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Verification of IMRT and RapidArc Localized Prostate Cancer Treatment Plans Using EPID and Delta4 in vivo Dosimetry Methods

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Abstract

Background: Quality assurance for intensity modulated radiation therapy (IMRT) depends on the type of dosimetry system and its evaluation procedure. We can check both the intensity and distribution of each field as the required pretreatment verification with dosimetry systems.

Method: Treatment verification for different plans (IMRT and RapidArc) applied on localized prostate cancer patients was done with electronic portal imager device (EPID), Delta^4). The EPID used was Varian aS1000 mounted on Varian (TrueBeam) Linac with gamma criteria set to ΔD=3% and Δd=3mm. RapidArc plans were designed by arcs (179.0o CCW to 181.0o and 181.0o CW to 179.0o) under the same gamma criteria of (ΔD=3%, DTA=3mm and Δ-index ≤1), while the threshold dose was 20%.

Results: Evaluation analysis is passed for IMRT prostate plans with the area gamma <1.0 which equaled 99.1% (99.1% of the pixels had gamma<1) within a tolerance of 95.0%, area gamma >0.8 (was equal to 2.1%) / area gamma >1.2 (was equal to 0.3%) and the average dose difference was 0.42CU. Delta^4 dosimetry system was assessed with RapidArc plan; the agreement between the measured and planned doses was ±1% and gamma analysis resulted in 100% data points with the same agreement conditions.

Conclusion: Portal dosimetry provided a good verification of the treatment unit ability to deliver doses according to plan. For an IMRT field comprised of several subfields, it could give rise to much more errors. RapidArc plans were verified using Delta^4 system, which generated excellent dosimetry results. Periodic calibration was recommended for Delta^4 dosimetry system; radiation damage affected sensitivity by >1% every 1kGy.

Keywords: Radiotherapy, Intensity-modulated, RapidArc, Radiometry, EPID, Delta^4

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Introduction

Intensity modulated radiation therapy (IMRT) radiation doses are more effective than 3-DCRT and conventional radiotherapy; it can be safely delivered with very few side-effects in the planning target volumes (PTV) because the ratio between normal tissue dose and tumor dose is reduced. However, IMRT requires long treatment times, additional efforts for planning, safety checks, and quality control prior to the start.[1] In other words, IMRT and RapidArc plans have to be verified before treatment using both electronic portal imager device (EPID) and Delta4 systems.[2] IMRT helps increase tumor doses and decrease the delivered dose to normal organs or tissues.

The calibration and configuration are also easy procedures that are not time-consuming; measurement of output factors is the step that takes time (a couple of hours). Radical radiation therapy is widely used for localized prostate curative treatment, providing a reduction in rectal toxicity.[3] IMRT is the most suitable for the treatment of lung, kidney, spine, prostate, liver, head and neck, and pancreas cancers. For some brain cases; IMRT is a solution when gamma knife is not available. IMRT dosimetric verification has to be done before the start of treatment to quantify the detected errors in the treatment.[4]

IMRT QA depends on the type of dosimetry system and its evaluation procedure.[5,6] The portal dose prediction is used for pre- or post-treatment verification to check both IMRT doses (intensity and distribution) in each field. We can check both the intensity and distribution of each field as the required pre-treatment verification with dosimetry systems, such as EPID, Delta4, 2D array, ArcCHECK, QUICKCHECK, and films that can be used for plan verification.[7,8] RapidArc delivers dose distributions similar to other IMRT techniques or higher.

We observe the area of irradiation using portal image obtained from fields (set-up or treatment) by use of a robotic portal imager employed in treatment verification and obtained from the megavolt irradiation.[9] The main use of portal images is to verify patient set-up; in this regard, the patient EPID images are matched with anterior and lateral digitally-reconstructed radiograph reference images for position verification of the patient.[10] Matched images verify the patient's bony landmarks, specifying the position of the organ. It is not sure that patient is stable in the same position relative to the bone landmarks. Different ways of verification using information from portal dose include the comparison of the acquired image and the measured dose image from the portal or the back projection of information from transmitted dose to calculate patient's dose compared with the dose distribution of the treatment plan.[11] Just before the treatment of patients; the MLC positioning errors are reduced using the above methods, the movement errors are reduced, LINAC dosimetry is done, and performance (mechanical) check is done for providing the highest plan accuracy level.[12]

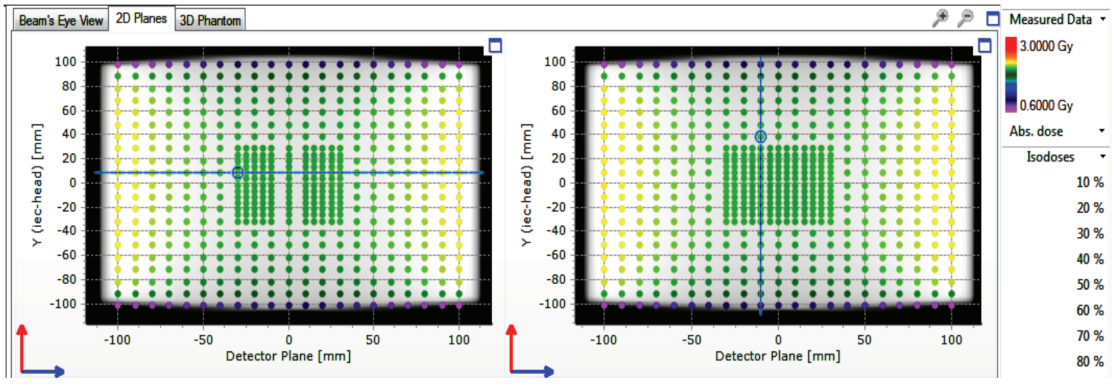


Figure1. This figure shows the planned and measured dose distributions of the four fields plan for the main and the wing detector boards.
* millimeter (mm), two dimensional (2D), three dimensional (3D)

Table 1. The evaluation data collected for different IMRT prostate fields in plans that passed the gamma evaluation under the gamma criteria of 3.0% and 3mm

Gamma criteria	Value				
	Field 1	Field 2	Field 3	Field 4	Field 5
Area gamma <1.0	99.1%	99.8%	99.7%	99.6%	98.0%
Maximum gamma	4.02	1.37	2.34	2.27	4.81
Average gamma	0.29	0.24	0.27	0.26	0.32
Maximum dose difference	0.09 CU	0.06 CU	0.05 CU	0.09 CU	0.10 CU
Average dose difference	0.01 CU	0.01 CU	0.01 CU	0.01 CU	0.01 CU

* Calibration unit (CU); IMRT: Intensity-modulated radiation therapy

Delta^4 (ScaniDos AB, Uppsala, Sweden) is the first quasi-3D dosimeter array with a diameter of 22cm cylindrical phantom made of poly methyl methacrylate (PMMA) divided into four sections with three removable detector boards created as X-shape in the axial direction. Diode sensitivity varies from one diode to another (approximately 5 nC/Gy).[13,14] In the main board, diodes are arranged in a rectangular plane (20×20cm^2) but the two wings are 20×10cm^2 planes. Diodes are spaced by 1cm; but they are spaced by 0.5cm in the central region (6×6cm^2). Gantry angle can be sensed independently using the inclinometer which attaches it to the gantry or the LINAC head. This allows us to identify the dynamic arc control point as the dose measurement point correcting for gantry angle for application.

To avoid errors in the treatment plan verification, the plan has to be calculated once again on the computed tomography (CT) scan of the phantom. Firstly, we calculate the dose at a reference location of detector using treatment planning system (TPS) with the same measurement geometries, a step called calibration. This LINAC output is scaled and inserted into the software to be the reference measured dose. Taking raw readings and applying correction factors produce the measured dose.[15] Also; we collect the specific sensitivity of diode across boards and apply correction factors corresponding to various sensitivities. There is also a directional dependence have to be corrected; for the beam angle and the position of diode along longitudinal axis.

Materials and Methods

Patients and verification of IMRT and RapidArc plans

Plan verification was done for the same plan on 20 cases (for RaidArc plan) using Delta^4 dosimetry system and three plans on 20 cases (for IMRT plans) using EPID dosimetry system.

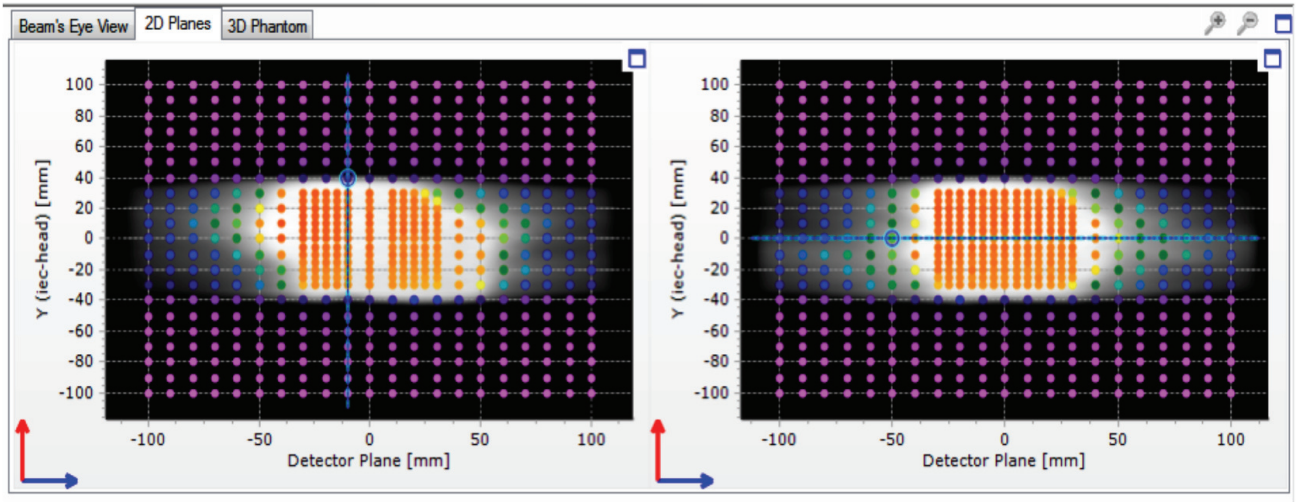


Figure 2. This figure shows one of the outputs of the RapidArc plans (prostate cases) obtained from the Delta^4 phantom showing the dose maps in the two planes.

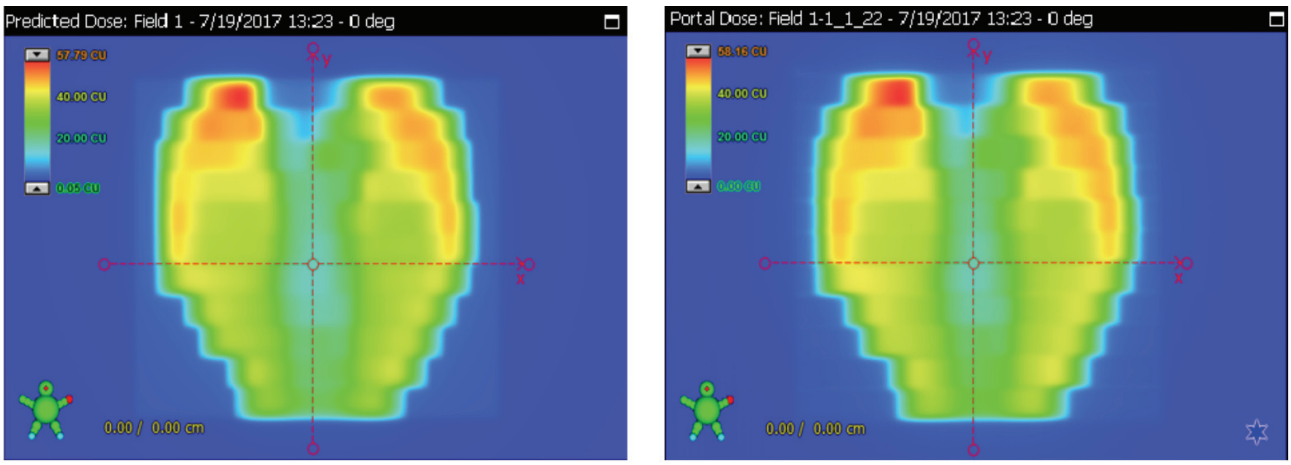
RapidArc plan was designed with two arcs (179.0º CCW to 181.0º and 181.0º CW to 179.0º) with 10 mega volt energy. The first IMRT plan (six fields' technique) was arranged by angles of (0º, 45º, 90º, 180º, 270º, and 315º) with eight segments per beam (the total number of beamlets is 48 beam openings). The first IMRT plan was with collimator angle of 0º, maximum MU/Fr of 90 MU, and minimum segment area of 1 cm^2. The second IMRT plan was the seven fields technique which was arranged by angles of (0º, 50º, 90º, 130º, 230º, 270º, and 310º) with six segments per beam (the total number of beam lets is 42 openings). The third IMRT plan was another seven field's technique arranged by 0º, 51º, 103º, 155º, 206º, 257º, and 308º with five segments per beam (the total number of beam lets is 35 openings). The third IMRT plan was with collimator angle of 90º, maximum MU/Fr of 60 MU, and minimum segment area of 1 cm^2.

We included prostate patients (20 patients with prostate volumes ranging from 23cc to 76cc) with intermediate risk group cancer prostate; these are patients with clinical stage T2b to T2c, Gleason score of 7, or a PSA value of 10ng/ml to 20 ng/ml. CT simulation was performed for all patients under the same protocol (positioned in the supine position) with 3 mm slice thickness. Immobilization was carried out by the knee support. All patients (20 patients) were immobilized (with full bladder comfortably and empty rectum) before every treatment secession as done first before CT scan and set-up. The clinical target volume included the whole prostate gland situated closer to the center of the seminal vesicles by 1cm. We created PTV by extending the clinical target volume by 1cm in all directions except the posterior (only 6mm) to reduce the dose to the rectum. Organs at risk (bladder, rectum, and both left and right femoral heads) were outlined. The prescribed dose was (74 Gy/7.5 weeks/ 37 fractions) with a dose per fraction of 2cGy.

Portal dosimetry system set-up

The EPID used in our work was zx Varian aS1000 mounted by a retractable robotic arm on a Varian (TrueBeam) linear accelerator. It allowed for vertical movement from isocenter 2.5 cm above and 82 cm below, lateral movement of ±16 cm and longitudinal movement up to +24 cm and -20 cm in the other direction. The imager active matrix or sensitive matrix was 30 cm × 40 cm with 768 × 1024 pixels (pixel size of 0.39 mm × 0.39 mm). The EPID was mounted on a robotic arm which had a steel bar with 20 mm width. IMRT portal dosimetry verification is a complicated process including portal dose image prediction (PDIP) software, portal dose image calculation (PDIC), and amorphous silicon portal imager (aS1000).

Eclipse, which generates IMRT treatment plans (sliding window, step and shoot or dynamic arcs),



(A) **(B)**

Figure 3. These images are from field 1; (a) predicted dose image and (b)portal measured dose image.
* Degree (deg), calibration unit (CU), centimeter (cm)

calculates the deposited doses in the imager's receptor for any defined location and splits arcs into several sub-arcs for RapidArc QA. The resulting predicted dose images are compared with the actual measured dose images from the Portal Vision imaging system. IMRT treatment plan is delivered directly to the EPID cassette after the cassette is moved to its position for acquiring the integrated images resulting from beam delivery. This 2D information is high resolution and sufficient for the characterization of the dose gradients of IMRT fields; these integrated images are converted into dose matrix for analysis.

This system enables point dose measure, line profiles, and image histograms; it also calculates dose differences with gamma assessment pass or fail criteria, providing image comparison that can detect small variations. Different step and shoot IMRT plans (six and seven beams) with a defined number of beamlets per field; results in dose distributions with high conformity. The portal dosimetry ARIA system evaluates the measured and predicted images and checks for any agreement. PDIP is not a TPS algorithm. Detectors in portal imager are at the same depths, 2D algorithm is used. After the imager of output factors is measured, PDIP algorithm is inserted in the eclipse configuration. Portal imaging and dosimetry have to be checked after portal dosimetry configuration, requiring calibration for the quality of IMRT-acquired images. Varian expresses (Gy) units as calibrated units (CU) in PDIP software.

Dose evaluation options had to be defined firstly because the gamma criteria were the same in all gamma evaluation methods and set to ΔD = 3% Δd = 3 mm. Also, we used gamma analysis tests for area gamma <1.0; it is more than certain percentage (likely 97%) with the maximum gamma and the average gamma. We defined dose difference tests as maximum dose differences (expressed in CUs) and average dose differences as well. We defined all parameters of plans (gantry and collimator angles, the same shaping of the dynamic multileaf collimator, energy, field sizes, dose rates, and MU).

Plans were diametrically assessed to confirm whether all measured and predicted images were in line. We had to set the same sequence of dynamic MLC, jaw, energy, MU, and dose rate as the original field was set before; however, we can choose suitable gantry and collimator angles and parameters with no effect on dosimetry. Three-

* Degree (deg), calibration unit (CU), centimeter (cm)

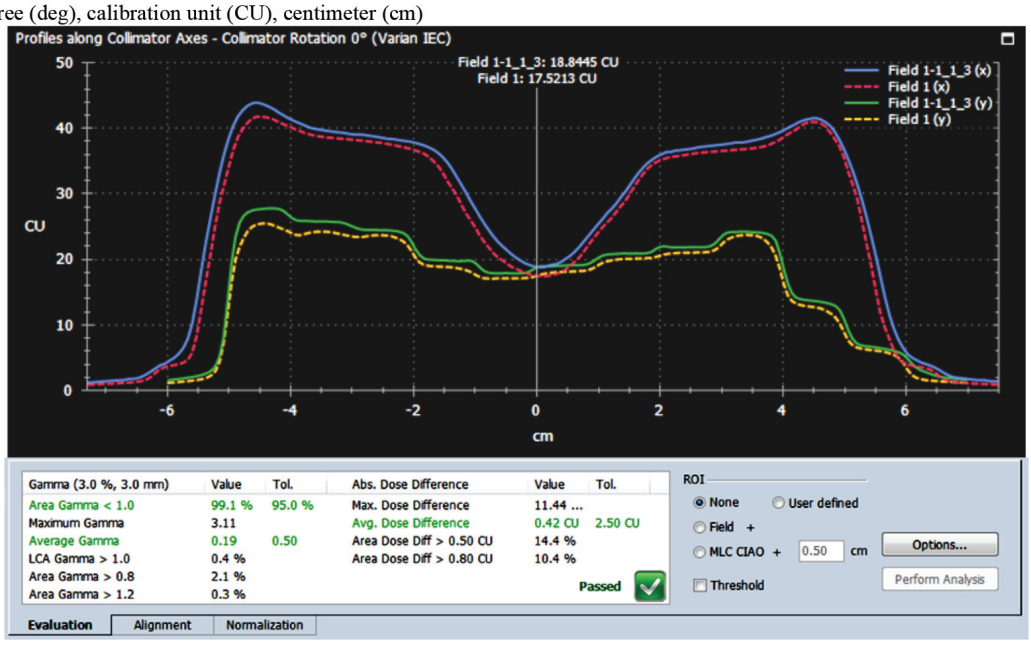


Figure4. This figure shows the profiles along collimator axes and its evaluation tab.
* Degree (deg), calibration unit (CU), centimeter (cm), Average (Avg), multiyear collimator (MLC)

dimensional portal dose measurement system (3D-PDM) accompanied with kilo-voltage cone beam CT (kV-CBCT) is QA precious tool that can be used to detect the changes in anatomy and the consequences during dosimetry treatment. The EPID was set to SDD =110 cm with a dose rate of 300 MU/min. A five field technique (eclipse) was arranged at 0º, 45º, 90º, 270º, and 315º angles; all open fields without wedges and with 15 mega volt energy were evaluated using portal dosimetry and PDIP algorithm under gamma criteria set to ΔD = 3% and Δd = 3mm. Every field was measured at gantry 0°. Of note, if one test fails, the overall result becomes invalid.

IMRT plans had to be verified on the phantom first. TPS optimized IMRT plans and dose distributions were calculated based on the patients' CT scan. Following IMRT optimization, every field was transferred to a reference homogeneous designed phantom with SSD = 95 cm. The created phantom had a size of 30 × 30 × 30 cm3. Dose distributions were measured at a depth of 5cm and in the field axis (isocenter), resulting in 2D calculated dose distribution through the isocenter with 1mm resolution without corrections for inhomogeneity. A 3D dose calculation on patient CT was performed with 3D gamma evaluation.

Delta^4 dosimetry system set-up

The Delta^4 phantom (of density 1.19g.cm-3) was SAD set-up with the center aligned to treatment isocenter of the LINAC; this alignment was done using laser lines at isocenter. To ensure accurate measurement, all features and limitations of Delta^4 dosimetry system had to be fathomed before use in the verification of RapidArc plans as it was response calibrated; we also checked for linearity and corrected directional response, at various temperatures; a four-field (box) plan was verified first as seen in figure 1; the plan was arranged with gantry angles of (0º, 90º, 180º, and 270º). We used gamma method with criteria, such as dose difference (ΔD=3%) and distance to agreement (DTA=3mm), 20% threshold dose, and a gamma index of ≤1 (percentage of points as a pass rate); they all passed. Afterwards, we checked the RapidArc plans designed by the two arcs (179.0º CCW to 181.0o º and 181.0º CW to 179.0º) under the same gamma criteria of (ΔD=3%, DTA=3mm and γ-index ≤1), while the threshold dose was 20%. Figure 2 depicts one of outputs of the RapidArc plans (prostate cases) obtained from the Delta^4 phantom detectors (2D plane and 3D plane).

Delta^4 software is used to compare dose volume histograms with comparisons provided by gamma analysis; it is done using a volumetric interpolation inside the phantom, which validates the 3D dose reconstruction on the phantom. 3D dose calculation using Delta^4 is dependent on the source of the available planned data and calculated by TPS or from PDD data. For arc plans, PDD data can be used to calculate 3D dose if the control point data is missed since depth dose distributions have to be inserted into Delta^4 software. PDD is

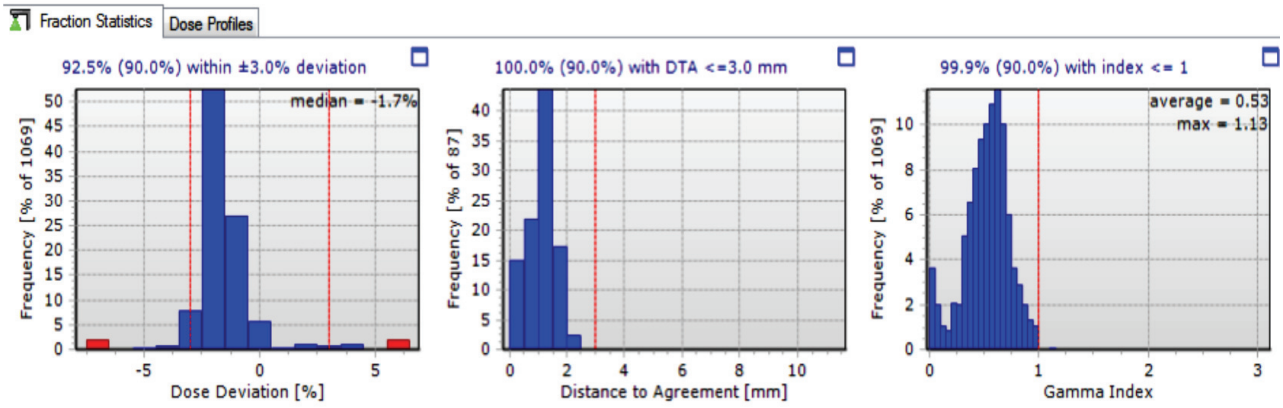


Figure 5. The verification and test plan (four fields) fraction statistics in the histogram shown for all fields; this figure shows the percentage of dose deviation, distance to agreement (DTA), and γ-index.

normalized to measured dose, for every control point and for every detector position. 3D dose for that control point comprises renormalized depth doses for all detector positions. For all control point, this step is repeated and doses were summed and then compared to planned dose using gamma analysis method. We transferred the regions of interest (ROI) to the phantom from patients; so, the passing rates of gamma analysis can be defined using ROI. 3D dose verification is done for RapidArc plans by use of Delta^4 phantom commissioned to be ready for clinical use. We used the global gamma analysis which involved the data relative to the whole plan dose used clinically, while local gamma analysis was more accurate (point-to-point agreement).

Results

IMRT plans verification with EPID

For all selected 20 prostate cases, IMRT plans were verified using EPID practical radiation dosimetry system. First of all, we found that dose distributions were not contentious but sampled as image pixels (discrete matrix); the pixel size had to be ≤0.33 of Δd as the calculated value could be lower or higher than the reference point which would reject many points; so, the pixel size should be much smaller than the DTA defined for the acceptance criteria. We were able to overcome this problem by interpolating our dose distribution and the calculation was stopped at certain points as soon as the criteria of area gamma <1.0 were found with the decrease in the calculation time. From the different layout screens of the evaluation software, we observed every field images for both the predicted dose on the left and the measured dose on the right (Figure 3).

We used both methods of gamma evaluation (DTA for high gradient region and the dose difference method in the low gradient region) to compare the two predicted and measured images at DTA=3 mm and 3% dose difference; evaluation of the images will pass the evaluation, if only they fulfill any of both gamma evaluation criteria. From software view, we detected the profiles along collimator axes expressing the evaluation data which was clear in the evaluation tab below showing area gamma criteria, maximum area, and dose difference average and maximum; all these criteria are conducive to accurate evaluation before treatment (Figure 4).

Same as before, we set the EPID for the Eclipse six-field technique IMRT plan for prostate cases with dynamic MLC arranged at 0º, 45º, 150º, 200º, 260º, and 310º under the same defined gamma criteria set to ΔD = 3% and Δd = 3mm. EPID can also be used for studying MLC errors. The gamma index method could be used for QA in a combination of different detectors or dosimetry systems.

Also, table 1 expresses the evaluation data for different IMRT prostate plan fields that passed gamma evaluation under the gamma criteria of 3.0% and 3 mm as an example.

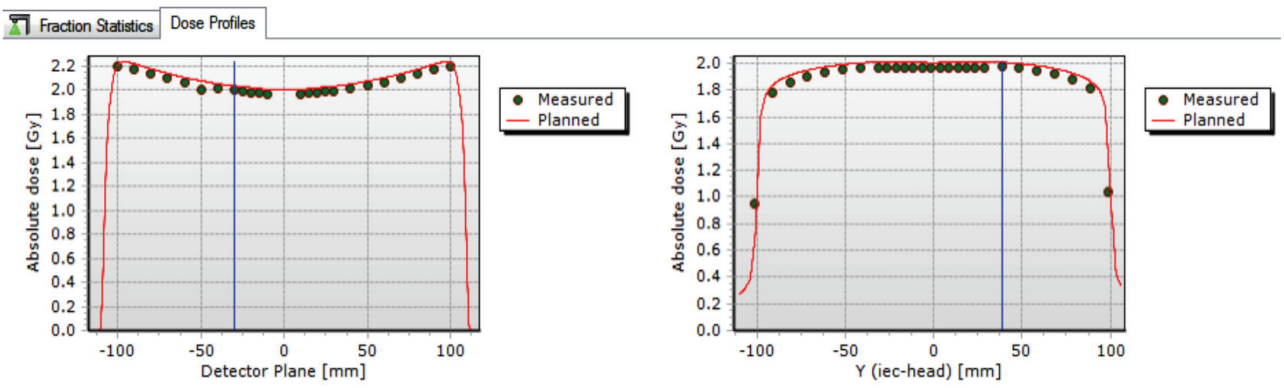


Figure 6. This figure shows the four-field plan dose profiles of both measured and planned doses for a typical verification and test plan.
*Distance to agreement (DTA), millimeter (mm), gray (Gy)

RapidArc plans verification with Delta^4

For all selected 20 prostate cases, RapidArc plans could be checked by EPID; but we verified these plans using Delta^4 practical radiation dosimetry system. First; we used the four-field (box) plan to test and verification before applying the RapidArc plans on patients. Gamma method is used with criteria of dose difference (ΔD=3%) and distance to agreement (DTA=3mm), 20% threshold dose and the gamma index is ≤1 (percentage of points passed as a pass rate). From the fraction statistics (for the four fields), we can see that dose deviation percentage is 92.5% within ±3.0% deviation, while the median dose percentage is = -1.7%; the distance to agreement (DTA) is 100.0% with DTA ≤ 3.0 mm, and the gamma index is 99.9% with γ-index ≤1; meanwhile, the average γ-index is = 0.53% and the maximum γ-index is = 1.13% as observed in figure 5. Data from the same measurement was compared to plan data per fraction, beam, and segment (MLC comparison due to non-available data from TPS) in the two measuring planes. Similarly, the data were calculated from the measuring planes to be shown for the complete volume per fraction and per beam; they were then compared with TPS data. Dose volume histogram was compared with the TPS data in terms of the semi-measured data for the patient structures applied to the phantom to evaluate the significance of any deviation. Dose profiles showed that both the measured and planned doses matched (Figure 6).

After we verified the four-field (box) plan and tested the Delta^4 system, we checked the set-up correction and output accuracy of the used Delta^4 phantom. We checked twenty RapidArc plans under the same previous gamma criteria of (ΔD=3%, DTA=3mm and γ-index≤1), while the threshold dose was 20%. The plan passed the test of gamma value by more than 90% (90% of the Delta^4 measured points in all positions passed the gamma); furthermore, we put dose threshold to avoid tests in the undesired region of low dose. From the fraction statistics (for the RapidArc plans), we can see that dose deviation percentage is 98.5% within ± 3.0% deviation, whereas the median dose is 1.1%, DTA is 100% with DTA ≤ 3.0 mm, and the gamma index is 100% (100% of the measured points) with γ-index ≤1; on the other hand, the average γ-index is = 0.29% and the maximum γ-index is = 0.99%, as seen from figure 7 for one sample case (from 20 cases). Dose profiles indicated that both the measured and planned doses matched (Figure 8). The evaluation of all the 20 dose distributions had a gamma passing rate of > 88% and 16 of these evaluations exceeded 100% for gamma. One of these evaluations is shown in figure 8 with a maximum γ-index of 0.99%; only one of the evaluations had a gamma passing rate below 92%. This means that all of the investigated dose distributions passed the gamma assessment according to the ICRU report 83 recommendations with the use of the Delta^4 dosimetry system.

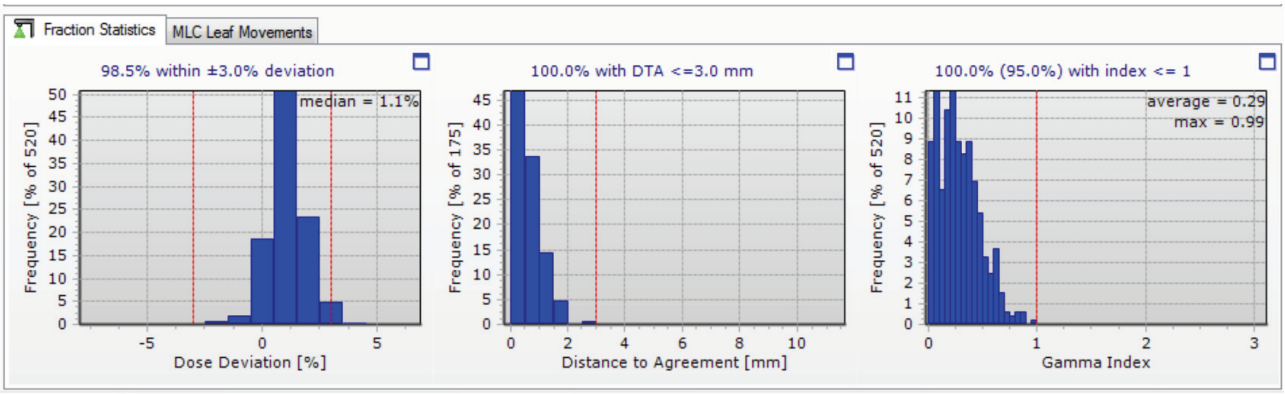


Figure 7. RapidArc plan verification and fraction statistics in the histogram shown for all fields; this figure shows the percentage of dose deviation, distance to agreement (DTA), and γ-index.

Calculated and measured doses were compared for the selected RapidArc plan (20 plan) to assess the treatment delivery accuracy using Delta[4] dosimetry system; this is because we detected consistence between the measured and planned doses, which was ±1%; also, the gamma analysis of this plan resulted in 100% of data points with gamma index <1 for both 3% dose and 3 mm distance to agreement conditions.

Discussion

The analysis of the dose differences in the organs of interest showed large unacceptable dose differences in certain cases; the absorbed high and low dose gradient regions had different distributions. Here, the evaluation for 4 of the 20 dose distributions was with large dosimetric differences; were seen to be with passing rates < 88 % to be failed in the evaluation process. EPID analysis results for the IMRT prostate plans were expressed in the bottom row (evaluation tab); the evaluation was passed with the following achieved conditions;

1. Area gamma <1.0 which equaled 99.1% (99.1% of the pixels have gamma<1) within the tolerance of 95.0%

2. Area gamma >0.8 was equal to 2.1%, area gamma >1.2 was 0.3%

3. The average dose difference was 0.42 CU).

For all the four cases, this was found for the evaluated regions of low gradient dose with relative ΔD<±3 %. The passing rate in the high gradient region using criterion of DTA<3 mm was more than 99 % in all cases. The AAPM TG-119 report focused on the commissioning of IMRT systems.[14] The 3%/3mm gamma analysis passing rate metric was used as the basis for proposed action levels of 90% (per-beam) or 88% - 90% (composite dose) when comparing the measured and calculated doses. Corrections for inhomogeneity in 3D dose distributions were calculated with 3 mm resolution in the x, y, and z directions. We checked 20 prostate RapidArc plans for several patients because all plans range from 98.5 to 100% passing rates with gamma criteria (3% dose and 3 mm distance) with the same threshold dose of 20%. The average γ-index was 95.9% (standard deviation (SD) = 1.5) with Min = 93.1% and Max = 98.3%. Delta[4] was used to assess the VMAT planning accuracy of a Philips TPS (beta version) by Feygelman et al.; they used 50 AAPM test plans for several institutions and compared their IMRT dosimetry.[17] We observed that the patient set-up and EPID was slightly poor in the central detector area as the backscatter increased due to the presence of the robotic arm which is the source of the problems. So, this arm and the surrounding metals had to be moved out of the active field to reduce the undesired back scatter; therefore, we moved the EPID robotic arm to be centered with movement away from the area of measurement by 28 mm and toward the gantry. If this field was measured again and no deviations were found, the problem source would not be the field itself but the arm and the surrounding metals. A comprehensive review

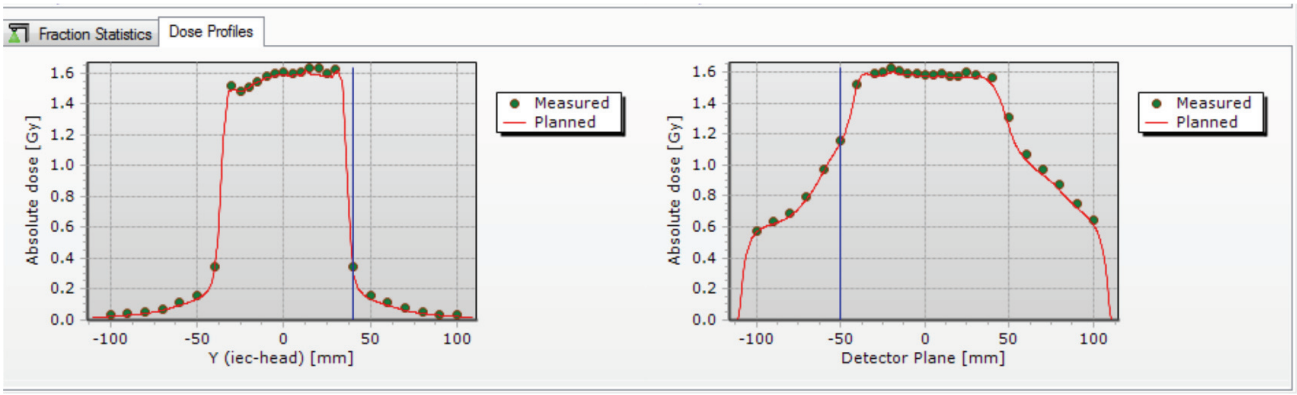


Figure 8. This figure shows the rapidArc plan dose profiles of both measured and planned doses.
* Distance to agreement (DTA), millimeter (mm), gray (Gy)

provided by the report of AAPM TG-218; was aimed at improving both the consistency and understanding of these processes as well as methodology recommendations and tolerance limits in specific IMRT QA.[18] Our result helped for better control on delivered doses for cancer tissues, sparing of the surrounding healthy tissue and risky structures in area under treatment leading to better quality control of patient's life.[19]

Verification of a planned dose distribution is a complex and time-consuming procedure because all described parameter (DTA, %DA, and γ-index) are highly important; moreover, using only one of them is not enough to accept a treatment plan. RapidArc plans could be verified using Delta^4 practical radiation dosimetry system, which gives excellent dosimetry results; however, the verification of a planned dose distribution is a complicated and time-consuming procedure. In portal dosimetry, field-by-field measurement increases the chances of detecting the delivery errors in the individual fields and the cause of errors such as misplaced MLC leaves; however, it does not provide much information about the total dose distribution. When small errors are present in any field, it is difficult to assure the accuracy of the results; even these errors add up or cancel each other. In the present study, the agreement between the acquired and predicted images was found to be very good for fields from a prostate plan (smaller, less complex fields). Delta^4 measures every dose pulse individually, making it possible to view any data (beam, plan, control point, segment, and increased angle) at any time. Periodic calibration for Delta^4 dosimetry system is recommended as sensitivity is affected by a radiation damage of >1% every 1kGy.

Conclusion

Portal dosimetry is an efficient and accurate tool for verifying the delivery of the treatment according to plan; however, it does not verify whether the plan gives the desired dose distribution. Delta^4 device is a straightforward method for real time measurement; nonetheless, it is a complex device which requires a careful QA before use. Delta^4 phantom output accuracy and the set-up correction checks have to be confirmed first. We had to check all RapidArc plans accepted to range between 98.5 to 100% passing rates; this elucidates the fact that Delta^4 phantom is an excellent dosimetry tool.

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Conflict of Interest

None declared.

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