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A phantom study for in-vivo dosimetry of high dose rate brachytherapy applicators

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Original Article

Abstract

Purpose: The aim of the current investigation was to calibrate the diode in-vivo dosimetry (IVD) system for high-dose-rate (HDR) brachytherapy and to design a phantom study for in-vivo dosimetry of HDR brachytherapy applicators. **Methods:** Gamma Med Plus with Abacus 3.1 treatment planning system (TPS), and diode dosimetry system has been used in this study. Calibration and different correction factors of diode have been measured in water phantom. Treatment simulation, planning of different applicators for esophagus, rectum/vagina and cervix (fletcher & ring), dose delivery and finally in-vivo verification at prescription point using diode in water phantom has been performed. **Results:** The mean calibration factor for diode for Ir-192 HDR source is 1.256 (N=15) with σ ± 0.0015. The overall average percentage difference between TPS dose and diode dose was 1.87% (σ ± 2.64) for all measurements, 1.86% (σ ± 2.73) for esophagus, 1.86% (σ± 2.94) for rectum/vagina and 1.67% (σ ±2.81) for fletcher and 2.07% (σ ± 2.26) for ring applicators, respectively. These results advocate that the dose calculated by TPS and dose measured using diode for the various clinical situations deliberated here are in good agreement (~2%) at the points of clinical importance. **Conclusion:** The in-vivo phantom dosimetry study gives both a confidence that the treatments are being delivered as prescribed and enhance the reliability of the HDR brachytherapy treatment. This may be used for acceptance testing/commissioning of new treatment planning system and to validate the new brachytherapy techniques in the clinics.

Keywords: Brachytherapy, In-vivo dosimetry, Phantom, Ir-192, HDR

1. Introduction

Brachytherapy is a vital part of radiotherapy for the treatment of malignancies and is frequently used with external beam radiation therapy (EBRT) for radical/palliative treatment. Several studies have suggested that control rates are considerably enhanced with EBRT and brachytherapy.[1,2] HDR remote after loading brachytherapy has been commonly used all over the world.[2] Radiation therapy is a chain like procedure. The ambiguity in each step may influence the accuracy of subsequent steps and, therefore can have an impact on the overall treatment results. Accuracy of dose delivery of HDR brachytherapy may be contributed to the success of aims of treatment, improve tumor control and lessened toxicity of normal tissue and is a challenging task in brachytherapy due to small treatment depths, steep dose gradients and large difference in absorbed dose in volumes of concern.

In recent past, a number of unwanted radiation incidents, which seriously affect the treatment objectives were noted in different countries.[3-7] Thomadsen *et al.* recognized 44 errors in HDR brachytherapy treatment in data (1980-2001) from the Nuclear Regulatory Commission and International Atomic Energy Agency.[8] IAEA Safety Report Series No 17[9] conferred 32 incidents involving brachytherapy,

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ICRP 86[10] identified potential errors in brachytherapy escalating from problems with equipment, calibration, treatment planning, and treatment delivery and ICRP 97[11] described over 500 accidents involving HDR brachytherapy. Those events highlighted the need of more accurate dose delivery to the patient undergoing brachytherapy. IVD is the measurement of radiation doses to patients undergoing brachytherapy in order to guarantee that the treatments are delivered as planned. IVD is recommended by the World Health Organization (WHO)[12], the International Commission on Radiological Protection (ICRP) [10], the International Atomic Energy Agency (IAEA)[13] and other bodies like American Association of Physicists in Medicine (AAPM) [14] and European Society for Therapeutic Radiology and Oncology (ESTRO)[15] for routine verification of the dose delivery for all groups of patients undergoing radiotherapy.

The significance of independent verification of dosimetry earlier to HDR brachytherapy treatment delivery by a simple method has been acknowledged universally and a significant literature is available[16-21] but these are not the alternate to the IVD. The need of patient-specific QA as well as independent verification of the planned dose are obvious[22-23] and have to be performed to ensure the safety and accuracy of the treatment dose delivery. Diode is used since it offer real-time response, high sensitivity, better spatial resolution, robustness, absence of bias voltage, etc. and it is available almost in every radiation therapy department.

Regarding in-vivo dosimetry in HDR brachytherapy, literature is available on verification of dose at organs at risk (bladder & rectum) [24-29] but no literature was found on verification of absorbed dose at prescription point. The key objective of the current investigation is to perform a phantom study similar to clinical setup and verify the absorbed dose in HDR brachytherapy at the prescription point. The dose verification is made with diode and it is based on the postulation that the covenant between the measured and calculated dose in setup that really mimics the clinical situations implies that the dose delivered to the target volume is the anticipated dose.

2. Methods and Materials

Measurements have been performed using photon source of Ir-192 for a HDR Gamma Med Plus (Varian Medical solution, USA) machine. The source has been calibrated using a well ionization chamber dosimetry system (HDR 1000 Plus, Sr. No. A040623 & Electrometer CDX-2000B, Sr. No. J033533 Standard Imaging, USA)).[30] The IVD system used in this study consist of PDM Model No. 37-721(electrometer, Nuclear Associates, NY, USA) and ISORAD n-type diode (9731-0 for 70-all energies i.e. energy compensated, Nuclear Associates, NY, USA). A 3-D water phantom (60×55×50-cm, Model 9750, Sr. No. 20075001, Multidata Systems International Corp., USA) has been used for the calibration of the IVD system. The diode IVD system has been calibrated as per recommended procedure in literature.[13] Diode has been placed in a 2 cm rectum cylinder filled with water and source catheter has been taped onto the surface of cylinder, center-to-center distance of 1 cm[13] and the whole assembly has been put in water phantom for calibration as shown in Figure 1a. A dose of 5 Gy has been delivered for calibration of diode IVD system at 1 cm center-to-center distance between diode and the dwell position, using the current strength of Ir-192 HDR source. Correction factors that are relevant to clinical use have been measured. The dependence of diode signal on distance has been measured at 1-5 cm with 1 cm interval, the arrangements are shown in Fgure 1b. A dose of 50 cGy has been delivered at each position. The directional dependence of the diode has been measured by placing the diode in center of after loading cylindrical PMMA phantom and source at 0^0, 90^0, 180^0, and 270^0 angles and then replace the position of the diode with the source as shown in Figure 1c & d. The temperature effect on diode was not investigated, since all measurements and calibration have been performed in water phantom at room temperature. If the first three readings were identical, it was taken as the average, if not the case; the average of five readings was used.

The diode and applicator (for esophagus, rectum/vagina and cervix) have been fixed at prescription treatment depth. The whole assembly has been put in the water phantom in position that mimics the clinical condition. Simulation has been performed for the above mentioned assembly and a radiograph has been taken shown in Figure 1e-h to reconstruct the position of diode and applicator in the TPS. Treatment planning has been performed using Abacus 3.1 TPS. Finally the treatment has been delivered and diode reading has been taken to calculate the delivered dose as shown in Figure 1i-l.

The dose from diode signal has been calculated using the following equation;

$$D = (R_{diode})\,(N_{Ir\text{-}192})\,(K_{direction})\,(K_{distance})$$

where, D is the diode dose; R_{diode} is the diode signal; $N_{Ir\text{-}192}$ is the calibration factor; $k_{direction}$ is the direction dependence correction factor and $k_{distance}$ is the distance correction factor. Then TPS and diode doses have been compared.

All dosimetric calculations have been performed for a nominal 37 GBq (10 Ci) source strength using ABACUS 3.1 (TPS, manufactured by Varian Medical Solutions, USA) and 5 Gy as prescribed doses at 0.4 cm depth away from the esophagus applicators, at 0.5 cm depth from rectum/vaginal applicators and 7 Gy dose at point A for fletcher/ring applicators. Treatment planning for

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brachytherapy using different available applicators was aimed to be verified with the IVD system. The dose has been measured at second, central and second last position for esophagus and rectum/vagina applicators and at point A (left & right) for fletcher & ring applicators and then average dose has been taken.

The applicators available at BINO for esophagus, rectum/vagina and cervix (fletcher & ring) manufactured by Varian Medical Solution, USA and are compatible with Gamma Med plus HDR unit and Abacus 3.1 TPS have been used for this study. MS Excels, SPSS 16.0 have been used for data analysis. EndNote 5 has been used for reference management.

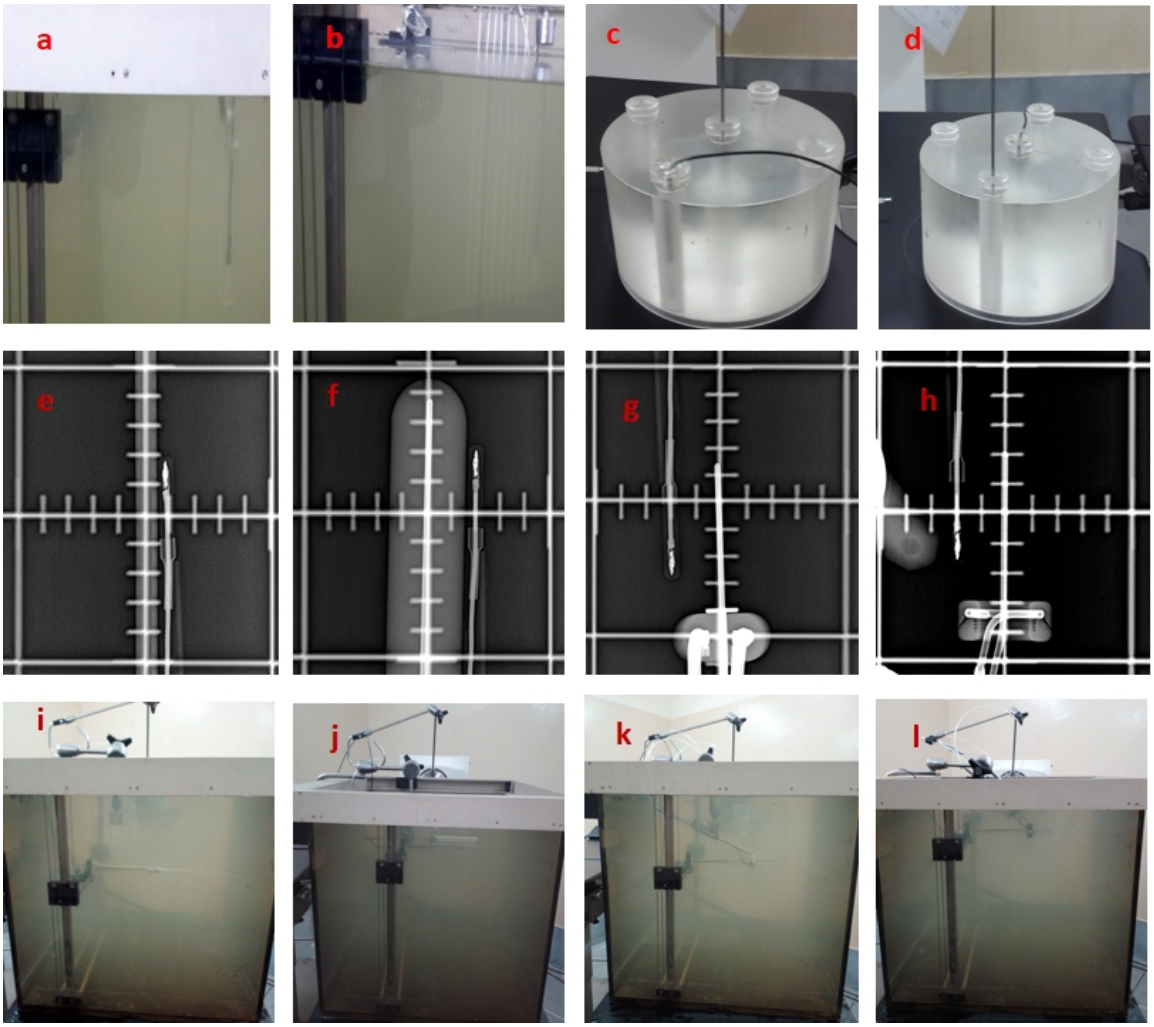

Figure 1: The setup for (a) calibration, (b) distance correction factor, (c) & (d) angle correction factor determination has been shown. The simulation films for (e) esophagus, (f) rectum/vagina, (g) fletcher and (h) ring applicators as well as diode are shown. The measurements arrangements for (i) esophagus, (j) rectum/vagina, (k) fletcher and (l) ring applicators and diode are shown in water phantom.

Table 1: Correction factors for diode in-vivo dosimetry system.

	Diode at center		Source at center		Distance between center of source and diode		
Position	R_{diode}	$K_{direction}$	R_{diode}	$K_{direction}$	Distance (cm)	R_{diode}	$K_{distance}$
0^0	7.4	1.00	7.40	1.00	1	30.7	1
90^0	7.4	1.00	7.4	1.00	2	31.2	0.984
180^0	7.5	0.99	7.5	0.99	3	31.7	0.968
270^0	7.4	1.00	7.3	1.01	4	32.3	0.950

3. Results

The aim was to characterize the diode for HDR brachytherapy treatment and finally to verify the absorbed dose calculated by TPS at prescription point using diode for different HDR brachytherapy applicators. The calibration factor has been measured on daily basis for fifteen days to check the consistency of the in-vivo dosimetry system. The calibration factor does not change significantly over the period of study and a good consistency has been observed. The mean calibration factor for diode for Ir-192 HDR source is 1.256 (N=15) with standard deviation ± 0.0015. The distance correction factor has been measured as per setup shown in Figure 1b and from 1-5-cm distance with 1 cm increment. The mean distance correction factor is 0.968 with standard deviation ± 0.026. The directional effect has been measured as per arrangements shown in Figure 1c & d. The mean directional effect is 0.998 with standard deviation ± 0.005 and 1.00 with standard deviation ± 0.008 for diode and source in the center respectively. The directional and distance correction factors for diode are presented in Table 1.

The absorbed dose at prescription point has been measured for different applicators available for esophagus, rectum/vagina, and cervix with diode IVD system in water phantom that mimics the clinical setup. The percentage difference between the TPS dose and diode dose has been calculated for different HDR brachytherapy applicators available for esophagus, rectum/vagina and cervix (fletcher & ring) and results are presented in the tables 2-5.

The data in the tables shows that the overall average percentage difference between TPS dose and diode dose was 1.87% (standard deviation ± 2.64) for all measurements, 1.86% (standard deviation ± 2.73) for esophagus, 1.86% (standard deviation ± 2.94) for rectum/vagina and 1.67% (standard deviation ±2.81) for fletcher and 2.07% (standard deviation ± 2.26) for ring applicators, respectively.

These results advocate that the dose calculated by TPS and dose measured using diode for the various clinical situations deliberated here are in good agreement (~ 2%) at most of the points of clinical importance.

Table 2: In-vivo phantom results for various diameter esophagus HDR brachytherapy applicators.

Applicator dia (cm)	Treatment Length (cm)	Treatment Depth (cm)	TPS Dose (cGy)	Diode Dose (cGy)	% Difference
0.80	4	0.30	500	504.70	-0.94
	6	0.30	500	485.30	2.94
	8	0.30	500	491.70	1.66
1.00	4	0.30	500	490.30	1.94
	6	0.30	500	506.30	-1.26
	8	0.30	500	478.50	4.30
1.20	4	0.30	500	475.90	4.82
	6	0.30	500	508.60	-1.72
	8	0.30	500	476.80	4.64
1.40	4	0.30	500	477.10	4.58
	6	0.30	500	511.30	-2.26
	8	0.30	500	481.60	3.68

Table 3: In-vivo phantom results for various diameter rectum/vagina HDR brachytherapy applicators.

Applicator dia (cm)	Treatment Length(cm)	Treatment Depth (cm)	TPS Dose (cGy)	Diode Dose (cGy)	% Difference
2.00	2	0.50	500	491.30	1.74
	3	0.50	500	511.30	-2.26
	4	0.50	500	475.10	4.98
2.30	2	0.50	500	493.20	1.36
	3	0.50	500	506.30	-1.26
	4	0.50	500	470.20	5.96
2.60	2	0.50	500	481.40	3.72
	3	0.50	500	513.40	-2.68
	4	0.50	500	483.80	3.24
3.00	2	0.50	500	476.30	4.74
	3	0.50	500	509.30	-1.86
	4	0.50	500	481.60	3.68
3.50	2	0.50	500	482.80	3.44
	3	0.50	500	479.50	4.10
	4	0.50	500	505.40	-1.08

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Table 4: In-vivo phantom results for various length and angle tandem fletcher HDR brachytherapy applicators.

Tandem Length(cm)	Tandem Angle (0^0)	Prescription Point	TPS Dose (cGy)	Diode Dose (cGy)	% Difference
2.00	30	A	700	680.10	2.84
	45	A	700	710.30	-1.47
	60	A	700	673.60	3.77
4.00	30	A	700	715.30	-2.19
	45	A	700	664.50	5.07
	60	A	700	670.10	4.27
6.00	30	A	700	711.70	-1.67
	45	A	700	691.30	1.24
	60	A	700	676.60	3.34

Table 5: In-vivo phantom results for various length and angle tandem ring HDR brachytherapy applicators.

Tandem Length (cm)	Tandem Angle (0^0)	Prescription Point	TPS Dose (cGy)	Diode Dose (cGy)	% Difference
2.00	30	A	700	711.90	-1.70
	45	A	700	671.80	4.03
	60	A	700	683.20	2.40
4.00	30	A	700	685.10	2.13
	45	A	700	668.90	4.44
	60	A	700	678.20	3.11
6.00	30	A	700	711.70	-1.67
	45	A	700	682.70	2.47
	60	A	700	675.80	3.46

4. Discussion

Though a sufficient literature is available on diode in-vivo dosimetry however mostly for external beam radiotherapy and some investigators focused on rectum dose verification for gynecological HDR brachytherapy [25-27,31] yet no literature was found on direct measurement of dose at prescription point. In the presented study, an in-vivo phantom study has been designed to simulate the clinical situation for verification of dose at prescription point for HDR brachytherapy. Treatment planning is a complex as well as a time taking process in radiotherapy in general and in brachytherapy in particular that includes the applicator insertion, a complex simulation, CT/MRI or Orthogonal radiograph, transfer of simulation data to treatment planning system and then the best possible treatment plan for an individual patient. Each step is prone to one or more sources of error, so it is essential to be performed with the greatest accuracy achievable. The ambiguity in each step may influence the accuracy of subsequent steps and, therefore can have an impact on the overall treatment results. Confirmation of the dose delivery before treatment in a phantom certainly ensures the accuracy, reliability and authenticity of all component processes.

The calibration factor does not change significantly over the period of study and a good consistency has been observed. The same effect has been observed previously.[26, 32] The angle and distance correction factors are insignificant and comparable to published data.[26]

A 5% difference between measured and TPS dose values is permissible as per International Atomic Energy Agency (IAEA) after their coordinated project on in-vivo dosimetry using MOSFET.[13] The size of diode is very large as compared to MOSFET that increase the possibility of more differences but most of the results (average of our results) is within the tolerance. Tables 2-5 show that the dose calculated by TPS and measured using diode are closely matched. The phantom measurements mimicking the actual clinical conditions agreed with the anticipated, i.e., TPS calculated values within ± 5% (standard deviation ± 2.64). Our results are comparable to published literature. [19, 25, 26] The maximum difference between the dose measured by diode and calculated by TPS was 5.96%.

This study may be helpful for verification of the precision and accuracy of dose calculation at the time of commission/acceptance testing of TPS and, following, for periodical quality control test. Further, it can be valuable in validating the new treatment procedures to guarantees the correctness of dose delivery and safety of the patients for brachytherapy treatments.

5. Conclusion

The diode IVD system has been characterized for HDR brachytherapy dose verification. The overall average percentage difference between TPS dose and diode dose was 1.87% ± 2.64 for all measurements, 1.86% ± 2.73 for esophagus, 1.86% ± 2.94 for rectum/vagina and 1.67% ±2.81 for fletcher and 2.07% ± 2.26 for ring applicators, respectively. These results revealed that the dose calculated by TPS and dose measured using diode for the different clinical settings reflected here are in good agreement (~2%) at most of the points of clinical importance. The in-vivo phantom dosimetry study gives both a confidence that the treatment is being delivered as prescribed and enhances the reliability of the HDR brachytherapy treatment.

Conflict of interest

The authors declare that they have no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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