast phantom adjacent to RADPOS. The breast phantom and LED markers were positioned on the chest platform of a Quasar Motion Phantom. Position logging began for RADPOS and Synchrony, Quasar motion started, and irradiation commenced. A coordinate alignment algorithm was implemented, allowing position tracking modalities to be compared in a common coordinate system. The average standard deviation of the differences between LED and RADPOS position measurements was 0.33, 0.39, and 0.56 mm along the left/right, superior/inferior, and anterior/posterior directions, respectively. Dose percent difference values during static phantom irradiations were 0.3% (RADPOS/RT), 1.3% (RADPOS/MC), 0.5% (Film/RT), 1.5% (Film/MC), and -0.2% (RADPOS/Film), while values during dynamic phantom irradiations were 2.0% (RADPOS/RT), 2.9% (RADPOS/MC), -1.0% (Film/RT), 0.0% (Film/MC), and 3.0% (RADPOS/Film). Average gamma results were greater than 96% for MC and RT dose calculation algorithms, and for dynamic and static treatments. Our work demonstrates that RADPOS is a useful tool for independent QA of CyberKnife treatments with Synchrony respiratory compensation.**

Keywords— **CyberKnife, RADPOS, Dosimetry, Film, QA.**

I. Introduction

Radiotherapy treatment becomes more difficult in cases where patient motion, such as breathing, causes movement of the treatment target or organs-at-risk. Several methods to deal with this problem are currently in use, such as increasing the treatment margins, implementing breath-hold techniques or other active breathing control approaches, and real-time tumor motion tracking[1], such as the motion compensation used by the CyberKnife system. This last solution has motivated this research and is the focus of this report.

The Accuray CyberKnife Robotic Radiosurgery System consists of a 6 MV compact linear accelerator mounted on a robotic arm, which gives it up to six degrees-of-freedom of motion. It is able to deliver small, high-intensity x-ray radiotherapy beams from many different non-coplanar directions to the tumor, resulting in highly conformal dose distributions. In addition, the CyberKnife system implements tumor tracking through the use of internally implanted metal fiducials and motion tracking through the use of external LED optical markers.

The CyberKnife system adjusts the direction of the beams during treatment (i.e. while beam is on) to correct for tumor motion due to breathing. The Synchrony Respiratory Motion Tracking System employs external optical LED markers and the imaging of internally implanted fiducials to build a predictive correlation model, which dynamically corrects beam delivery based on a patient's breathing pattern. Throughout a treatment, the model is continuously updated with the latest tracking data, correcting for drifts in the patient breathing pattern and tumor position. With such a complex delivery system, there is a need for thorough quality assurance which can look at different components of this system independently.

This can potentially be accomplished with the use of RADPOS. RADPOS is a 4D dosimetry system consisting of a microMOSFET dosimeter combined with an electromagnetic positioning sensor. RADPOS has the ability to perform real-time dose and position measurements simultaneously[2], making it an excellent candidate for acting as an independent QA tool for the Cyberknife Synchrony tracking algorithm.

The RADPOS system is composed of the MOSFET reader, which is responsible for dose measurements, and the transmitter, pre-amplifier and 3D-guidance-tracker, which are responsible for position measurements. The RADPOS

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dosimeter probe acts as the point of measurement. The position sensor and microMOSFET are separated by 8 mm in order to limit radiation attenuation and disturbance of the particle fluence near the dosimeter.

In order to perform dose measurements, RADPOS' microMOSFET dosimeter measures a threshold voltage difference which is induced when the MOSFET is irradiated. It is this threshold voltage difference which is proportional to the absorbed dose. In terms of position measurements, the DC magnetic field transmitter emits a pulsed 3D magnetic field which is detected and used by RADPOS' electromagnetic positioning sensor in order to determine its position coordinates.

The goal of this work is to quantitatively demonstrate RADPOS' effectiveness as a dose and position quality assurance tool for radiotherapy with CyberKnife. This is done by comparing RADPOS and GafChromic film dose measurements to one another as well as to CyberKnife TPS calculations, and also using RADPOS to verify internal fiducial and external LED position measurements.

II. Methods

RADPOS and GafChromic films were calibrated in Solid Water (5 cm depth, 80 cm source-detector distance, 60 mm cone) using an Exradin A1SL ion chamber and Fluke Model 35040 electrometer. A CT based treatment plan was created for a Solid Water breast phantom containing metal fiducials and the RADPOS probe. Dose calculations were performed using the MultiPlan treatment planning system with ray tracing and Monte Carlo-based algorithms.

The semi-spherical solid water breast phantom has a few components positioned inside of it. The RADPOS detector probe fits into a custom grove within the inner surface of the phantom. Also, four metal fiducial markers were fixed within small groves on the inner phantom surface. Then, a piece of EBT3 GafChromic film was inserted adjacent to the RADPOS probe and the phantom was closed.

A Quasar Respiratory Motion Phantom provided motion for the breast phantom. Having the breast phantom on the chest platform of the moving Quasar represents the motion of a breast during the respiratory cycle, which predominantly takes place in the anterior/posterior direction. Synchrony LED optical markers were also positioned on the Quasar chest platform next to the breast phantom. Once everything was setup, position logging began for RADPOS (10 Hz) and the Synchrony tracking system (25 Hz). Next, the sinusoidal Quasar motion was initiated, and the treatment was delivered (see Figure 1).

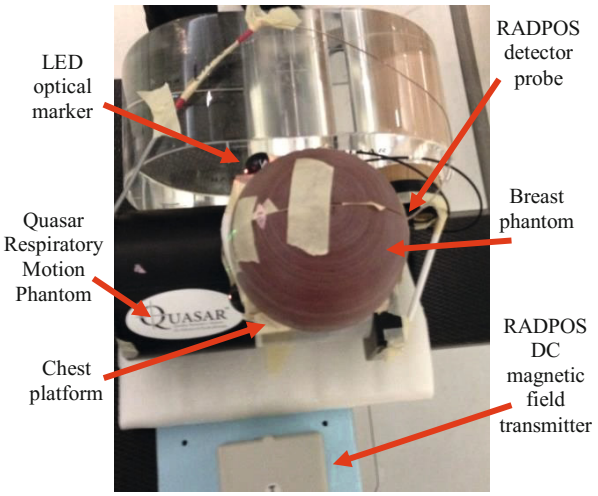

Fig. 1 Apparatus and setup for experimental CyberKnife treatment

During an experiment, three position measurement datasets are generated: fiducial log files for fiducial position measurements, Synchrony log files for LED position measurements, and RADPOS output files for RADPOS position measurements. In order to consistently compare RADPOS position measurements to those of the fiducials and LEDs, the three position tracking modalities had to be analyzed within a common coordinate system. The stereoscopic camera is able to be moved around in the room freely, changing the origin and orientation of the axes of the LED coordinate system.

An algorithm put forth by Arun et al.[3] and later modified by Umeyama[4] offers a good solution to this problem. It is shown that the condition in Equation 1 can be fulfilled:

$$p' = Rp + T \tag{1}$$

where p and p' are initial and final 3D point sets, respectively, R is a rotation matrix, and T is a translation matrix. This algorithm finds R and T in order to compute the least-squares solution to Equation 2:

$$\Sigma^2 = \Sigma^N_{i=1} \| p_i' - (Rp_i + T_i) \|^2 \tag{2}$$

where Σ^2 is the parameter to be minimized and N is the number of data points. In other words, the algorithm transforms p to p' via unique rotation and translation matrices.

Implementation of this algorithm transformed the LED and RADPOS position measurements into the coordinate system of the fiducials, which is considered to be the absolute coordinate system of the room. The three position tracking modalities can then be compared consistently within a common coordinate system.

There are a few details about the experiment itself that are important to note. Four different irradiations were delivered over the course of the experiment. Irradiation 1 in-

volved irradiating films 1 and 2 at the same time. For this irradiation, the Quasar was off and the breast phantom was stationary. Irradiations 2, 3 and 4 had one film irradiated at a time, and involved films 3, 4 and 5. For these irradiations, the Quasar was operational and the breast phantom was mobile. The RADPOS probe was present within the breast phantom for all irradiations.

III. Results

A. Position

Once the LED and RADPOS position data were aligned to the fiducial coordinate system, the average difference between fiducial and LED position measurements or fiducial and RADPOS position measurements was less than 0.01 mm in any direction. For this reason, the focus is on comparing RADPOS and LED position measurements within the fiducial frame of reference. To do this, the standard deviation of the differences was selected as the comparative metric to give a reliable measure of how different the motion signal distributions were.

Overall, the LED and RADPOS position measurements are in good agreement to the sub-millimeter level (see Figure 2).

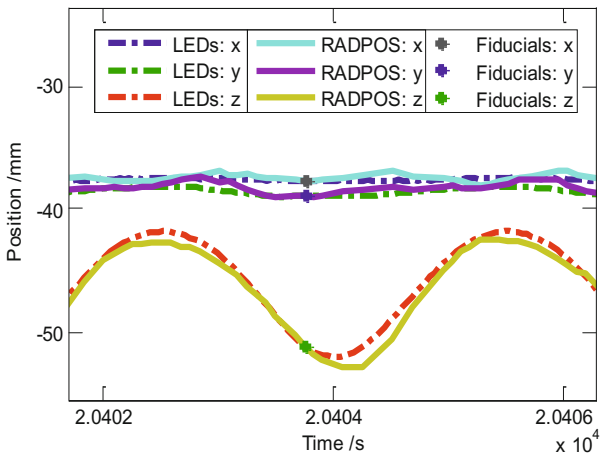

Fig. 2 All the components of the three position tracking modalities after implementation of the alignment algorithm. The RADPOS and LED signals, represented by the solid and dashed curves, respectively, are fixated around the fiducial points, represented by the dots

The standard deviation of their difference in the x, or left-right direction, is 0.33 mm when averaged over the three dynamic irradiations. Along the y, or superior-inferior direction, it is 0.39 mm on average, and along the z, or anterior-posterior direction, it is 0.56 mm on average. More information can be found in Table 1.

Table 1 Standard deviation of the difference between LED and RADPOS position measurements

Standard Deviation: LEDs – RADPOS (mm)				
Direction	Irradiation			
	2	3	4	Average
X (Left/Right)	0.30	0.39	0.31	0.33
Y (Superior/Inferior)	0.30	0.48	0.39	0.39
Z (Anterior/Posterior)	0.53	0.63	0.53	0.56

B. Dose

The TPS calculated dose values are 146.7 cGy for ray tracing and 145.3±1.0% for Monte Carlo, with an additional dosimetric uncertainty of 0.5% for both resulting from TPS beam data. RADPOS dose readings made during the dynamic irradiations are a few percent higher than all of the other experimental dose values. The gamma results for 3%/1 mm all have greater than 96% agreement on average and remain consistent between the treatment planning algorithms, as well as between dynamic and static treatments. More details can be found in Table 2.

IV. Discussion

A. Position

During the experiment, the breast phantom was set to move in the anterior-posterior direction on the Quasar, and so the majority of the recorded motion was in the z direction. Much of the measured x and y motion is from residual movement from the z direction, as well as noise.

There are a couple of important position measurement uncertainties to recognize. First, the optical marker sampling rate was fixed by the Synchrony system, while the RAPDOS sampling rate was set to be as frequent as possible. The optical marker positions were sampled approximately 2.5 times as frequently as the RADPOS positions. The relatively low RADPOS position sampling frequency introduced an uncertainty with respect to time when compared to the LED marker signal. Second, in order to effectively implement the coordinate alignment algorithm, the algorithm has the user manually select a common point on two motion signals which is then used to automatically synchronize the signals in time.

To account for these two temporal uncertainties, the time uncertainties of the LED and RADPOS measurements were summed in quadrature. In both cases, these uncertainties were taken as half of the sampling rate for LEDs (38.5 ms)

Table 2 Average measured dose values for the film and RADPOS, along with 3%/1 mm gamma values

Phantom	RADPOS Dose (cGy)	% diff (RADPOS/RT)	% diff (RADPOS/MC)	Film Dose (cGy)	% diff (Film/RT)	% diff (Film/MC)	% diff (RADPOS/Film)	γ-index, 3%/1 mm (RT)	γ-index, 3%/1 mm (MC)
Static	147.2±1.3%	0.3%	1.3%	147.5±1.9%	0.5%	1.5%	-0.2%	97.2	96.7
Dynamic	149.6±1.2%	2.0%	2.9%	145.3±1.8%	-1.0%	0.0%	3.0%	97.3	97.0

and RADPOS (100 ms). This resulted in an overall uncertainty in time (σ_t) of approximately 53.6 ms. In order to obtain the uncertainty in position, σ_t was added and subtracted from the point of signal alignment. This yielded an upper and lower bound on the standard deviation of the difference values, and led to position uncertainties of ±0.02, ±0.04, and ±0.19 mm along the left/right, superior/inferior, and anterior/posterior directions, respectively.

Also, the position measurements performed by RADPOS were limited to a 0.1 mm resolution. As a result, an additional uncertainty of 0.05 mm must be included for all directions.

B. Dose

The percent comparisons between RADPOS, film, and TPS dose values are in good agreement, all being within 2σ of experimental uncertainty. More information can be found in Table 3.

Table 3 Main sources of experimental dosimetric uncertainty

Beam Delivery	Single Beam	Radial error = 0.21±0.24 mm	0.5%
		MU chamber stability	0.25%
	Whole Plan (20 beams)	Radial error	0.1%
		MU chamber	0.06%
Beam Dosimetry	Calibration	User dependent	0.3%
		Calibration data	0.85%
		k_q approximation	0.3%
Detector Measurement	Film	Beam delivery	0.1%
		Beam dosimetry	0.95%
		Phantom material	0.7%
		Detector variability[5]	
		2 films	1.44%
		3 films	1.39%
		Film total	
		2 films	1.9%
		3 films	1.8%
	RADPOS	Beam delivery	0.1%
		Beam dosimetry	0.95%
		Phantom material	0.7%
		Detector variability	0.5%
		RADPOS total	
		1 measurement	1.3%
		2 measurements	1.2%

The dose values calculated by the ray tracing and Monte Carlo algorithms of the treatment planning system have negligible difference and are within 1%, which is within the overall uncertainty of Monte Carlo calculations. This is because both calculations were done for primarily homogeneous, unit-density material.

V. Conclusions

It has been demonstrated that RADPOS can be used to independently verify positioning information for each component of the Synchrony tracking method as well as provide dosimetric verification in a phantom. RADPOS position measurements closely matched LED marker positions with a (0.43±0.13) mm standard deviation between them, averaged over the x, y, and z directions. In addition, percent comparisons between RADPOS, film, and TPS dose values are in good agreement, all being within 2σ of experimental uncertainty. In conclusion, this study demonstrates that the RADPOS system is a useful tool for the independent quality assurance of CyberKnife treatments.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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