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ORIGINAL ARTICLE

Impact of energy variation on Cone Ratio, PDD_{10}, TMR^{20}_{10} and IMRT doses for flattening filter free (FFF) beam of TomoTherapy Hi-Art™ machines

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Summary

Purpose: *The beam energy (PDD_{10}: Percent depth dose) of a Tomotherapy Hi-Art™ machine was varied in a controlled experiment from -1.64 to +1.66%, while keeping the output at 100% and the effect of this on IMRT output, MU chamber ratio (MUR), cone ratio (CR) and Tissue Maximum Ratio (TMR^{20}_{10}) was studied*

Methods: *In this study, Injector Current Voltage (V_{IC}) and Pulse Forming Network Voltage (V_{PFN}) were changed in steps such that the PDD_{10} was varied from golden beam value incrementally between -1.64 to +1.66%. The effect of this on other energy indicators was studied to verify the sensitivity of TMR^{20}_{10}, MUR, and detector data-based-CR. To quantify the effect of energy variation on Intensity Modulated Radiation Therapy (IMRT) dose, multiple ion-chamber based dose measurements were recorded by irradiating a cylindrical phantom with standard IMRT plans. Dose variation across each commissioned Field width (FW) was tabulated against energy variation.*

Results: *Good agreement between PDD_{10} and TMR^{20}_{10}, MUR, CR was observed. CR was more sensitive to energy change than PDD_{10}. More variation was observed across standard IMRT plan with increasing energy.*

Conclusion: *CR is more sensitive to energy changes compared to PDD_{10}, and CR with MUR can definitely be used as surrogates for checks on a daily/weekly basis. Variation in output across the 6 standard IMRT plans can vary up to 2.8% for a 1.6% increase in energy. Hence, it is of utmost importance to manage the PDD_{10} tightly around ±0.5% in order to regulate standard IMRT QA agreement to within 1% and patient IMRT QA within ±3%.*

Key words: *Cone Ratio, IMRT, PDD, TMR,Tomotherapy*

Introduction

The helical Tomotherapy Hi-ART™ (HT) unit (Accuray Systems, Sunnyvale, CA) is a specifically designed modality for IMRT. Tomotherapy beam is unique due to its flattening free beam, and the absence of Dose Control System (DCS) in older units. The fundamentals of linear accelerator (linac) operation are complex and very dynamic [1]. The modulator converts 3-phase input AC power to DC, which drives transformers and a thyratron-switched Pulse Forming Network (PFN). The prime function is to supply a negative high-voltage pulse to the cathode of the magnetron, while the same pulses are applied to the electron gun. While the thyratron is in non-conductive state, the PFN is charged and then discharged with the firing of the thyratron. The length of the pulse is determined by the properties of PFN, and its voltage is determined by the power supply. The frequency of the charge-hold-discharge cycle is determined by the pulses applied to the thyratron and this is called the Pulse Repetition Frequency (PRF).

A high peak power, mechanically tunable magnetron or klystron is pulsed at a high PRF and current. The magnetron or klystron generates pulsed RF power, which is coupled to the linac

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structure through an RF window, while the electron gun injects a stream of electrons down the beam center-line. In the case of Tomotherapy, the thyratron-based modulator is replaced by a solid state modulator.

Two of the most crucial parameters in tuning of output and energy are with pulse forming network (V_{PFN}) voltage and Injector Current Voltage (V_{IC}). As explained in [2], the V_{PFN} parameter controls the PFN pulse amplitude and the input current to the magnetron . When V_{PFN} is adjusted, the stored energy in PFN changes and thus variations in magnetron output power occur. This ultimately affects the accelerated electron energy, resulting in change in output and energy. The V_{IC} controls the amplitude of the electron gun pulse. When V_{IC} is increased or decreased, the amount of injected electrons entering the linear accelerator increases or decreases respectively. This in turn affects the beam loading characteristics of the accelerating waveguide. Thus, an increase in V_{IC} decreases the energy. Therefore, the beam energy and output will be affected by changes in V_{IC}. Variations in V_{PFN} and V_{IC} can affect the radiation beam output and energy to different degrees. Unlike conventional accelerators, fine tuning of energy is not accomplished by controlling the steering coils.

These two parameters are basic and essential component for beam tuning of the machine. For HT units whether equipped with DCS or not, due to degrading radiofrequency (RF) chain components, physicists in coaction with Field Service Engineers (FSE) have to occasionally tune the V_{IC} along with V_{PFN} to keep the energy and output within ±1%. Hence, understanding RF chain effects, i.e. effect of tuning V_{IC} and V_{PFN} on the output and energy, is of utmost importance for a stable beam production. In the case of Tomotherapy Hi-ART™ units, the Treatment Planning system data is not commissioned by the clinical physicist, but only matched to a golden beam data. Hence, it becomes more crucial for the physicist to understand the above parameters after any repair/tuning to ensure that they are within an acceptable window/limits and that the treatment beam is matched within acceptable limits to golden beam data as accepted at the time of commissioning. After any component replacement such as Magnetron, Gun, Linac, Target or DCS, the Accelerator Output Machine (AOM) parameters are adjusted by FSE to match the beam to the golden beam based on detector data. Although TG 40 [3] provides tolerances for beam quality and output, TG 142 furnished tighter tolerances considering the effects of beam quality and output variability on IMRT delivery.

In accordance with TG-142, the tolerance for beam quality variations is 1% for the Percent Depth Dose (PDD_{10}) or TMR^{20}_{10}. TG 148 [4] specifically provides tolerances and QA methodologies for HT, and as per its guidelines, the radiation beam output and energy, including consistency of cone profile are recommended to be within 2% and 1% as Monthly Quality Assurance Tolerances [4]. Table 2 in TG 148 provides daily QA recommendations, however does not provide tolerances for beam quality. Gutierrez et al. [2] have characterized the dependency of these two parameters on the radiation beam output and energy for a HT unit. They have quantified the impact of variations of both V_{PFN} and V_{IC} values on output and energy.

Several parameters indicate change in energy, namely PDD_{10}, TMR^{20}_{10}, Detector Cone Ratio, ratio of charge readings of the sealed monitor unit (MU) chambers. It is important to understand how these parameters compare with PDD_{10} and how do they vary as a function of energy. These parameters which describe beam quality, are key indicators for quality assurance of any linear accelerator and finally its effect on deviations in IMRT treatment delivery would be the primary goal of physicists. In this study, we varied the V_{PFN} and V_{IC} in a controlled manner to vary energy in increments of approximately 0.5% between -1.64 to +1.66%, while maintaining constant output. Since, both parameters affect the energy and output, this was achieved by varying V_{IC} gradually, till the desired beam quality was reached , and then V_{PFN} was fine-tuned to achieve the required output which affected the beam quality minimally. Since V_{PFN} also affects energy, V_{IC} was further retuned if necessary to achieve the desired beam quality. The change in the above mentioned energy indicators were compared to changes in PDD_{10}. Changes in IMRT dose output of standard IMRT Plans as a function of energy were also studied.

Methods

Tomotherapy Hi-Art™ unit and procedure to acquire Detector Cone Ratio and MU Chamber Ratio

The Tomotherapy Hi-Art™ Radiation Delivery Subsystem (RDS) includes a ring gantry-mounted short linear accelerator which generates X-rays that are collimated into a fan beam using a binary Multi-Leaf Collimator (MLC) to modulate the intensity along a rotational delivery. The RDS software components are responsible for reading, translating, and transferring data throughout the delivery subsystem. Its major components are the Data Acquisition System (DAS), the Data Receiver Server (DRS), the On-Board Computer (OBC), and the Stationary Computer (STC). The detector used in the HT system is an arc-shaped CT detector array [5]. The detector array consists of 738 cells filled with xenon with a 0.73 mm width at isocenter, and each cell is comprised of two gas cavities that are divided by thin tungsten septal plates 2.54 cm long beam direction. The entire detector file covers a wide range of data are separated. The MVCT detector channels´ readout is correlated with the lateral profile.

In this study, we varied the parameters V_{PFN} and V_{IC} to incrementally change the energy while the following parameters were calculated:

1. Cone Ratio (CR): CR is an average of the ratio of each detector in current cone profile with the reference cone profile. The irradiation sequence introduced to acquire CR is a rotational treatment with a gantry speed of 20 sec, all leafs open, the jaws set to 5 cm, and the couch out of the bore. This "rotational variation" procedure is delivered to create a detector file that is then compared against the gold standard detector file previously approved against ionization chamber measurements. Only the detectors mentioned in the center (70 to 570) are taken into account for calculating CR

$$CR = 1\frac{1}{500}\sum_{j=70}^{570} \mathrm{CR}j \qquad (1)$$

2. MU Chamber Ratio (MUR): Two parallel-plate sealed ion chambers are located upstream of the y-jaw and their purpose is to monitor the dose rate to be within a specified window in Tomotherapy systems not equipped with DCS. MUR was computed as

$$\mathrm{MUR} = \mathrm{MU1}/\mathrm{MU2} \qquad (2)$$

Where MU1 and MU2 are readings from the Monitor chamber 1 and 2 respectively.

3. PDD_{10} or TMR_{10}^{20}: For measuring PDD_{10} and TMR_{10}^{20}, ion chamber readings were measured in solid water phantom using a static beam with gantry positioned at 0 degrees with a FW of 5 x 40cm for a 120 sec procedures.

4. IMRT Dosimetric Verification: Because of the special design of the machine, the rotational isocenter (where the static measurement is performed) is not necessarily located in the center of the tumor, as is the case on a conventional machine. This implies that the dose in a given point is again a combination of output, cone shape, and MLC modulation. Standard IMRT plans were designed to treat two targets (T1 and T2) as shown in Figure 1, T1 centrally located in the phantom and T2 located 5 cm laterally to the left side of the phantom.

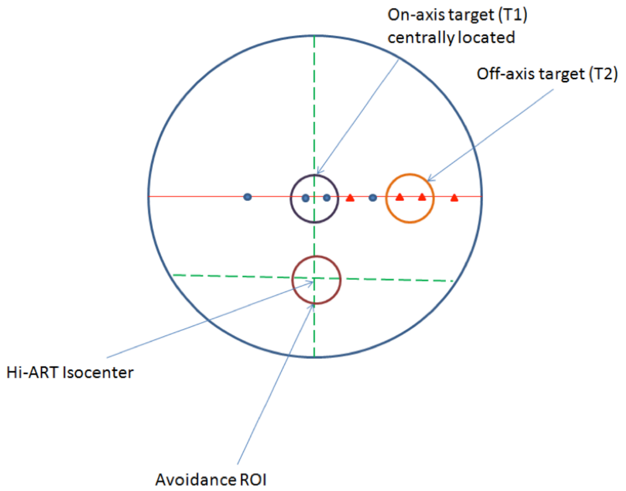

Figure 1. Schematic showing the on-axis and off-axis targets on a cylindrical solid-water phantom. Placement of ion chambers for point dose measurements for on-axis vs. off-axis target delivery is shown in blue circles and red triangles, respectively.

Target T1, the centrally located target, is on-axis in the LR and AP direction while T2 is off-axis both in the LR and AP direction. On and off axis is to indicate the location of the targets with respect to the axes of the machine i.e., axis through the machine isocenter. Plans targeting T1 and T2 are interchangeably referred to as on-axis vs off-axis plans in this study. Optimized plans were generated to deliver 2 Gy/fraction uniformly to T1 and T2 cylindrical targets for each commissioned field width (1 cm, 2.5 cm and 5 cm FW) width. A normal dose calculation grid (4 mm x 4 mm x 4 mm) was used for the dose calculation. Odd-numbered plan (Plan 1, Plan 3, Plan 5) were planned to cover the target volume T1 as indicated in Figure 1 for FW 5 cm, 2.5 cm and 1 cm respectively. Even numbered plans (Plan 2, Plan 4 and Plan 6) were planned to provide uniform dose to the off-axis target, T2. These generic IMRT plans were created and delivered on a cylindrical phantom (GAMMEX-RMI, Middleton, US). The contribution to the dose delivered to the on-axis target volume is mainly by a combination of the center and lateral part of the cone profile, with minor leaf modulation. The dose to target volume T2, located off-axis in the AP and LR direction is composed of dose contribution by different regions of the cone profile representing a combined effect of output and cone shape.

Multiple point dose measurements were made along the central horizontal plane passing through the targets using A1SL ion chambers for plans 1 through 6 with two points located within the respective targets.

In Figure 1, the blue circles and red triangles represent the dose points used for point-dose measurement for on-axis and off-axis plans respectively. Percentage dose difference between measured and expected dose at points where the ion chambers are located within the target was calculated for plans 1 through 6. To quanti-

Table 1. Tabulated are V_{IC} and V_{PFN} used for setting the desired beam quality along with beam-quality indicators

	Increasing Energy			*Base line*	*Decreasing Energy*		
	1	*2*	*3*	*4*	*5*	*6*	*7*
V_{IC}	4.430	4.550	4.670	4.900	5.180	5.460	5.740
V_{PFN}	3.940	3.840	3.760	3.670	3.630	3.630	3.650
Cone Ratio	96.3	97.4	98.4	100.0	101.6	103.1	104.4
Rdg from MU Chamber 1	873.7	883.9	892.4	900.0	925.8	942.9	951.8
Rdg from MU Chamber 2	885.2	891.3	897.6	900.0	919.7	931.7	936.5
MU Ratio	0.987	0.992	0.994	1.000	1.007	1.012	1.016
PDD_{10}	0.620	0.617	0.613	0.610	0.606	0.603	0.600
	0.535	0.532	0.529	0.522	0.521	0.518	0.515
On-axis/Off-axis output for 2.5 cm FW	1.014	1.004	1.001	1.000	0.998	0.991	0.990
On-axis/Off-axis output for 1.0 cm FW	1.012	1.014	1.009	1.000	0.995	0.988	0.987
DV_{Max} across 6 plans	1.028	1.018	1.012	1.001	1.005	0.994	0.991

fy the variation in measured dose discrepancy between on-axis and off-axis delivery, two dose variation quantities were defined as

a. Dose Variation for on-axis vs off-axis plans (DV_{12}): The ratio of average percent dose difference (absolute) for on-axis plans vs average percent dose difference for off-axis plans (absolute) for each field width was calculated.

b. Maximum Dose Variation (DV_{Max}): Max (Percent Dose Difference of all plans) – Min (Percent Dose Difference of all plans).

In this study, we defined PDD_{10} as the gold standard indicator for energy. V_{PFN} and V_{IC} were modified in a controlled manner to maintain the output while modifying the energy incrementally between -1.64 to +1.66% .The change in PDD_{10} was compared to TMR_{10}^{20}, CR, MUR, DV_{12} and DV_{Max} were also plotted as a function of PDD_{10}.

Results

The Tomotherapy system baseline was based on the original commissioned parameters settings. The baseline V_{PFN} and V_{IC} values were 3.67 volts, and 4.9 volts, respectively. This produced a dose rate of 900 MU/min for a 120 sec static beam. This is also the output measured at isocenter and depth of d_{max}. V_{PFN} values ranging from 3.63 V to 3.94 V and V_{IC} ranging from 4.43 V to 5.74 V was used to incrementally change the PDD_{10} from -1.64 to +1.66% while maintaining the output constant within 0.2%.

Table 1 lists all the parameters measured for each of the settings, numbered 1 through 7. Columns are arranged in the order of decreasing energy from left to right. Baseline or nominal values corresponding to the state at which the machine is clinically operated, are presented in Column 4. The respective V_{IC} and V_{PFN} values and the corresponding CR as described in equation 1 are presented in rows 1 through 3 for the seven settings shown.

Dose readings from MU Chamber 1 and MU Chamber 2 and MUR, as defined in equation 2 are shown in rows 4 through 6, respectively. PDD_{10} and TMR_{10}^{20} values are displayed for the seven settings in rows 7 and 8, respectively. DV_{12} for field width 1 cm and field width 2.5 cm are shown in rows 9 and 10 for the seven settings which is almost linearly proportional to change in PDD_{10}. This indicates that the on-axis plans are about 1% lower or higher than the off-axis plans. Finally, DV_{Max} across all 6 plans for the seven settings is shown in row 11. DV_{Max} which indicates maximum dose difference across all 6 plans (3 field widths and across on-axis and off-axis plans) can vary up to 2.8% with 1.64% change in PDD_{10}

Figure 2 (a) shows a plot of PDD_{10} against both V_{IC} and V_{PFN} to show the reader the dependence of PDD_{10} on V_{IC} and V_{PFN} while maintaining the output constant. Variation of PDD_{10} as a function of V_{IC} is shown in Figure 2(b) and shows a linear dependence with correlation coefficient of 0.97.

Figure 3 (a) through (c) shows the relation of CR, MU Chamber ratio and TMR_{10}^{20} against PDD_{10} and a linear relationship between each of the above parameters with correlation coefficient of 0.98, 0.99, and 0.97 was observed.

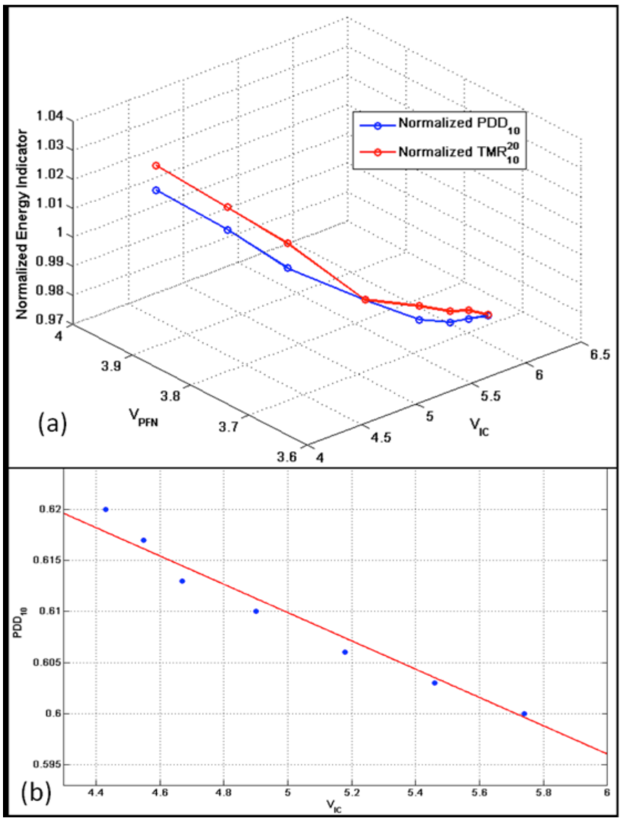

Figure 2. (a) shows plot of PDD_{10} against both V_{IC} and V_{PFN}; **(b)** shows PDD_{10} plotted against V_{IC}.

Conclusion

Plots of variation of the studied parameters on Helical Tomotherapy machine (SN 46) were plotted against PDD_{10} variation. All quantities were normalized to the base measurement at PDD_{10}=0.61. From the results, it can be deduced that CR is the most sensitive parameter to energy changes and thus it is advisable to maintain this quantity within ±1%. TMR_{10}^{20} is more sensitive to increasing energy than decreasing energy. MUR can be a quick and easy way to assess changes in cone profile during patient treatments to assess any sudden changes such as pitted or stuck target.

IMRT delivery is a function of MLC modulation coupled with lateral cone profile, and any discrepancy could be a result of one or more of the following: change in energy (Lateral Profile), MLC leaf parameters, spot size, and output. Thus, for commissioning and annual dosimetric validation, standard IMRT plans are designed to treat on-axis and off-axis cylindrical targets for each commissioned field size. Discrepancy in expected values in these standard IMRT plans provides an insight into any degradation or changes in beamline components. Thus, understanding the effect of change in energy in the standard IMRT plans is essential. Ratio of on-axis dose difference with off-axis dose

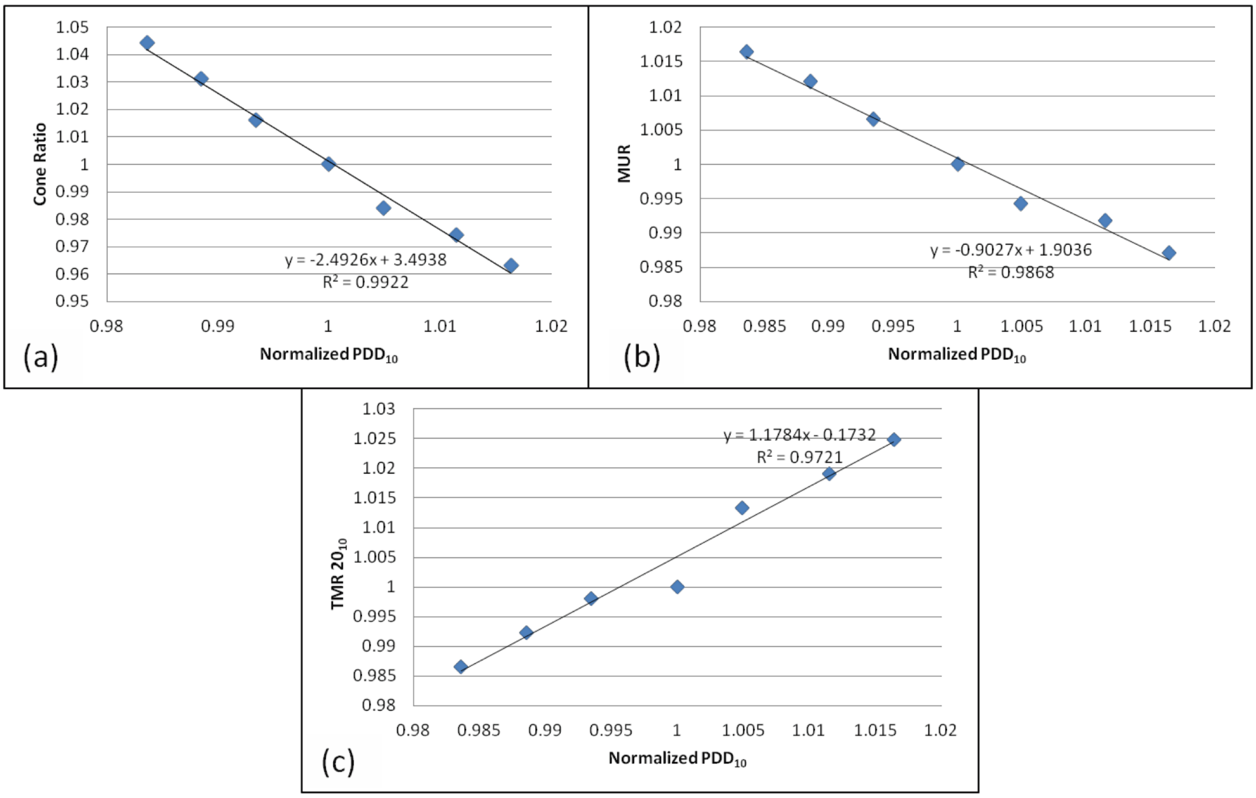

Figure 3. (a) (b) and **(c)** show plots of CR, MUR and TMR_{10}^{20} plotted against PDD_{10}, respectively.

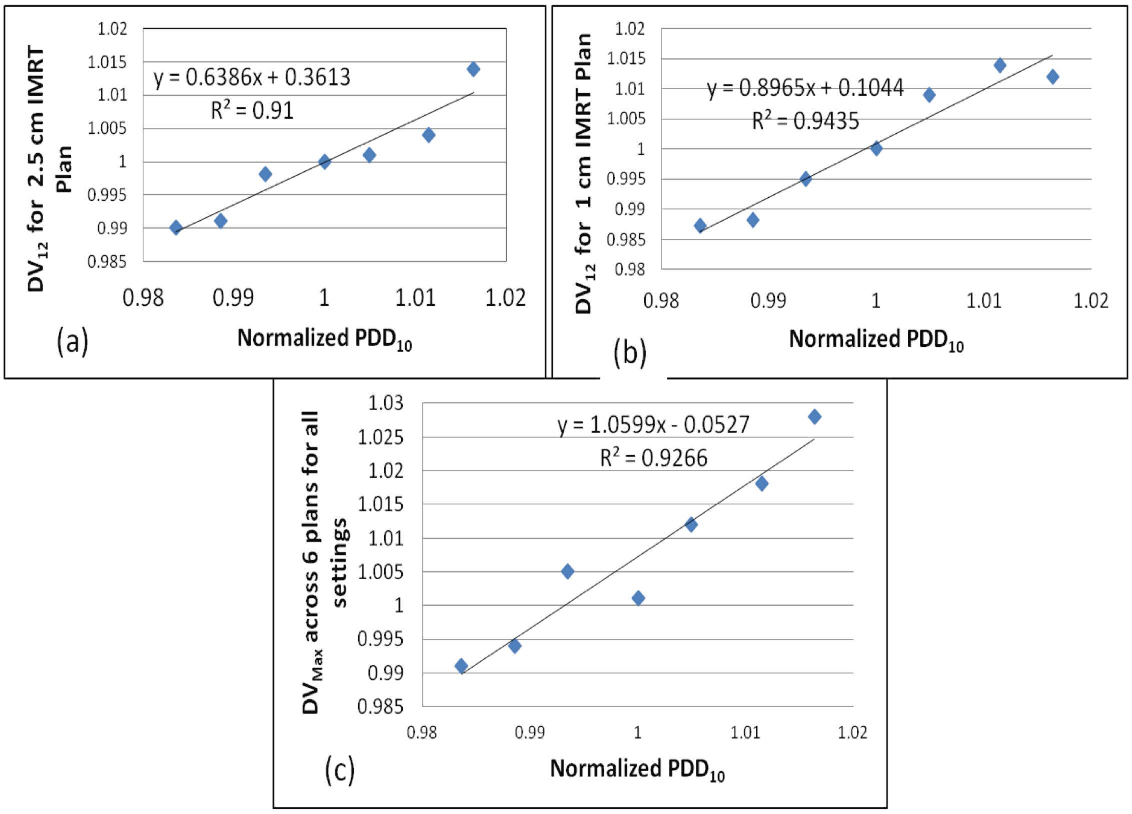

Figure 4. (a) and **(b)** show plot of Dose Variation for on-axis vs off-axis plans (DV_{12}) for IMRT plans delivered with FW 1 cm and 2.5 cm plotted against PDD_{10}, respectively; **(c)** shows the maximum variation across all plans plotted against PDD_{10}.

difference is a function of energy, as seen in Figures 4 (a) and 4 (b). We observed that the max variation across the 6 plans correlates strongly with energy change and up to 2.8% dose variation can be observed with 1.64% increase in energy. Hence, it is of utmost importance to manage the PDD_{10} tightly around ±0.5%. This allows physicists to tune the output of the machine better, such that all standard IMRT plans agree well with each other and with the gold standard within 1%. It was also observed that the standard IMRT variations were differentially sensitive with positive vs negative energy drifts but this cannot be generalized across all IMRT plans. The observation is specific to the plan under consideration. The dependence of IMRT QA output can be different in different cases for varying energy causing large or small variations across Delivery QA patient plans. More studies with spot size variation and longitudinal profiles will have to be conducted for better understanding of this variation.

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