Investigations of interference between electromagnetic transponders and wireless MOSFET dosimeters: A phantom study

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Purpose: To evaluate both the Calypso Systems' (Calypso Medical Technologies, Inc., Seattle, WA) localization accuracy in the presence of wireless metal–oxide–semiconductor field-effect transistor (MOSFET) dosimeters of dose verification system (DVS, Sixel Technologies, Inc., Morrisville, NC) and the dosimeters' reading accuracy in the presence of wireless electromagnetic transponders inside a phantom.

Methods: A custom-made, solid-water phantom was fabricated with space for transponders and dosimeters. Two inserts were machined with positioning grooves precisely matching the dimensions of the transponders and dosimeters and were arranged in orthogonal and parallel orientations, respectively. To test the transponder localization accuracy with/without presence of dosimeters (hypothesis 1), multivariate analyses were performed on transponder-derived localization data with and without dosimeters at each preset distance to detect statistically significant localization differences between the control and test sets. To test dosimeter dose-reading accuracy with/without presence of transponders (hypothesis 2), an approach of alternating the transponder presence in seven identical fraction dose (100 cGy) deliveries and measurements was implemented. Two-way analysis of variance was performed to examine statistically significant dose-reading differences between the two groups and the different fractions. A relative-dose analysis method was also used to evaluate transponder impact on dose-reading accuracy after dose-fading effect was removed by a second-order polynomial fit.

Results: Multivariate analysis indicated that hypothesis 1 was false; there was a statistically significant difference between the localization data from the control and test sets. However, the upper and lower bounds of the 95% confidence intervals of the localized positional differences between the control and test sets were less than 0.1 mm, which was significantly smaller than the minimum clinical localization resolution of 0.5 mm. For hypothesis 2, analysis of variance indicated that there was no statistically significant difference between the dosimeter readings with and without the presence of transponders. Both orthogonal and parallel configurations had difference of polynomial-fit dose to measured dose values within 1.75%.

Conclusions: The phantom study indicated that the Calypso System's localization accuracy was not affected clinically due to the presence of DVS wireless MOSFET dosimeters and the dosimeter-measured doses were not affected by the presence of transponders. Thus, the same patients could be implanted with both transponders and dosimeters to benefit from improved accuracy of radiotherapy treatments offered by conjunctive use of the two systems. © 2011 American Association of Physicists in Medicine. [DOI: 10.1118/1.3578602]

Key words: electromagnetic transponder, wireless MOSFET dosimeter, interference, target motion, *in vivo* dosimetry, localization accuracy, adaptive radiotherapy

I. INTRODUCTION

In radiotherapy, delivering the prescribed dose accurately to a target is the key to maximizing tumor eradication and normal tissue conservation. If target organ motion (e.g., prostate movement)^{1,2} is not taken into account in treatment simula-

tion, planning, and delivery, it can potentially reduce the efficacy of radiation therapy. The Calypso System (Calypso Medical Technologies, Inc., Seattle, WA) tracks targets with implanted electromagnetic transponders in real time without ionizing radiation.³ It provides an efficient tool to manage both interfractional and intrafractional tumor motion.⁴

Besides the target motion monitoring, it is also desirable to know the amount of dose delivered to the target in each fraction using *in vivo* dosimetry. Traditional *in vivo* dosimetry measures entrance or exit dose to ensure that the proper amount of radiation is delivered; however, the dosage the target receives is uncertain, especially for a target with intra-fractional organ motion. Sichel's dose verification system (DVS, Sichel Technologies, Inc., Morrisville, NC) wireless metal-oxide-semiconductor field-effect transistor (MOSFET) dosimeters are implanted into a tumor to directly measure dose to the target.⁵⁻⁸ Using *in vivo* dosimeter, dosimetric impact due to target and surrounding organs intrafraction motion/deformation is recorded. Compared to dose reconstruction from sampled target positions, the *in vivo* approach is straight forward and accumulating dose in real time. Using implanted transponders and dosimeters during the same treatment course could be beneficial for radiotherapy patients with mobile and/or easily deformed target (e.g., prostate and breast).^{9,10} To our knowledge, this is the first study that investigates the potential interference between the transponders and dosimeters when they are placed in the same target volume. The results of this study have significant clinical implications, i.e., a true dose guided adaptive radiotherapy.¹¹

II. MATERIALS AND METHODS

II.A. Calypso system and Sichel dose verification system

The Calypso system is an implantable, electromagnetic, transponder-based, target-localization and monitoring system. The source/receiver array uses electromagnetic pulses to excite the implanted transponders and detect their relaxation signals and determine their locations. Before treatment, the locations of the implanted transponders are identified on a patient computed tomography (CT) data set and imported into the Calypso tracking computer. During treatment, the system detects the real time location of these transponders and records their various locations in 10 Hz.

The Sichel DVS is an implantable MOSFET dosimeter-based system designed for *in vivo* dose verification. The dosimeter has two MOSFETs, corresponding electronics assembly, and a miniature antenna enclosed in a glass capsule.⁷ Radiation changes the threshold voltage of the MOSFET. A manufacturer calibration can convert this voltage change into delivered radiation dose. After patient CT simulation, the MOSFET end of the dosimeter is identified in the CT data set and its point dose computed by treatment planning system (TPS) is exported to the DVS database computer. Before and after each irradiation, the dosimeter is read by an in-room base station through magnetic-field modulation. The corresponding radiation dose is recorded in the DVS database computer.

II.B. Phantom design and experiment preparation

For this study, we obtained a set of three Calypso transponders (left base, right base, and apex) from Calypso

FIG. 1. Inserts of (a) parallel configuration, (b) orthogonal configuration, and (c) their placement inside custom-made solid-water phantom. Note, objects a, b and c are electromagnetic transponders and objects d, e and f are MOSFET dosimeters.

Medical Technologies, Inc., and six wireless MOSFET dosimeters from Sichel Technologies, Inc. A solid-water phantom base ($30 \times 30 \times 5$ cm³ block machined with an 8-cm diameter hole at the center) and a set of five circular inserts (8-cm diameter) were custom-made for this study. Two of the inserts were designed with grooves to accommodate both transponders and dosimeters. The grooves were oriented so that the dosimeter was parallel with and orthogonal to the transponders in the two inserts (Fig. 1). The distances between the transponders' and dosimeters' centroids were designed to be 0, 1, and 2 cm for left-base, right-base, and apex positions (comparable to clinical implants inside of a prostate), respectively.

This solid-water phantom with the inserts of transponders and dosimeters in parallel and orthogonal configurations was CT scanned, respectively, with 1-mm-slice thickness and imported into the Pinnacle³ TPS (Philips, Andover, MA). In the Pinnacle³, each transponder was contoured separately and a corresponding point was placed at its centroid. A treatment isocenter was set at the centroid of three transponders. The coordinates of the three transponder points and the isocenter point were manually imported into the Calypso system. A treatment plan was generated using one anterior-posterior (AP) beam and one posterior-anterior (PA) beam of 6 MV photon with a 16×16 cm² field size. The active part of each MOSFET dosimeter was also marked as a point in the treatment plan and the corresponding point dose was recorded as planned dose. The treatment plan was then exported to the record-and-verify system and was delivered by a linear accelerator.

TABLE I. Wilk's lambda tests comparing the means of X , Y , and Z simultaneously for control (no dosimeter) and for dosimeter at d, e, and f positions.

Configuration	Transponder position	Lambda	F value	D. F.	Den. D.F.	$P > F$
Orthogonal	a	0.53	8.99	9	275.16	<0.0001
Orthogonal	b	0.35	16.34	9	275.16	<0.0001
Orthogonal	c	0.58	7.73	9	275.16	<0.0001
Parallel	a	0.35	16.01	9	262.99	<0.0001
Parallel	b	0.28	20.10	9	262.99	<0.0001
Parallel	c	0.27	20.82	9	262.99	<0.0001

II.C. Transponder localization tests

To test dosimeter interference to transponder localization accuracy, repeated Calypso target-localization measurements were performed using both the phantom with no dosimeter present and with a dosimeter placed at positions d, e, and f, one at a time, for both parallel and orthogonal configurations. The Calypso array was set approximately 15 cm above the transponder plane inside the phantom. The data acquired with transponders only (with no dosimeter) were the control data set. These measurements were repeated 30 times. Similarly, three test data sets were obtained by repeating measurements with a single dosimeter placed in slots d, e, and f. Localization measurement data were exported from the Calypso system and converted to a readable format for data analysis. Three dimensional coordinates of each transponder were obtained for each measurement.

To test the null hypothesis: the mean localized coordinates of each transponder are the same between the control data set and the test data sets, we performed the Wilk's lambda test, a one-way multivariate analysis of variance (MANOVA). In this test, the independent variable was the testing group and the dependent variables were the coordinates of the localized transponders. The Wilk's lambda test simultaneously compared the mean values of X , Y , and Z coordinates for each transponder position between the control and test data sets. The statistical bound (i.e., 95% confidence interval of the transponder coordinate differences between the test and control data sets) was also evaluated. The upper and lower bounds of this confidence interval were

compared to the positioning resolution of Calypso system used in clinics.

II.D. Dosimeter reading constancy tests

Besides evaluating transponder localization accuracy, the other goal of this study was to identify if there were any significant statistical differences between dose-response measurements with and without a transponder present inside the phantom; therefore, it was not our intention to compare the measured fraction dose to the planned dose in this study. The dosimeter's accuracy was studied by several other investigators using phantoms with or without temperature control.⁵⁻⁷

Other factors (i.e., phantom daily setup and linear-accelerator output variations), besides the dosimeter's intrinsic dose-response variation, contribute to the total dose uncertainty. To minimize these uncertainties in the study, an approach of alternating the transponder presence in a series of identical fraction dose deliveries and measurements was implemented. In this approach, for each transponder and dosimeter configuration, the phantom was first set up by the Calypso system; thereafter, seven fractions of the AP/PA treatment plan with 100 cGy per fraction were sequentially delivered to the three dosimeters in the phantom without transponders (fractions 1, 3, 5, and 7) and with transponders (fractions 2, 4, and 6). The measurements were performed in one day with fixed time gap between consecutive fractions and strictly followed the dose-reading protocol recommended by Sicel. The DVS recorded fractional doses were exported after delivery of all seven fractions for the configuration. Both the parallel configuration (three dosimeters) and orthogonal configuration (three other dosimeters) were studied using this approach to test the null hypothesis: there is no statistically significant mean-dose difference between data sets with and without the presence of transponders.

This experimental approach has the advantages of minimizing uncertainties from daily setup and linear-accelerator output variation. However, its radiation delivery pattern may introduce different dosimeter dose-fading characteristics than the one fraction per day pattern. To analyze the effects of presence of transponders and fraction-delivering time, a two-way analysis of variance (ANOVA) test was performed

TABLE II. 95% confidence intervals of transponder coordinates difference between control and test data sets with dosimeter located at d, e, and f position, respectively.

Position	Orthogonal			Parallel		
	$\Delta(\text{ctrl-d}) (\mu\text{m})$	$\Delta(\text{ctrl-e}) (\mu\text{m})$	$\Delta(\text{ctrl-f}) (\mu\text{m})$	$\Delta(\text{ctrl-d}) (\mu\text{m})$	$\Delta(\text{ctrl-e}) (\mu\text{m})$	$\Delta(\text{ctrl-f}) (\mu\text{m})$
a(x)	(-19, 3)	(1, 23)	(-3, 19)	(-67, -30)	(-76, -39)	(-23, 14)
a(y)	(34, 57)	(17, 41)	(23, 47)	(-64, -11)	(-15, 38)	(35, 88)
a(z)	(-17, 13)	(-8, 22)	(1, 31)	(-30, 12)	(17, 59)	(0, 43)
b(x)	(-7, 19)	(37, 63)	(-7, 19)	(-102, -61)	(-101, -60)	(-23, 18)
b(y)	(8, 32)	(-21, 3)	(25, 49)	(38, 88)	(-29, 22)	(12, 63)
b(z)	(-19, 14)	(-9, 24)	(8, 41)	(-30, 5)	(15, 49)	(10, 44)
c(x)	(1, 22)	(2, 23)	(3, 23)	(-94, -58)	(-76, -41)	(-29, 7)
c(y)	(8, 33)	(19, 44)	(21, 46)	(37, 90)	(-25, 27)	(26, 79)
c(z)	(-4, 23)	(4, 31)	(6, 33)	(-38, 1)	(13, 51)	(22, 60)

TABLE III. Two way analysis of variance for transponder effect, fraction time effect, and their interactions for both orthogonal and parallel configurations.

Fraction		Orthogonal			Parallel		
		Transponder presence	Fraction time	Interaction	Transponder presence	Fraction time	Interaction
(1, 3, 5) to (2, 4, 6)	<i>F</i> value	1.580	8.170	9.790	0.100	1.260	0.680
	<i>P</i> value	0.232	0.006	0.003	0.761	0.318	0.524
(3, 5, 7) to (2, 4, 6)	<i>F</i> value	1.980	2.210	0.720	0.030	0.860	0.790
	<i>P</i> value	0.184	0.152	0.507	0.862	0.449	0.474

for the measured doses; thus, there were three null hypotheses: (1) H0A: There is no mean-dose difference between groups with and without transponder presence; (2) H0B: There is no mean-dose difference between groups delivered in different fraction time; (3) H0AB: There is no interaction between fraction delivery time and transponder presence. Furthermore, a relative-dose analysis method was used to evaluate trends in dose differences between with and without transponders for each individual dosimeter readings and average readings among the three dosimeters for each configuration. In this dose analysis method, we obtained second-order polynomial fits of the doses for fractions 1, 3, 5, and 7 and calculated the differences between measured doses (fractions 2, 4, and 6) and polynomial interpolated doses. This second-order polynomial fit minimized influence of the potential dose-fading effect due to the delivery time. Any systematic higher or lower dose differences between measured and polynomial fit for fractions 2, 4, and 6 indicated a transponder effect.

III. RESULTS

III.A. Transponder localization tests

Table I shows the results of Wilk's lambda tests for the localization data sets; the test rejected the null hypothesis for both orthogonal and parallel configurations with less than 0.0001 probability of a type I error. This result indicated that there were statistically significant differences between the transponder localized coordinates of the control and test data sets for both insert configurations. Therefore, dosimeters did affect the transponder localization accuracy in the phantom. To quantify the localized transponder coordinate differences due to the presence of MOSFET dosimeter, the 95% confidence intervals of transponder coordinate differences between control and test data sets were obtained from the

Wilk's lambda test and presented in Table II. The maximum absolute value of the upper or lower bounds of the 95% confidence interval was approximately 100 μm . This value is significantly smaller than the clinical positioning resolution of 0.5 mm, which is used in Calypso systems in all radiotherapy clinics.

III.B. Dosimeter reading constancy tests

Table III shows the two-way ANOVA results for both orthogonal and parallel configurations with *F*- and *P*-values for transponder-presence effect, fraction-time effect, and their interactions. The *P*-values for the transponder-presence effect were relatively large for both configurations; hence, we could not reject the null hypothesis H0A that the mean-dose for the data set with the transponder and without the transponder was the same for both configurations. For fractions 1–6, the *P*-value for the fraction-time effect in the orthogonal configuration was 0.006. This result indicated that we could reject the null hypothesis H0B of no mean-dose difference between different dose fractions. There was an interaction between transponder-presence effect and fraction-time effect, which was confirmed by its *P*-value of 0.003. No other fraction-time effect had a significant *P*-value warranting rejection of null hypothesis H0B or H0AB. Tables IV and V present the differences between polynomial-fitted and measured-dose values at fractions 2, 4, and 6 for orthogonal and parallel configurations, respectively. The maximum dose difference was 1.75%. No obvious trend was observed in the dose deviations between measured and fit ones.

IV. DISCUSSION

We investigated the interferences between electromagnetic transponders and wireless MOSFET dosimeters in a

TABLE IV. Measured doses for orthogonal configuration and their deviations from predicted doses by second-order polynomial fit using fractions 1, 3, 5, and 7.

Fraction	Transponder presence	Measured dose @ d (cGy)	Measured dose @ e (cGy)	Measured dose @ f (cGy)	Average dose (cGy)	Dose delta @ d (%)	Dose delta @ e (%)	Dose delta @ f (%)	Average dose delta (%)
1	No	108.2	108.5	107.3	108				
2	Yes	104.3	105.8	106.1	105.4	−1.71	−0.40	−0.15	−0.74
3	No	103.3	104.4	104.5	104.1				
4	Yes	106	105.2	106.6	105.9	1.59	1.15	1.45	1.40
5	No	105.8	104.3	105.7	105.3				
6	Yes	103.1	104.5	105.7	104.4	−1.12	−0.08	1.54	0.12
7	No	104.3	105.8	103.3	104.5				

TABLE V. Measured doses for parallel configuration and their deviations from predicted doses by second-order polynomial fit using fractions 1, 3, 5, and 7.

Fraction	Transponder	Measured dose @ d (cGy)	Measured dose @ e (cGy)	Measured dose @ f (cGy)	Average dose (cGy)	Dose delta @ d (%)	Dose delta @ e (%)	Dose delta @ f (%)	Average dose delta(%)
1	No	104.9	101.9	105.3	104				
2	Yes	103.2	100.3	104.7	102.7	−0.03	−1.75	0.22	−0.51
3	No	101.2	101.7	102.7	101.9				
4	Yes	103.1	101.3	104	102.8	1.23	−1.14	−0.27	−0.07
5	No	102.9	103.1	106	104				
6	Yes	102.9	102.5	105.5	103.6	0.81	0.19	0.82	0.61
7	No	102.4	101.8	104.5	102.9				

custom-made phantom in this study. We explored the feasibility of concurrent application of both devices in a single treatment course. To our knowledge, this has not been previously reported.

The phantom was designed with the consideration of two potential factors for transponder-dosimeter interferences: relative orientation and relative distance. Therefore, we designed parallel and orthogonal configuration inserts, which represent both most likely clinical scenarios (parallel) and extreme case scenarios (orthogonal). These inserts were 8 cm in diameter, which was big enough to enclose most prostate-sized targets in radiotherapy; however, the findings from this study can be applied to a larger target, since the distances between the transponder and dosimeter may be larger than those in this study and in turn have potentially smaller interference among them.

In the transponder localization accuracy test, we positioned source/receiver array 15 cm from the transponder plane. This position was chosen based on manufacturer recommended array/transponder distance (less than or equal to 17 cm) for target localization and tracking patients. We believe that the advantage of concurrent use of both systems lies in the real time target tracking and *in vivo* dose measurement.

During the transponder localization, the dosimeter's antenna coil may react to the electromagnetic pulse excitation from the Calypso array, acting as a noise source. If we calculate the mean values of these 95% confidence intervals in Table II, the parallel configuration value (~ 0.043 mm) is slightly larger than that of orthogonal configuration (~ 0.026 mm). One of the possible explanations is that a stronger electromagnetic induction between transponders and dosimeters may exist in the parallel configuration than the orthogonal configuration.

In the dosimeter readings constancy test, the relative-dose analysis method did not detect any systematic differences between measured dose and polynomial-fit value for fractions 2, 4, and 6. Moreover, the differences between measured and fit doses (Tables IV and V) are comparable to the dosimeter's intrinsic reading variability of roughly 2%.⁷ Even though there was no observable dosimetric effect from the transponder, we focused this study on the electromagnetic compatibility between the two devices and intentionally avoided a dose-shadowing effect from the transponder by keeping the dosimeters and transponders in the same horizontal plane, which was orthogonal to AP/PA treatment fields.

V. CONCLUSIONS

This study investigated the potential transponder-dosimeter interferences between the Calypso system and the Sixel wireless MOSFET dosimeter system when they are placed in the same target volume. The results of these transponder localization tests prove that, for clinical application, transponder localization and tracking was minimally affected by the presence of wireless MOSFET dosimeters. The results of dosimeter readings demonstrated that electromagnetic transponders do not alter dosimeter dose readings; thus, transponders and dosimeters can be used simultaneously in the same patient.

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