Original Article

A study on rectal dose measurement in phantom and *in vivo* using Gafchromic EBT3 film in IMRT and CyberKnife treatments of carcinoma of prostate

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ABSTRACT

The objective of this study is to check the feasibility of *in vivo* rectal dose measurement in intensity-modulated radiotherapy (IMRT) and CyberKnife treatments for carcinoma prostate. An in-house pelvis phantom made with bee's wax was used in this study. Two cylindrical bone equivalent materials were used to simulate the femur. Target and other critical structures associated with carcinoma prostate were delineated on the treatment planning images by the radiation oncologist. IMRT treatment plan was generated in Oncentra Master Plan treatment planning system and CyberKnife treatment plan was generated in Multiplan treatment planning system. Dose measurements were carried out in phantom and in patient using Gafchromic EBT3 films. RIT software was used to analyze the dose measured by EBT3 films. The measured doses using EBT3 films were compared with the TPS-calculated dose along the anterior rectal wall at multiple points. From the in-phantom measurements, it is observed that the difference between calculated and measured dose was mostly within 5%, except for a few measurement points. The difference between calculated and measured dose in the in-patient measurements was higher than 5% in regions which were away from the target. Gafchromic EBT3 film is a suitable detector for *in vivo* rectal dose measurements as it offers the possibility of analyzing the dose at multiple points. In addition, the method of extending this *in vivo* rectal dose measurement technique as a tool for patient-specific quality assurance check is also analyzed.

Key words: Gafchromic EBT3, *in vivo* dosimetry, rectal dose measurement

Introduction

Intensity modulated radio therapy (IMRT) and CyberKnife (Accuray Inc., Sunnyvale, CA, USA) robotic radiosurgery technique have proven the possibility of delivering highly conformal dose to the tumor while reducing the dose to the surrounding normal structures. As a result, the total dose delivered to the tumor in IMRT treatments has been escalated to achieve a better tumor control.[1,2] With the α/β value of prostate tumor cells being low, hypofractionated dose regimen is preferred for carcinoma prostate in CyberKnife treatments.[3,4] Hypofractionated dose delivery of 35-36.5 Gy in five fractions with CyberKnife treatments has reduced the prostate-specific antigen level from a pretreatment value of 7.67 ng/mL to 0.64 ng/mL posttreatment.[5] Various authors have reported that the biological equivalent dose of the total dose delivered in hypofractionated treatments is high compared to the conventional dose regimens when converted using the linear quadratic model or normalized tumor dose method.[6,7]

The above-mentioned dose protocols and recommendations have taken into account the toxicity for the surrounding normal tissues. However, verification of the actual dose received by these normal tissues gives higher confidence level in adapting to these dose protocols. Hypofractionated dose regimen in CyberKnife and escalation

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in overall dose to the target in IMRT necessitates stringent quality assurance tests to verify the dose delivered to the tumor and surrounding organs at risk (OARs). Pretreatment patient specific quality assurance checks in phantom are the standard practice to ensure accurate delivery of planned dose in high precision treatments. Higgins *et al.* reported that *in-vivo* measurements can be performed in addition to pre treatment phantom measurements as a quality assurance check for IMRT treatments.[8] For carcinoma prostate patients, *in vivo* dose measurement in the anterior rectal wall could be useful in estimating the actual dose received by the rectum. In addition, dose measurements at the anterior rectal wall could be used to ensure the dose delivered to target as well, since the anterior rectal wall is either covered inside or just adjacent to the planning target volume in most of the cases.

In few published studies, authors have used implanted dosimeters to verify the dose delivered to the tumor, which can also be used as a fiducial marker to track the movement of the target.[9-12] Hardcastle *et al*. have studied the rectal dose in 3D conformal radiotherapy (3DCRT) and IMRT by using metal oxide semiconductor field effect transistor (MOSFET) detectors with rectal balloons.[13] In this study that was experimented in phantom, the authors have raised caution about the temperature dependency of the MOSFET and the reproducibility in positioning of the detector if the same technique has to be used in a patient. In a thermo luminescent dosimeter (TLD) based *in vivo* study done by Hsi *et al*., dose to rectal wall was measured in IMRT and proton treatments by attaching the TLD in the rectal balloon.[14] This study has also attempted to improve the reproducibility in positioning of the rectal balloon by keeping radio opaque metallic markers in the rectal balloon and verifying their alignment from orthogonal X-ray radiographs.

In both of these studies, the anterior rectal wall dose was measured at a single point only. Both groups of authors have discussed that the overall trend of rectal dose cannot be investigated by measuring the dose at a single point. Hence, dose measurement at multiple points along the anterior rectal wall in the craniocaudal direction is required to know the pattern of dose received by the rectum. To achieve this, it is essential to use either multiple numbers of point dose detectors or a single 2D detector. Gafchromic EBT3 film (International Specialty Products Corporation, Wayne, NJ, USA) is one such dosimeter, since a single film piece can be used to measure the dose along the anterior rectal wall. The use of gafchromic EBT film to measure the rectal dose has been reported for intraoperative radiotherapy.[15] However, the use of newly released Gafchromic EBT3 is not yet studied for *in vivo* dosimetry in IMRT and CyberKnife treatments. The objective of this study is to analyze the potential use of Gafchromic EBT3 film as an *in vivo* dosimeter to measure dose to the anterior rectal wall in IMRT and CyberKnife treatments.

Materials and Methods

In our center, transrectal ultrasound based localization of the prostate target is done for suitable and willing patients, prior to treatment planning imaging and before each fraction of treatment delivery in IMRT and CyberKnife. This technique is used to localize the prostate tumor and minimize its movement during treatment. With the patient on the treatment table, transrectal ultrasound imaging is done to localize the prostate. Positioning of the ultrasound probe is adjusted in such a way that prostate is just sitting above the probe holder. Cone beam computed tomography (CBCT) images are obtained, and the entire geometry of prostate and rectum with the probe and its holder is matched with the same geometry in the treatment planning images. The probe is then replaced with a dummy plastic rod in the holder which serves as a hard and stable base for prostate and reduces the intrafraction movement during treatment of the prostate. This technique which was used to immobilize the tumor during treatment enables the possibility of *in vivo* rectal dosimetry by keeping a dosimeter with the dummy plastic rod.

Choice of the detector

Gafchromic EBT film has proven to be suitable dosimeter to measure the dose distribution in QA of high-precision radiotherapy treatments.[16] It is nearly tissue equivalent and offers a very high spatial resolution in dose measurement. Various authors have evaluated the use of Gafchromic EBT film in IMRT and CyberKnife treatments to measure the delivered dose distribution or beam profile.[17,18] Gafchromic EBT3 film is the new and improved version of the Gafchromic films. Studies comparing the dosimetric characteristics of the EBT3 film with the earlier versions show that the uncertainties in dose measurement using Gafchromic EBT3 are reduced compared to the previous versions of the film.[19,20]

It is reported that the relative error in dose measurement at standard irradiation conditions is less than 2% for Gafchromic EBT3 film.[20,21] Unlike the old versions of the film, Gafchromic EBT3 film is symmetric in structure as it is made by sandwiching the active substrate layer between two polyester layers of equivalent thickness. The symmetric design of the EBT3 film eliminates the scanning side dependency reported for EBT2 film.[19]

EBT3 film dosimetry

EBT3 films used in this study were taken from the same batch. EBT3 film sheets were cut into pieces of required size for dose measurement. A calibration curve of the film response as a function of dose was generated for a dose range of 0-1000 cGy. Film pieces of 4 cm × 4 cm size were irradiated in a field size of 10 cm × 10 cm. Films were kept inside solid water phantom (density: 1.03 g/cc) at a depth of 5 cm at 100 cm source to surface distance. A post-irradiation waiting time of 24 hours in

room temperature was maintained for the irradiated film pieces to achieve saturation in darkening. Epson expression 10000 XL flatbed scanner was used to scan the irradiated films. A recommended scanning protocol was maintained uniformly during calibration and experiment.[22] Film pieces were always scanned in the approximate central position of the scanner in the landscape orientation. The manufacturer of the EBT3 film recommends that the film be scanned in the red color channel for doses up to 8 Gy. However, since the calibration curve is generated up to 10 Gy, films were scanned in the RGB mode both during calibration and dose measurement. RIT software (Radiological Imaging Technology, Colorado springs, CO, USA) was used to analyze the scanned images of the films. An unexposed film was also scanned to get the film response for 0 dose.

Design of the phantom

The study was initially carried out on the in-house phantom for IMRT and CyberKnife treatments and extended to *in vivo* measurements on a patient treated by IMRT technique. Pelvic contours from three patients with carcinoma prostate were copied and averaged out to obtain the shape of the phantom. A phantom depicting pelvis was made using bee's wax [Figure 1a]. Two bone inserts were kept in the phantom to simulate the femur head. Rectum was simulated in the phantom with an opening slightly larger in diameter compared to the diameter of the ultrasound probe. The phantom was then scanned in a computed tomography (CT) machine for treatment planning. A plastic rod that was used to simulate the ultrasound probe was kept in the rectal opening during CT scanning. Images were transferred to the Oncentra Master Plan (Nucletron, Veenendaal, the Netherlands) treatment planning system for contouring and IMRT planning. The target and other OARs were delineated by the radiation oncologist. Images with the structure set (tumor and OARs) were transferred to Multiplan treatment planning system (Accuray Inc.) for CyberKnife treatment planning.

Placement of EBT3 film in the phantom

EBT3 film sheets were cut into rectangular pieces of 1 cm × 7 cm size. A small mark was made on one corner of the film pieces to track the orientation of the original film sheet during scanning. EBT3 film pieces to be used for dose measurement were packed and sealed in a polythene cover. The film with cover was then wrapped around the plastic rod with the length of the film parallel to the axis of the rod [Figure 1b]. The rod with EBT3 film was then inserted into the rectal opening of the pelvic phantom in such a way that the central axis of the film touches the anterior surface of the rectal opening.

IMRT treatment planning and dose measurement in phantom

A seven-field IMRT treatment plan using 6 MV X-rays was generated for the phantom images with hypothetical structures [Figure 2]. The dose prescribed to the target was 2 Gy per fraction. Collapsed cone convolution algorithm was used for dose calculation. The treatment plan was then evaluated using the radiation therapy oncology group (RTOG) constraints and transferred for treatment delivery. IMRT treatment was delivered from the SIEMENS ARTISTE (Ms. Siemens, Erlangen, Germany) linear accelerator. CBCT images were obtained and registered with the planning CT images to verify the accurate positioning of the isocenter in the phantom. Plastic rod and the bone inserts were clearly visible in both the planning CT images and the CBCT images. Treatment position of the phantom was verified three dimensionally by alignment of planning CT and CBCT images using the plastic rod and bone inserts as markers [Figure 3].

CyberKnife treatment planning and dose measurement in phantom

A CyberKnife treatment plan was generated for the phantom to deliver a dose of 36.25 Gy in five fractions to the

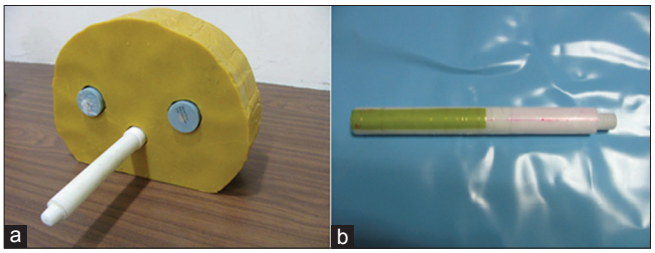

Figure 1: (a) Phantom depicting human pelvis and (b) EBT3 film pasted around the plastic rod

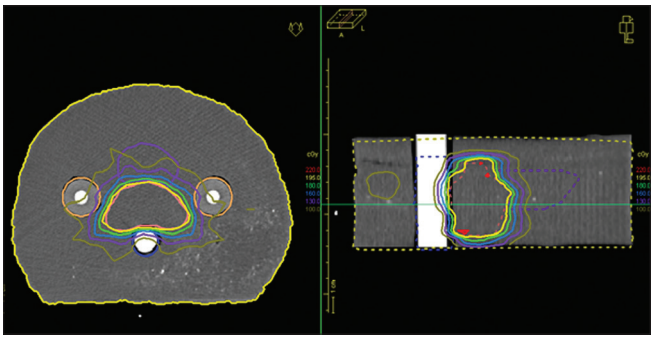

Figure 2: IMRT dose distribution in phantom in the axial and sagittal views

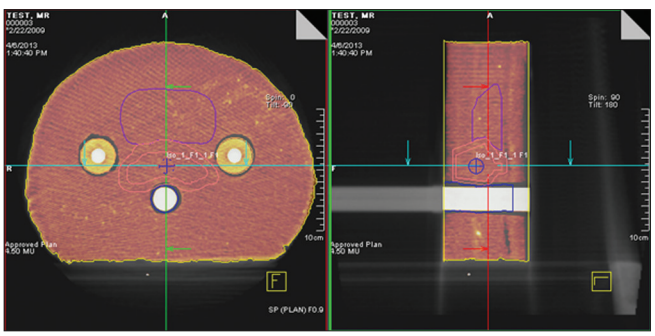

Figure 3: Registration of CBCT and planning CT images of the phantom prior to treatment execution

target. Ray tracing algorithm was used to calculate the dose distribution in the phantom [Figure 4]. Collimator sizes of 30 mm, 40 mm, and 50 mm from the iris collimator were used in the treatment plan. Totally 128 beams from 49 node positions were used to deliver the dose. Total number of monitor units from the treatment plan was of 17,123.

CyberKnife treatments were executed on the phantom with EBT3 films to measure the dose delivered to the rectum. In CyberKnife treatments, tracking of multiple fiducial markers implanted on the target is the standard practice to track the movement of prostate during treatment. Since the hypothetical target in the phantom is static, no fiducial marker was implanted on the phantom. However, it is not possible to execute the CyberKnife treatment without using any of the available tracking mechanisms. Hence, in this study, X-sight spine tracking algorithm was used wherein the bone inserts served as the markers.

Comparison of calculated and measured dose in phantom

The treatment planning system (TPS) calculated dose to the upper surface of the plastic rod in IMRT and CyberKnife treatment planning was recorded for every 1 cm distance, starting at 1 cm from the tip of the rod for the next 5 cm distance. The TPS calculated anterior rectal wall dose from these points were compared with the measured point doses from EBT3 films. An uni-dimensional dose profile along the center of the film was generated from all the irradiated films using the RIT software. The maximum dose delivered to the anterior rectal wall was analyzed from the profile.

In vivo dose measurement in patient

After analyzing the results of the phantom-based rectal dose measurements, the study was extended to *in vivo* measurement. Rectal dose measurements were carried out on a patient treated with IMRT for carcinoma prostate. Treatment plan was generated with prescription doses of 180 cGy and 200 cGy to the contoured volumes of CTV and GTV, respectively [Figure 5]. EBT3 film pieces of 1 cm width by 10 cm length were used to measure the anterior rectal wall dose in the patient. Transrectal ultrasound based localization of the prostate was done by radiation oncologists during imaging and treatment execution. The ultrasound probe was then removed from its holder and EBT3 film with the rod was kept inside the holder. The insertion of the plastic rod was ensured to be straight using a line drawn on the surface of the rod to avoid rotation of the film while inserting the rod into the holder. CBCT images were obtained to verify the local geometry comprising prostate, ultrasound probe holder, and the isocenter. IMRT treatments were executed after alignment of the patient using CBCT images and planning CT images. EBT3 film was removed from the rectum after treatment and scanned after a 24-h wait time interval. *In vivo* rectal dose measurement in the patient was done for 10 treatment fractions. The measured dose from the film was then compared with the TPS calculated dose for multiple points at a uniform interval of 1 cm distance along the length of the film. The maximum dose delivered to the anterior rectal wall was obtained from the film profile generated along the length of the film.

Results

Calculated dose to the anterior rectal wall in phantom from the TPS-generated plan was noted at multiple points along the anterior surface of the plastic rod. In IMRT planning, the maximum dose from the points of interest in the anterior rectal wall was 193 cGy. The TPS calculated dose to the anterior rectal wall in the 1 cm interval points varied from 96 to 193 cGy [Table 1]. The measured dose from the EBT3 films in all five treatment fractions showed good agreement with the TPS calculated dose. The measured dose along the length of the films showed a similar pattern of dose to anterior rectal wall along the craniocaudal direction in-phantom from the TPS. The difference between the calculated and measured dose from the all the treatment fractions varied from −5.93% to 9.3%. A maximum difference of 9.3% between the calculated and measured dose was observed at a point in the second treatment fraction. In each treatment fraction, the difference was above 5% on at least one random point. The maximum dose measured from the film profile was 204.47 cGy.

In CyberKnife treatments, dose delivered to the target was 6.25 Gy per fraction. Anterior rectal wall dose measured using the film was compared with the TPS calculated dose

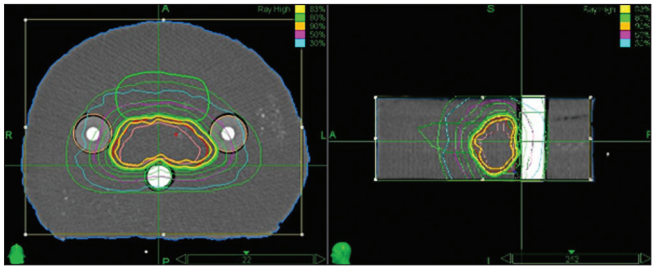

Figure 4: Dose distribution in phantom for CyberKnife treatment plan in axial and sagittal views

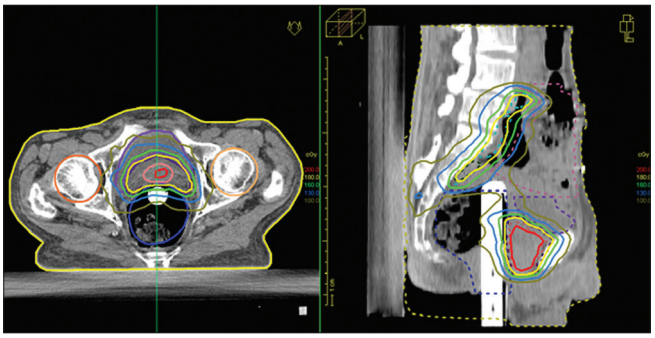

Figure 5: Dose distribution in-patient images for IMRT plan in axial and sagittal views

for the central 5 cm distance in the film. From the TPS calculated dose, dose to the points at 1 cm interval along the anterior rectal wall ranged between 388.46 and 689.15 cGy. The measured dose along the 1 cm interval points from the EBT3 films varied between 394.18 and 721.35 cGy [Table 2]. Except the inferior-most point, the difference between the calculated and measured doses was less than 5% in all other points in the CyberKnife treatments. The maximum deviation observed between the TPS calculated and EBT3 film measured dose in CyberKnife treatments was 9.12%. The maximum anterior rectal wall dose measured from the film profile was 723.17 cGy.

For *in vivo* dose measurement in patient, dose measured from the central 8 cm in the EBT3 film was compared with the TPS calculated dose. TPS calculated dose to the anterior rectal wall in patient varied between 28 and 171 cGy. The measured dose at 1 cm interval points from EBT3 film in patient ranged between 26 and 177.65 cGy [Figure 6]. TPS-calculated dose to the anterior rectal wall was close to the target prescription dose in those regions where the target was just above the rectum. The dose measured from EBT3 film in this region showed minimal deviation with the calculated dose. Difference between the calculated and measured dose along the points at 1 cm interval in the anterior rectal wall varied between −7.26% and 9.12% [Table 3]. The maximum dose measured from the dose profiles in patient using EBT3 film was 177.65 cGy.

Discussion

In this study, dose to the anterior rectal wall was measured using EBT3 films in phantom for IMRT and CyberKnife treatments and in-patient measurements were done for 10 fractions of IMRT treatments. It was possible to analyze the point doses at multiple locations along the anterior rectal wall in the craniocaudal direction with EBT3 film. Since the dose received by the entire anterior wall could be measured with films, it is possible to analyze the maximum dose

Table 1: Dose to anterior rectal wall in phantom from IMRT treatments

Distance from the tip of the rod (cm)	*TPS calculated dose (cGy)*	*Measured dose from EBT3 films in phantom (cGy)*				
		Fraction I	*Fraction II*	*Fraction III*	*Fraction IV*	*Fraction V*
1	96	96.17	104.93	93.13	94.81	94.16
2	178	183.33	184.59	175.46	180.16	175.93
3	193	197.55	196.14	193.06	196.94	192.83
4	190	196.96	195.1	201.03	196.64	195.72
5	178	190.87	184.21	188.51	188.66	190.66
6	135	127	129.33	134.36	139.68	139.36

IMRT: Intensity-modulated radiotherapy

Table 2: Dose to anterior rectal wall in phantom from CyberKnife treatments

Distance from the tip of the rod (cm)	*TPS calculated dose (cGy)*	*Measured dose from EBT3 films in phantom (cGy)*				
		Fraction I	*Fraction II*	*Fraction III*	*Fraction IV*	*Fraction V*
1	558.25	580.64	565.24	569.13	545.42	523.75
2	687.46	721.35	660.96	695.86	691.27	675.96
3	689.15	713.96	682.39	703.28	713.31	700.05
4	669.23	698.45	654.26	667.85	672.85	668.5
5	598.91	628.6	606.79	602.23	614.8	621.53
6	388.46	422.13	394.18	414.54	423.87	422.37

Table 3: Difference between calculated and measured doses during IMRT *in vivo* measurements

Distance from the tip of the rod (cm)	*Difference between calculated and measured doses for IMRT in vivo measurements (%)*									
	Fraction I	*Fraction II*	*Fraction III*	*Fraction IV*	*Fraction V*	*Fraction VI*	*Fraction VII*	*Fraction VIII*	*Fraction IX*	*Fraction X*
1	0.14	4.18	−1.94	−2.17	−2.68	9.12	−5.1	2.51	4.61	3.74
2	2.75	−7.26	−2.48	−5.23	−1.36	1.37	−1.24	2.17	−1.57	−2.42
3	3.89	3.6	−1.46	2.15	−1.72	2.1	−1.07	−1.09	2.61	1.01
4	−1.51	1.63	4.26	1.73	0.23	4.01	−0.28	3.19	3	1.8
5	3.63	−3.15	5.31	1.42	3.74	3.27	2.61	2.41	2.41	−2.4
6	−0.51	−6.42	5.18	−4.52	1.42	−2.61	3.18	3.96	3.04	3.3
7	7.35	−5.73	7.59	6.27	3.51	3.61	5.27	4.84	4.91	6.18
8	4.28	2	6.24	−5.47	3.27	6.37	5.72	5.38	5.14	5.65
9	7.14	5.14	3.51	5.13	2.51	6.12	5.24	4.83	9.03	5.08

IMRT: Intensity-modulated radiotherapy

received by the anterior rectal wall, whereas in the earlier studies reported with TLD or MOSFET as the detector, it was possible to measure the dose at one point only.

In total, phantom measurements were done for five treatment fractions each in IMRT and CyberKnife treatments. *In vivo* rectal dose measurements in patient were carried out for 10 treatment fractions. From the results, the measurements done in phantom showed better agreement with the TPS calculated dose compared to the in-patient measurements. Less uncertainty in dose calculation and the phantom being static during the treatment could be the reasons for lesser deviations observed in phantom measurements. In addition, the rectal filling in the patient may not be the same during imaging and each treatment fraction. *In vivo* dosimetry results in the patient show ≥5% difference with the calculated dose for 35% of total point measurements. However, it was observed that the difference between calculated and measured dose was less in the points posterior to the prostate where the dose delivered was uniform and close to the prescription dose. In the points at low-dose regions which are away from the target, a small difference in absolute value between calculated and measured dose appears to be larger deviation when the absolute values are converted to relative. For the measurements done in phantom for IMRT and CyberKnife, only at a few points the difference with the calculated dose was >5%. The maximum difference between the calculated and measured dose was above 9% for both in-phantom and in-patient measurements. However, in both situations, the maximum difference occurred at points in the high dose gradient regions. Though the positioning of the dosimeter with the plastic rod was verified using CBCT, a small error in reproducibility in positioning of the film could lead to significant difference between the calculated and measured dose due to the high-gradient nature of the dose distribution in IMRT and CyberKnife treatment plans. In addition, the inherent uncertainty of the EBT3 film dosimetry and accuracy of the TPS dose calculation might have contributed to the difference in agreement between the calculated and measured doses.

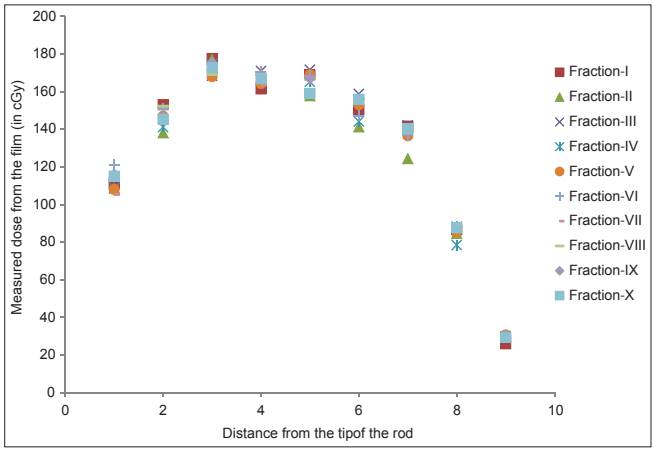

Figure 6: Measured dose in the anterior rectal wall in patient using EBT3 film

The *in vivo* dosimetry technique discussed in this study could be extended as a patient-specific quality assurance check as the delivered dose is measured on a line for the entire treatment length [Figure 7]. However, there are few limitations in comparing the measured dose profile with the calculated profile. In IMRT patient-specific quality assurance tests, the treatment planning systems transfer the whole three-dimensional (3D) dose grid to the IMRT verification systems. Either a dosimetric film or an array of detectors is used to measure the delivered dose. A point-by-point comparison of the measured two-dimensional (2D) dose distribution with the calculated dose distribution in the isocenter plane is carried out using the gamma index method.[23] Accurate registration of the calculated dose and measured dose data set is crucial while comparing the calculated and measured dose distributions.

With the technique used in this study, measurement of 2D dose distribution is ruled out since the film is wrapped over the cylindrical surface of the rod. The next option to check the accurate delivery of the treatment plan is to compare the calculated and measured dose profile along the craniocaudal direction. However, current features available in the TPSs used in this study do not facilitate extraction of a single one-dimensional dose profile along the anterior rectal wall. Also, the measured dose profile could not be registered with the calculated dose profile in the verification systems as the film was wrapped over the cylindrical surface of the rod during measurement.

Conclusion

This study has evaluated the use of Gafchromic EBT3 film as the detector for the *in vivo* rectal dosimetry. With Gafchromic EBT3 film, the dose delivered to anterior rectal wall along the entire length of the rectum was measured in this study. The measured dose was in close agreement with the calculated dose (within 5% difference) in the regions

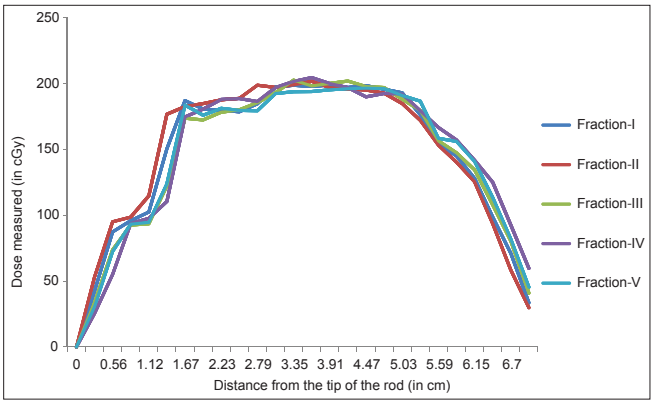

Figure 7: Measured dose profiles using EBT3 from IMRT in phantom

of uniform distribution in patient and almost in the entire measurement locations except for a few points in phantom. The EBT3 film was used as a dosimeter in an existing in-house protocol for prostate immobilization in IMRT and CyberKnife treatments. The same shall be analyzed as a dosimeter in other techniques such as rectal balloon. Also, methods of registering the measured one-dimensional dose profile with the calculated profile shall be investigated further to extend this technique as a patient-specific quality assurance check.

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