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Original research article

Commissioning and Acceptance Testing of the existing linear accelerator upgraded to volumetric modulated arc therapy

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ARTICLE INFO

Article history:
Received 13 December 2012
Received in revised form
17 April 2013
Accepted 8 July 2013

Keywords:
Volumetric modulated arc therapy
Dynamic MLC
EDR2 film
Film dosimetry
EPIQA
Portal dosimetry

ABSTRACT

Aim: The RapidArc commissioning and Acceptance Testing program will test and ensure accuracy in DMLC position, precise dose-rate control during gantry rotation and accurate control of gantry speed.

Background: Recently, we have upgraded our linear accelerator capable of performing IMRT which was functional from 2007 with image guided RapidArc facility. The installation of VMAT in the existing linear accelerator is a tedious process which requires many quality assurance procedures before the proper commissioning of the facility and these procedures are discussed in this study.

Materials and methods: Output of the machine at different dose rates was measured to verify its consistency at different dose rates. Monitor and chamber linearity at different dose rates were checked. DMLC QA comprising of MLC transmission factor measurement and dosimetric leaf gap measurements were performed using 0.13 cm^3 and 0.65 cm^3 Farmer type ionization chamber, dose 1 dosimeter, and IAEA 30 cm × 30 cm × 30 cm water phantom. Picket fence test, garden fence test, tests to check leaf positioning accuracy due to carriage movement, calibration of the leaves, leaf speed stability effects due to the acceleration and deceleration of leaves, accuracy and calibration of leaves in producing complex fields, effects of interleaf friction, etc. were verified using EDR2 therapy films, Vidar scanner, Omnipro accept software, amorphous silicon based electronic portal imaging device and EPIQA software.[1–8]

Results: All the DMLC related quality assurance tests were performed and evaluated by film dosimetry, portal dosimetry and EPIQA.[7]

Conclusion: Results confirmed that the linear accelerator is capable of performing accurate VMAT.

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http://dx.doi.org/10.1016/j.rpor.2013.07.008

1. Background

Our institute has been functional since 2007 with a Varian linear accelerator capable of performing IMRT with 6 and 15 MV photons. Recently, we have upgraded this existing linear accelerator with an Image guided RapidArc facility. RapidArc or volumetric modulated arc therapy is a novel treatment planning and delivery system that has recently been made available for clinical use.

The idea of using a traditional linear accelerator gantry for a rotational IMRT treatment was first suggested by Yu et al. in 1995 as an alternative to tomotherapy, which necessitated specialized equipment and struggled with abutment problems between treatment slices at that time. Yu's alternative was called intensity modulated arc therapy (IMAT) and utilized a large field size, traditional linear accelerator, continuous gantry rotation, and dynamic MLC. To create an intensity distribution, IMAT was delivered in multiple overlapping arcs. Each arc delivered only one level of intensity; therefore, multiple arcs were required for multiple levels of intensity. The two-dimensional intensity distribution at each angle was a composition of multiple radiation fields of uniform intensity with different shapes and sizes. Developments in rotational delivery capabilities of traditional linear accelerators in the last few years, specifically variable dose rate and variable gantry speed, have sparked a new interest in rotational IMRT delivery and IMAT. Volumetric modulated arc therapy (VMAT) has been developed using the basic principles of IMAT, coupled with these new machine capabilities.

VMAT offers potential dosimetric and efficiency advantages by being able to deliver modulated cone-beam radiation from a single or multiple arc. During a VMAT treatment, MLC leaves dynamically shape the beam to treat the entire volume of the planning target volume (PTV) with every rotation, and the dose rate and/or gantry rotation speed is continuously varied as the gantry of the linear accelerator rotates around the patient. Three key components of VMAT rotational delivery are dynamic MLC, variable dose rate and gantry speed. The MLC leaf speed is kept within a prespecified maximum tolerance of 2.5 cm/s during the optimization. The gantry speed is then maximized at 4.8°/s unless the required MU per degree exceeds the maximum dose rate of 400 MU/min, in which case the gantry slows down to accommodate the required MU/degree. VMAT treatments must use a dynamic MLC because the beam is on during the entire treatment as the gantry rotates around the patient. For VMAT treatment, the MLC leaves move as a function of gantry position, not time. The leaves reposition according to where the gantry is located in its rotation and each angle of rotation sees only one segment shaped by the MLC. In short, VMAT delivery combines varying leaf motion with varying dose rate and/or gantry rotation speed to modulate beam intensity.[1–6]

The introduction of advanced irradiation techniques into a radiotherapy clinic requires extensive dose verification measures that go beyond current routine clinical practice. Amorphous silicon electronic portal imaging devices (*a*-Si EPIDs) were originally designed for patient set-up verification; however, their use has been extended to dose verification over the past few years, since portal images also contain dosimetric information. EPID can be a powerful tool in the reduction of treatment setup errors and the quality assurance and verification of complex treatments. Film imaging is time consuming and labor intensive.

Portal imaging systems are therefore developed to provide both geometrical and dosimetric information. Compared to previous systems, the amorphous silicon-based EPID provides better quality portal images. The aS500 EPID consists of a 1 mm Cu top plate, a 0.3 mm Gd oxysulphide phosphor screen, and a 0.18 mm polyester reflector as an active element. The light generated in the scintillator is detected by a 40,330 cm^2 (512 × 384 pixel, 0.78 mm × 0.78 mm pixel pitch) array of amorphous-Si photodiodes. Each diode is connected to a thin-film transistor and can be read out separately. The image acquisition system acquires images by scanning each row of the detectors sequentially. By averaging a large number of frames, an EPID can continuously scan the matrix of silicon detectors during the irradiation of a field, sum all acquired frames and send an averaged image to the console computer upon completion of radiation delivery. A separate dose image prediction algorithm Portal Dosimetry Image Prediction (PDIP) is part of the Eclipse Treatment Planning System. It converts the pixel data to absolute dose.[8–11]

Several studies of dose–response characteristics have shown that *a*-Si EPIDs are suitable for dose verification. These studies have shown that the pixel signal is approximately linear with dose and can be converted to absolute dose by measuring the response over a wide range of parameters. In addition, the response of the *a*-Si EPID is stable within ±0.5% over long periods, up to at least 2 years, provided there are no electronic failures. EPID measurements are simple to perform with minimum set-up requirements, they can be repeated easily and digital data is obtained immediately, unlike films which require additional time for developing and digitizing. Once an EPID is calibrated for a certain linac and energy, EPID images can be immediately converted to absolute dose images, whereas each film batch requires a new calibration, involving additional measurements. So, we did all the 2D fluence measurements on film as well as the EPID, so that once we finished calibrating, we could use EPID for regular quality assurance of VMAT.

Epiqa is a program that allows to convert a dosimetric image acquired by an EPID into a dose map and to compare the dose map with a reference dose distribution. It is possible to utilize Epiqa for verification of static as well as intensity modulated fields, including RapidArc® fields. The portal dosimetry image conversion to dose map is based on the GLAaS algorithm – an absolute dose calibration algorithm for an amorphous silicon portal imager. The verification with EPIQA helps us to cross check the PDIP measurements.[7–11]

2. Aim of the study

In VMAT, there are three interrelated machine parameters that are allowed to vary: the MLC leaf speed, the gantry speed and the dose rate. The installation of VMAT in the existing linear accelerator is a tedious process which requires many quality assurance procedures before a proper commissioning of the facility. For RapidArc, gantry was calibrated for continuous

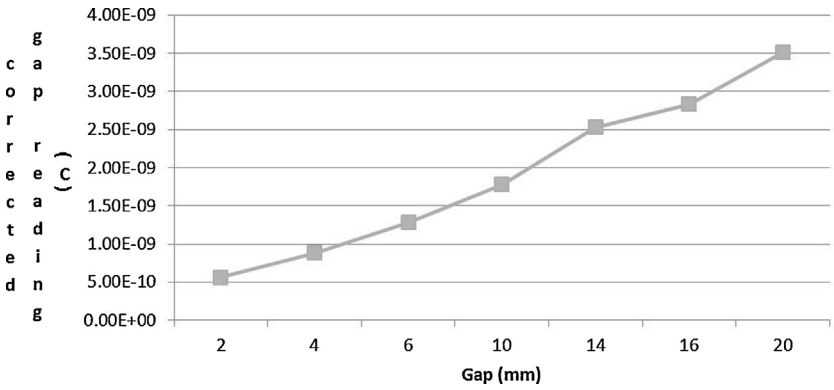


Fig. 1 – The graph obtained from DLS measurements.

rotation with changing dose rate and MLC leaf positions. The VMAT commissioning and Acceptance Testing program will test and ensure reliable system capabilities that are incremental to those of IMRT-DMLC. The three most important elements are (1) accuracy in DMLC position, (2) precise dose-rate control during gantry rotation and (3) accurate control of gantry speed.

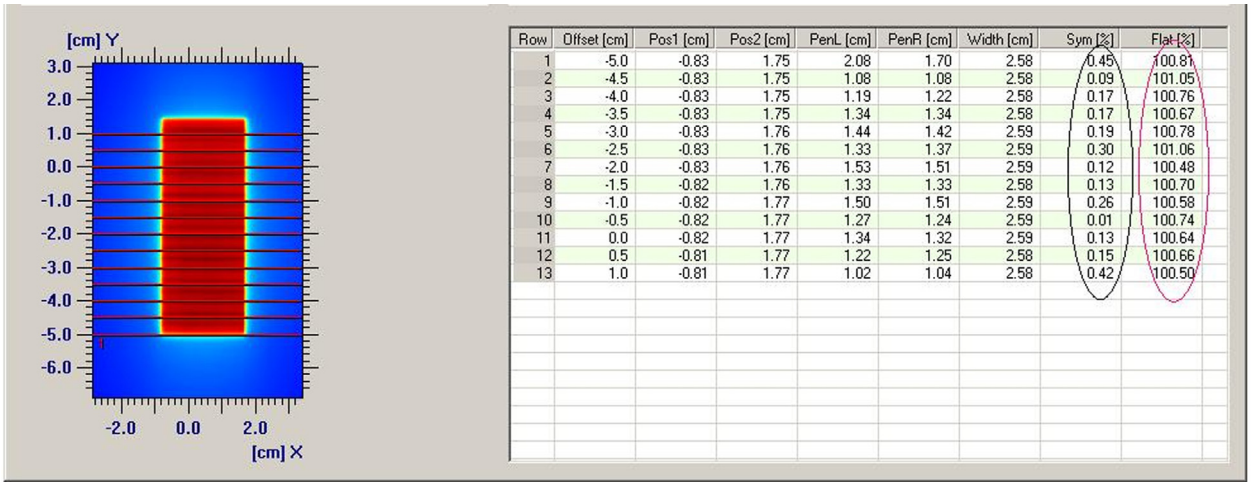
The highlight of the study is that all the fluence measurement parameters are not only measured on film but also on the Electronic Portal Imaging Device (EPID) with Portal Dose Image Prediction (PDIP) software and EPIQA software. So, the efficiency of the latter software was evaluated and analyzed. The advantage is that in the later stage, when performing the machine specific and patient specific quality assurance on everyday basis, the analysis can be done on the EPID and evaluated using PDIP and EPIQA software which is simpler and easier when compared to film measurements.

3. Materials and methods

The installation and quality assurance of this upgraded facility is a tedious process. After installation of VMAT, output of the machine at different dose rates was measured to verify its consistency at different dose rates, monitor and chamber linearity at different dose rates were checked, DMLC QA comprising of MLC transmission factor measurement, dosimetric leaf gap measurements, picket fence test, garden fence test, testing of leaf positioning accuracy due to carriage movement, calibration of the leaves, leaf speed stability effects due to acceleration and deceleration of leaves, accuracy and calibration of leaves in producing complex fields, effects of interleaf friction, etc. were all performed.

3.1. *MLC transmission factor*

The ionization chamber (FC 65G) was placed in a water phantom, fixed at isocenter at a depth of 10 cm, with a field size of 10 cm × 10 cm. The monitor response for the open field was recorded. The monitor response for the closed MLC field was obtained by placing the chamber below the MLC leaves which was at an over travel distance of 3 cm from the field center. The same was repeated by moving the other bank of MLC. The applied voltage was 300 V to the electrometer and the readings were taken for 6 MV and 15 MV. The MLC transmission factor is the ratio of meter reading obtained for the closed MLC field to the meter reading obtained for the open field. The mean reading of the MLC transmission factor of the two banks of MLC was taken to be the MLC transmission factor. The same measurements were also done for a field size of 20 cm × 20 cm.



Row	Offset [cm]	Pos1 [cm]	Pos2 [cm]	PenL [cm]	PenR [cm]	Width [cm]	Sym [%]	Flat [%]
1	-5.0	-0.83	1.75	2.08	1.70	2.58	0.45	100.81
2	-4.5	-0.83	1.75	1.08	1.08	2.58	0.09	101.05
3	-4.0	-0.83	1.75	1.19	1.22	2.58	0.17	100.76
4	-3.5	-0.83	1.75	1.34	1.34	2.58	0.17	100.67
5	-3.0	-0.83	1.76	1.44	1.42	2.59	0.19	100.78
6	-2.5	-0.83	1.76	1.33	1.37	2.59	0.30	101.06
7	-2.0	-0.83	1.76	1.53	1.51	2.59	0.12	100.48
8	-1.5	-0.82	1.76	1.33	1.33	2.58	0.13	100.70
9	-1.0	-0.82	1.77	1.50	1.51	2.59	0.26	100.58
10	-0.5	-0.82	1.77	1.27	1.24	2.59	0.01	100.74
11	0.0	-0.82	1.77	1.34	1.32	2.59	0.13	100.64
12	0.5	-0.81	1.77	1.22	1.25	2.58	0.15	100.66
13	1.0	-0.81	1.77	1.02	1.04	2.58	0.42	100.50

Fig. 2 – Flatness and symmetry results from film dosimetry.

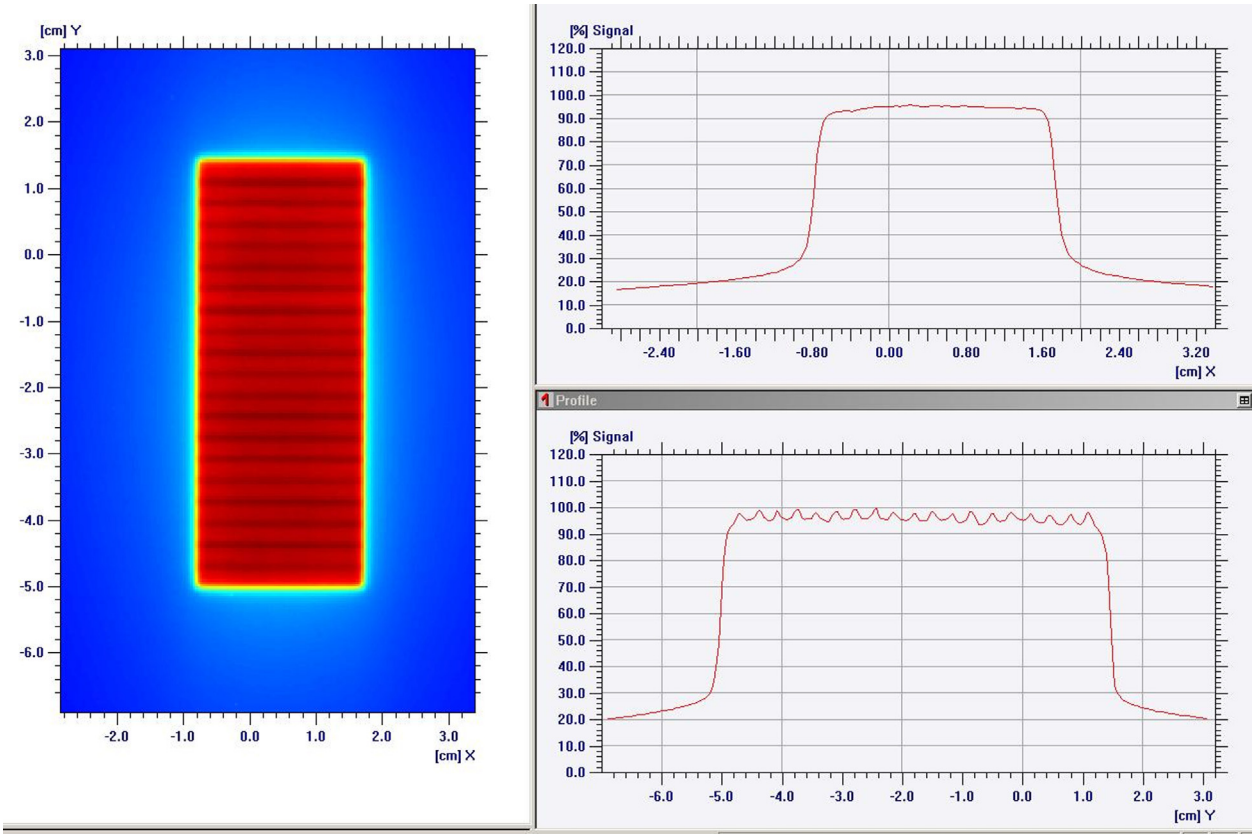


Fig. 3 – Results for dosimetric test from film dosimetry.

3.2. *DLS (dosimetric leaf separation)*

Leaf transmission and leakage through the rounded leaf ends is known as dosimetric leaf separation. The ends of the Varian MLC leaves are rounded to achieve acceptable off-axis dosimetric characteristics while keeping a linear leaf trajectory. Because of the round shape, a significant dose is found between leaves even if the leaf pair is completely closed. This phenomenon is called the rounded leaf transmission. The rounded leaf transmission has more significance in

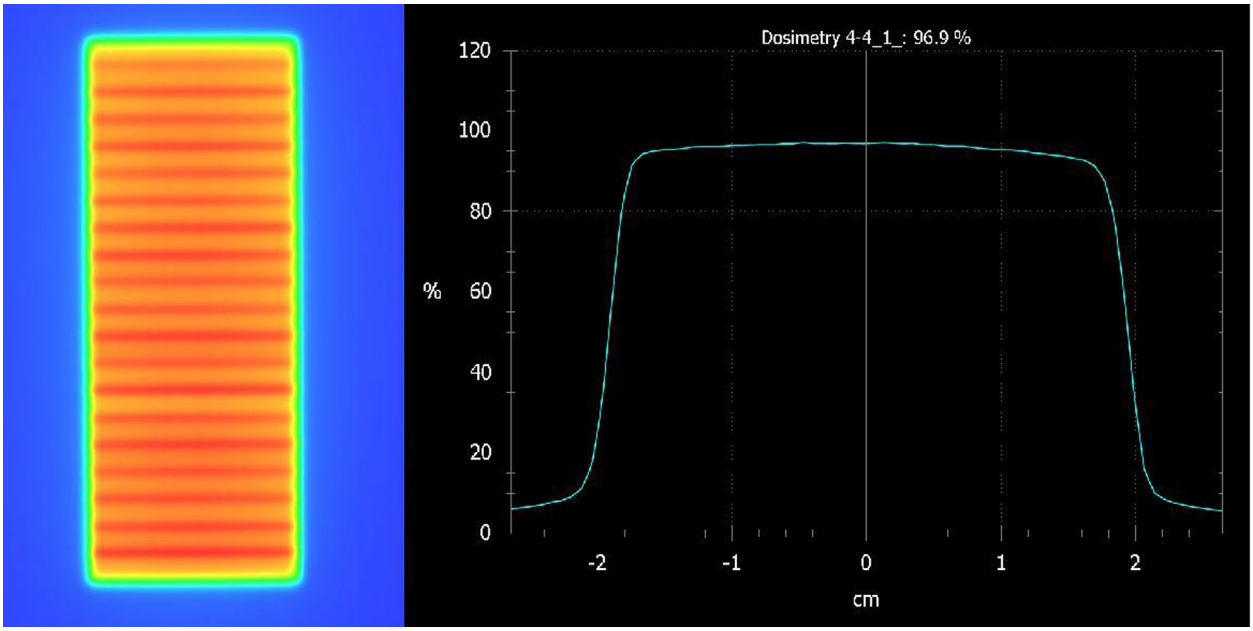


Fig. 4 – Result obtained for dosimetric test from portal dosimetry.

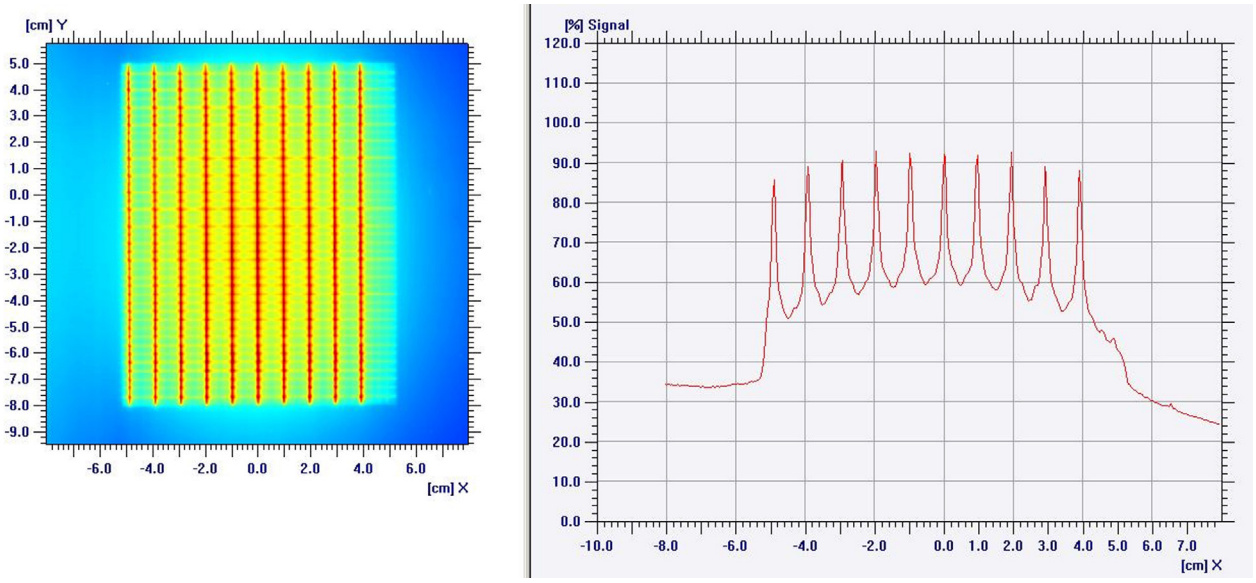


Fig. 5 – The image obtained for the picket fence test at a stationary angle on a EDR2 therapy film.

treatments using dynamic MLC than in those using a static MLC delivery technique. The DLS is the quantity added to the leaf gap to compute the dose more accurately, especially for small gaps. It is used by the leaf motion calculator as an offset value on leaf position.

Literatures have suggested obtaining the DLS value through extrapolation to zero of dose plotted as a function of the gap between opposite leaves. For this, we first measured open field output for a field size of 10 cm × 10 cm. Then transmission readings for MLC Bank A and MLC Bank B were measured. The fields with sliding MLC gap of gap sizes 2, 4, 6, 10, 14, 20 mm were created. The gap moved from −60 mm to +60 mm with constant speed with respect to MU. The meter readings for every gap were noted. The corrected gap reading was calculated using transmission for the leaves. A graph was drawn with gap along the X-axis and corrected gap reading along the Y-axis. The graph was extrapolated to get the gap required between opposite leaves to obtain the zero dose.

3.3. *Output and linearity checks at different dose rates*

The ionization chamber was placed in a water phantom at 10 cm depth with a field size of 10 cm × 10 cm and 100 cm SSD. For output measurement, 100 MU was given and monitor response at 300 V for dose rates 100 MU/min, 200 MU/min, 300 MU/min and 400 MU/min were noted. The output at different dose rates were calculated and intercompared. For

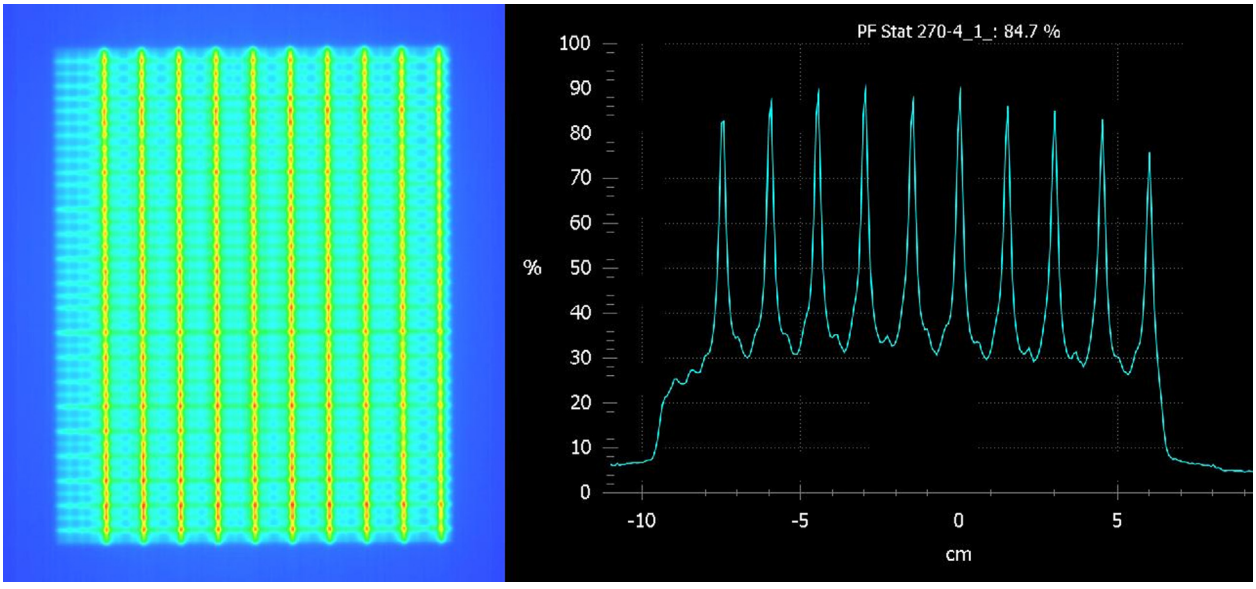


Fig. 6 – The image obtained for the picket fence test at a stationary angle on a EPID and evaluated using the Portal Dose Prediction Software.

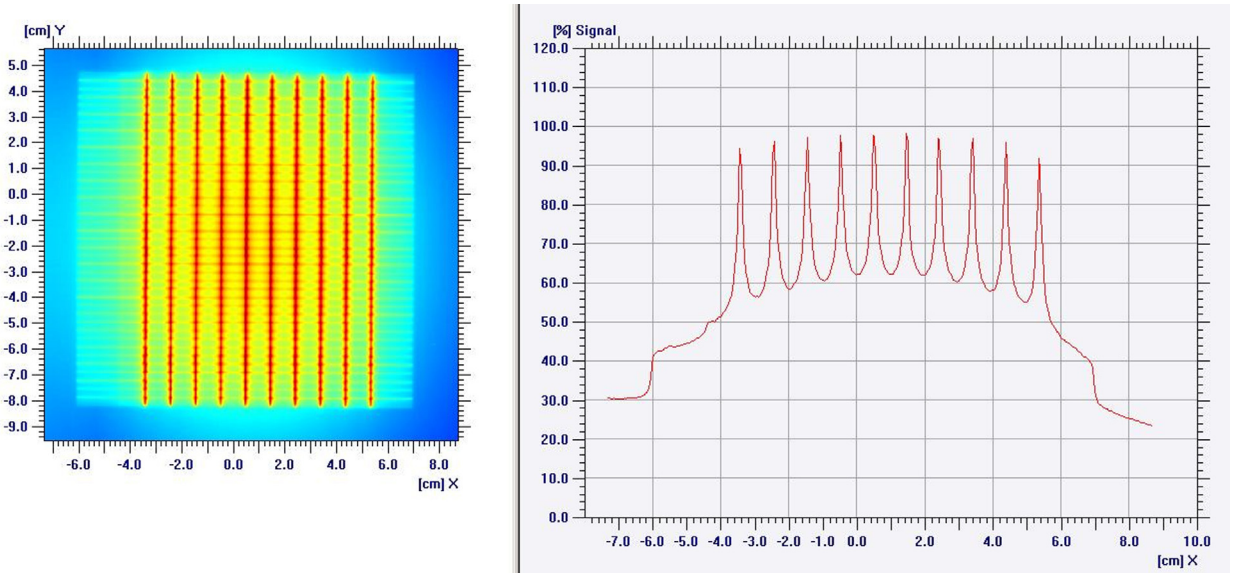


Fig. 7 – The image obtained for the picket fence test at a stationary angle and during gantry rotation on a EDR2 therapy film.

linearity verification, the monitor response for different MU were recorded and compared with the above said dose rates.

3.4. *DMLC QA*

DMLC QA with different complex fields were performed to verify the leaf positioning accuracy, leaf speed, calibration of leaves, effect on leaf positioning accuracy and leaf speed due to carriage movement, inter leaf friction, etc. These fields are inherently loaded in the treatment console computer by the vendor. Various QA tests were used to verify the mechanical and dosimetric stability of the MLC of the linear accelerator when operated in dynamic mode. The mechanical QA test also verified the positional accuracy and kinetic properties of the DMLC.

4. Results

4.1. *MLC transmission factor, dosimetric leaf gap, output and linearity checks*

The MLC transmission factor for the Bank A and Bank B were obtained separately. The obtained transmitted meter readings were averaged and used to calculate the MLC transmission factor. It was found to be 1.39% for 6 MV and 1.7% for 15 MV.

The extrapolated gap to obtain zero dose was found to be −1.44mm for our 120 leaves DMLC (Fig. 1).

The output of the machine measured for different dose rates 100 MU/min, 200 MU/min, 300 MU/min and 400 MU/min remained the same with a variation less than ±2%. The linearity checks at different dose rates 100 MU/min, 200 MU/min,

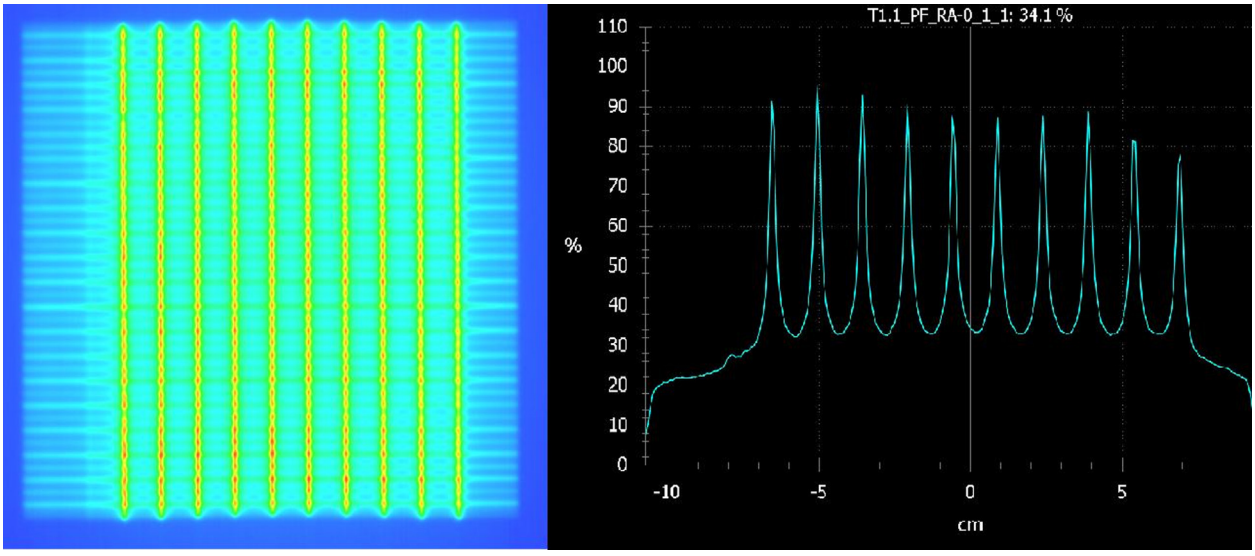


Fig. 8 – The image obtained for the picket fence test at a stationary angle and during gantry rotation on EPID and evaluated using the Portal Dose Prediction Software.

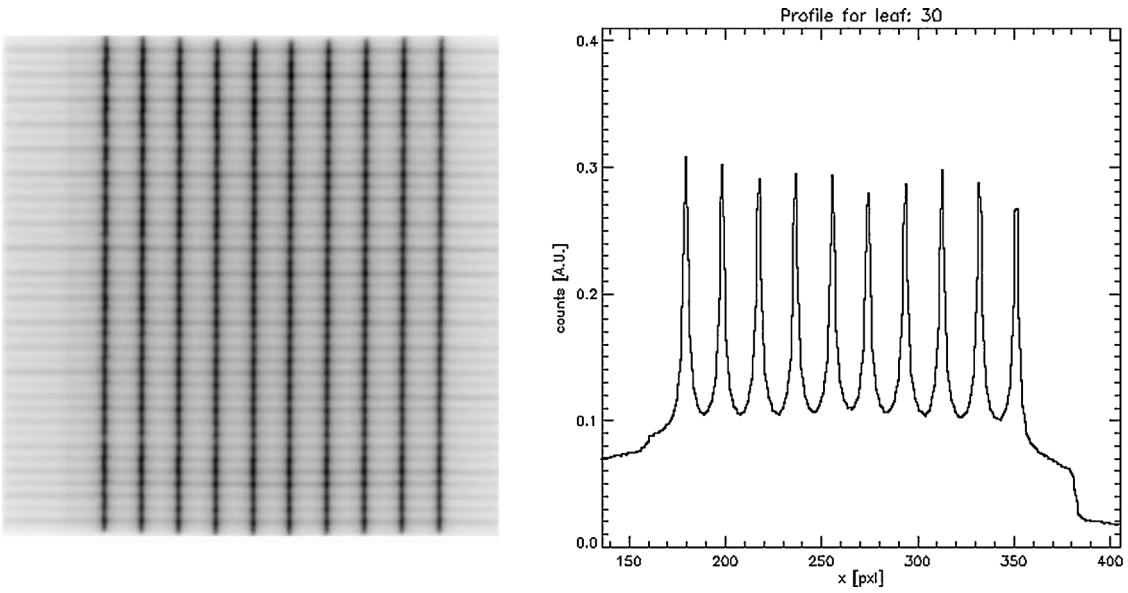


Fig. 9 – The image obtained for the picket fence test at a stationary angle and during gantry rotation on EPID and evaluated using the EPIQA.

300 MU/min, and 400 MU/min for MU ranging from 5 to 400 MU were verifed and all were found to be linear in the entire range for the above said dose rates.

4.2. *Routine DMLC QA*

Routine DMLC QA pattern tests are done to evaluate the stability and efficiency of the MLC leaves in delivering dynamic treatments. The tests include picket fence test, garden fence test, synchronized segmented strip, non-synchronized segmented strip, X Wedge, Y Wedge, pyramid shape, complex fields, etc. Picket fence test and garden fence test show the stability and reproducibility of leaf gap between MLC leaves in DMLC mode. The other tests verify the accuracy and calibration of the leaf position and carriage movement, effects of interleaf friction on leaf positioning and the ability of the leaves to interdigitate, leaf speed stability, acceleration and deceleration, the ability of DMLC leaves to produce complex intensity modulated pattern, etc. These tests are done using EDR2 therapy films as well as Electronic Portal Imaging Device. The EPID image is evaluated using Portal Dose Prediction Software as well as EPIQA. All these test results were satisfactory confirming the efficient functioning of the DMLC for IMRT fields.

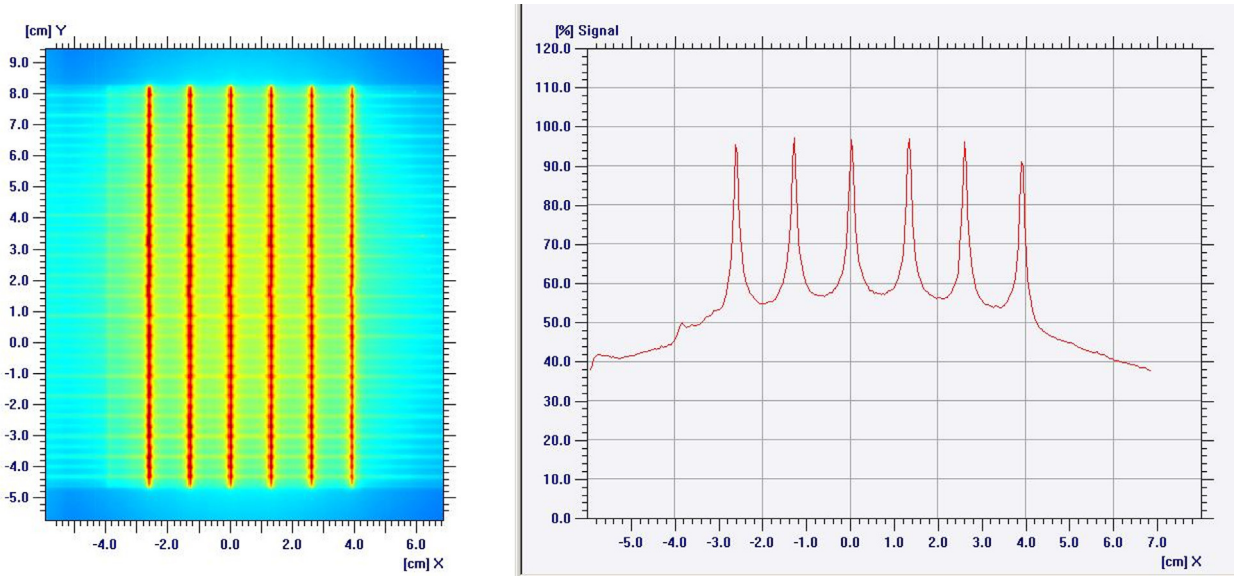


Fig. 10 – The image obtained for the picket fence test with a sub millimeter error introduced taken on EDR2 therapy film. The planned error is exactly observed in the image.

Table 1 – Results obtained by EPIQA and the deviation from the reference values is well within the limits for different gantry angles.

Gantry angle (°)	Deviation from reference value (%)
0	0.402
270	−0.025
90	−0.452
180	0.075
Reference average value: 0.141 ± 0.00	

4.3. *DMLC QA pertaining to rotational arc treatments*

Each test plays a major role in evaluating the accurate functioning of the MLC movement, MLC speed, dose rate variation and gantry rotation to deliver the planned dose.

4.4. *DMLC dosimetry*

The dose delivered and the dose planned should not vary as it would lead to overdosage or underdosage to patients. The DMLC dosimetry is done to verify the dose at different gantry angles for a dynamic treatment field. The deviation between the calculated and measured dose is tabulated below and one could note that the deviation is well within acceptable limits. The maximum variation in symmetry is only 0.45% and that in flatness is only 1.06% which is within the 2% acceptable tolerance limit. The dose measured along the *x*- and *y*-axes normalized to 100% is found to be within 2% in both film dosimetry and portal dosimetry. Whereas the dose variation measured with epiqa had a maximum value of −0.45% and an average value of 0.141% (Figs. 2–4 and Table 1).

(a) Picket fence test
The picket fence test consists of eight consecutive leaf movements of 5 cm wide rectangular fields spaced at 5 cm intervals. The field information is contained in three test files, which are run in sequence. These three files are exposed in a single film. This test is used to verify the leaf positioning accuracy and also calibrates the carriage positioning accuracy (Figs. 5 and 6).
It is clear that the dynamic MLC stability and reproducibility of leaf gap between MLC leaves are satisfactory.

(b) Picket fence test during RapidArc
The above test is repeated at a stationary gantry angle and during gantry rotation. This test is done to verify the effect of gantry rotation on the MLC positional accuracy (Figs. 7–9).
The images obtained show perfectly superimposed images obtained at a stationary gantry angle and during gantry rotation with no discrepancies.

(c) Picket fence test during RapidArc with intentional errors
This test is to demonstrate that the above test can detect sub-millimeter errors during RapidArc (Figs. 10–12).

(d) Accurate control of dose rate and gantry speed during RapidArc delivery
This test uses 7 combinations of dose-rate, gantry range and gantry speed to give equal dose to seven 1.8 cm strips in a RapidArc field (Figs. 13 and 14 and Table 2).

Table 2 – Results from EPIQA for accurate control of dose rate and gantry speed during RapidArc delivery. The table shows that the deviation between the planned and delivered dose is well within the acceptable limit of ±2%.

ROI number	Deviation from reference value (%)
1	1.57
2	0.36
3	−0.17
4	−0.35
5	−0.66
6	−0.77
7	0.03
Reference average value: 0.1509 ± 0.0012	

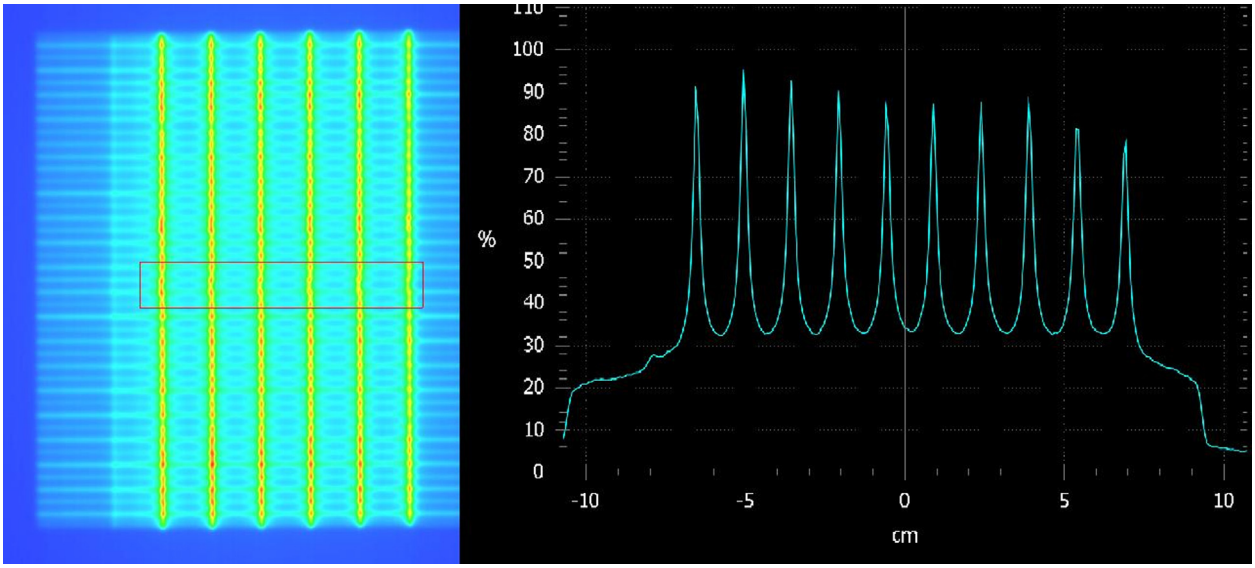


Fig. 11 – The image obtained for the picket fence test with a sub millimeter error introduced taken on EPID and evaluated using the Portal Dose Prediction Software. As seen above the portal dose image also shows the sub millimeter error introduced in the MLC position.

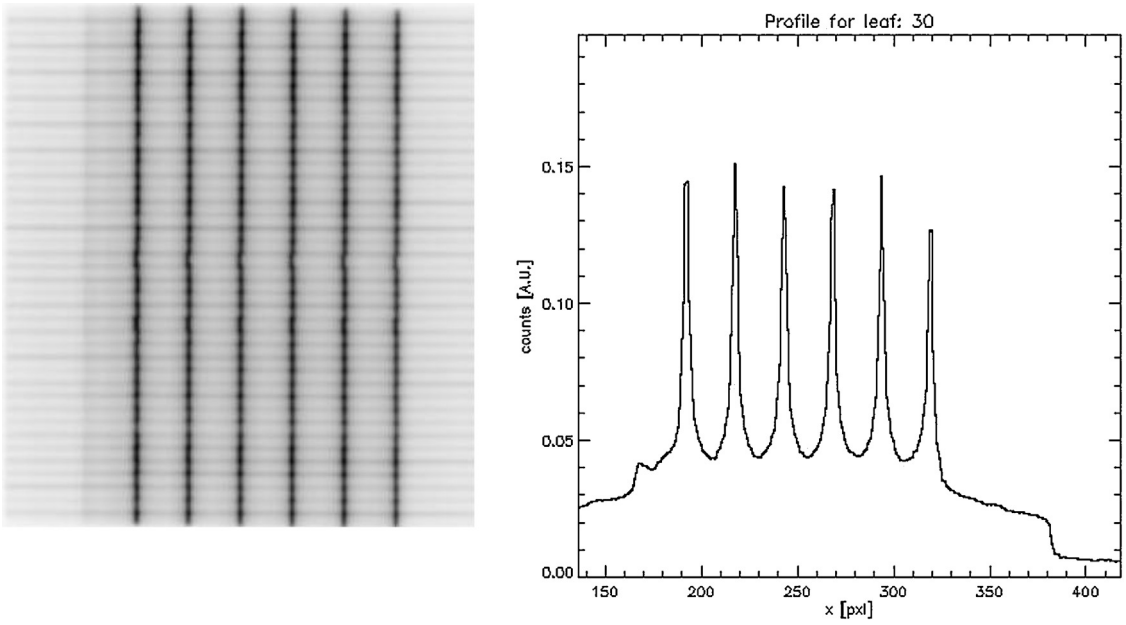


Fig. 12 – The image obtained for the picket fence test with a sub millimeter error introduced taken on EPID and evaluated using the EPIQA. Intentional errors introduced in the picket fence pattern were clearly noticeable.

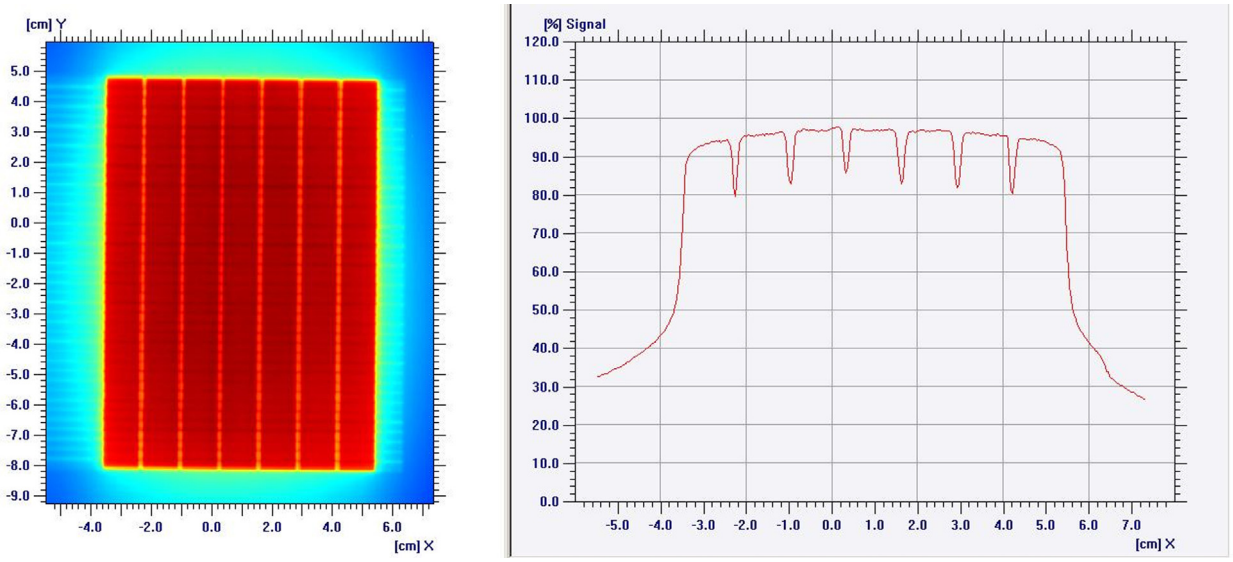


Fig. 13 – The image taken on EDR2 therapy film to evaluate accurate control of dose rate and gantry speed during RapidArc delivery. All the strips show equally exposed regions when evaluated with Omnipro software.

(e) Accurate control of leaf speed during RapidArc delivery
This test uses 4 combinations of leaf speed and dose-rate to give equal dose to four strips in a RapidArc field. The films (both with variable leaf speed and open field MLC) are analyzed and the profiles are superimposed to see whether they are closely matched. The result showed well matched profiles at all leaf speeds and dose rates (Figs. 15 and 16 and Table 3).

(f) Record of machine performance during RapidArc
Machine performance during RapidArc was recorded in two Dynalogs files. The Clinac control system captures MU and gantry angle every ~50 ms, and its Dynalog report

Table 3 – Results from EPIQA for accurate control of leaf speed during RapidArc delivery, shows that the deviation between the planned and delivered dose is well within the acceptable limit of 2%.

ROI number	Deviation from reference value (%)
1	0.24
2	0.08
3	−0.74
4	0.43
Reference average value: 7.0852 ± 0.0365	

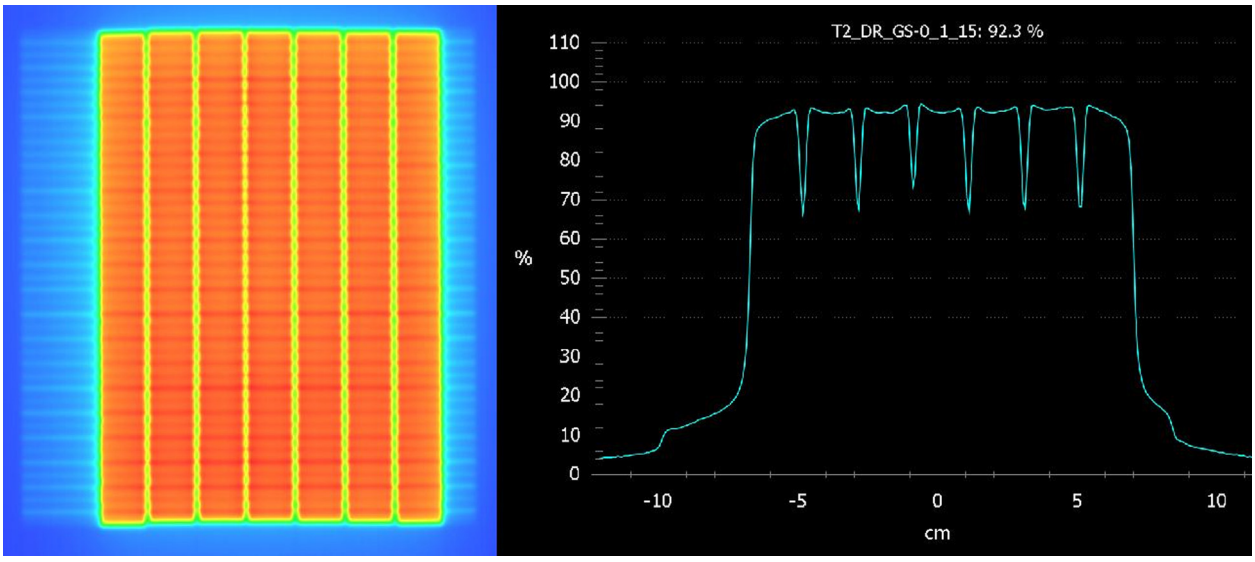


Fig. 14 – The image taken on EPID and evaluated using the Portal Dose Prediction Software to evaluate accurate control of dose rate and gantry speed during RapidArc delivery. Even the portal dose shows equal exposures in all strips.

gives comparison of planned gantry angle and cumulative MU vs. the recorded values. The second Dynalog (from the MLC control computer) recorded MLC positions and gantry angle every ~50 ms.

The Dynalog from the Clinac, which recorded gantry angle and cumulative MU at each control point for comparison with the segmented treatment table, indicated mean standard deviations of ~0.04 MU and ~0.26 MU for all of the RapidArc QA plans. The Dynalogs from the MLC control computer that recorded MLC positions and gantry angle every 50 ms were analyzed. The analysis indicated precise position of all leaves for the picket fence test. Detectable leaf position errors were only present during the motion of the 1-mm strip to the next position with speed of ~2 cm/s. The histogram of >52,000 MLC positions showed that ~65% were within 0.05 mm, ~3% between 0.05 and 0.5 mm, ~28% between 0.5 and 1 mm, ~4% between 1.0 and 1.5 mm, and none >1.5 mm.

For another test, the MLC leaves were moved to the next position with the speed of ~1 cm/s. The histogram of MLC position deviations (~150,000 values) indicated ~90% of all errors <0.5 mm. Analysis of MLC Dynalog file of Test 3 indicated that leaf position error increased linearly with leaf speed and was highest when DMLC ran at 2.76 cm/s. Nevertheless, the histogram showed that ~87% were within 0.5 mm, ~7% between 0.5 and 1 mm, ~4% between 1.0 and 1.5 mm, ~2% >1.5 mm, and none >2.5 mm. The profiles matched correctly with very minimal deviation.

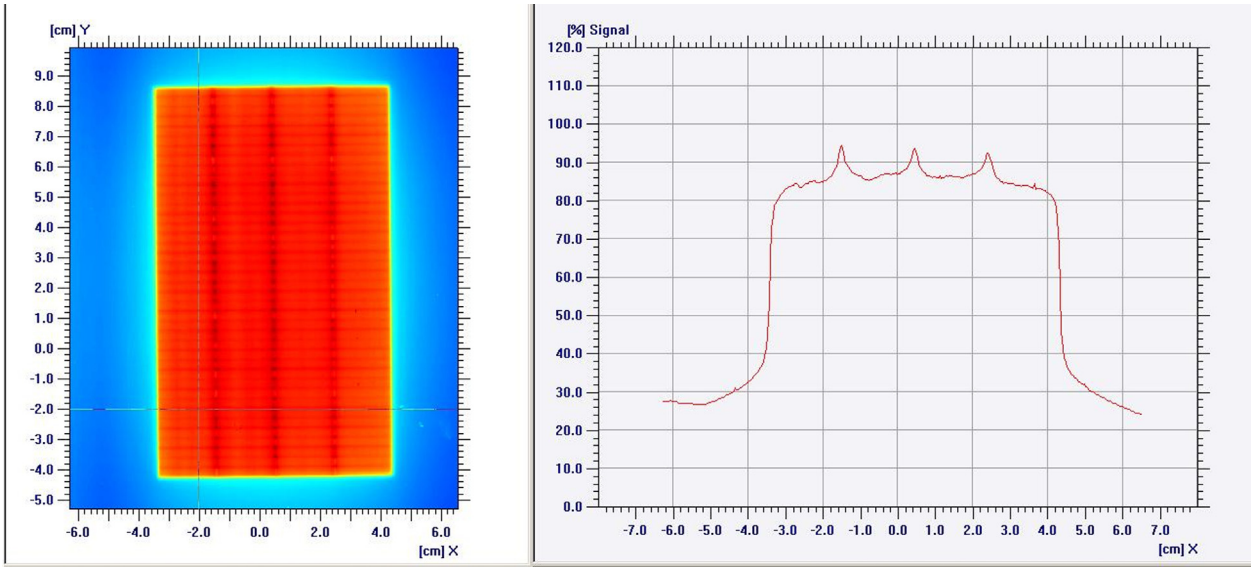


Fig. 15 – The image obtained on EDR2 therapy film to evaluate accurate control of leaf speed during RapidArc delivery.

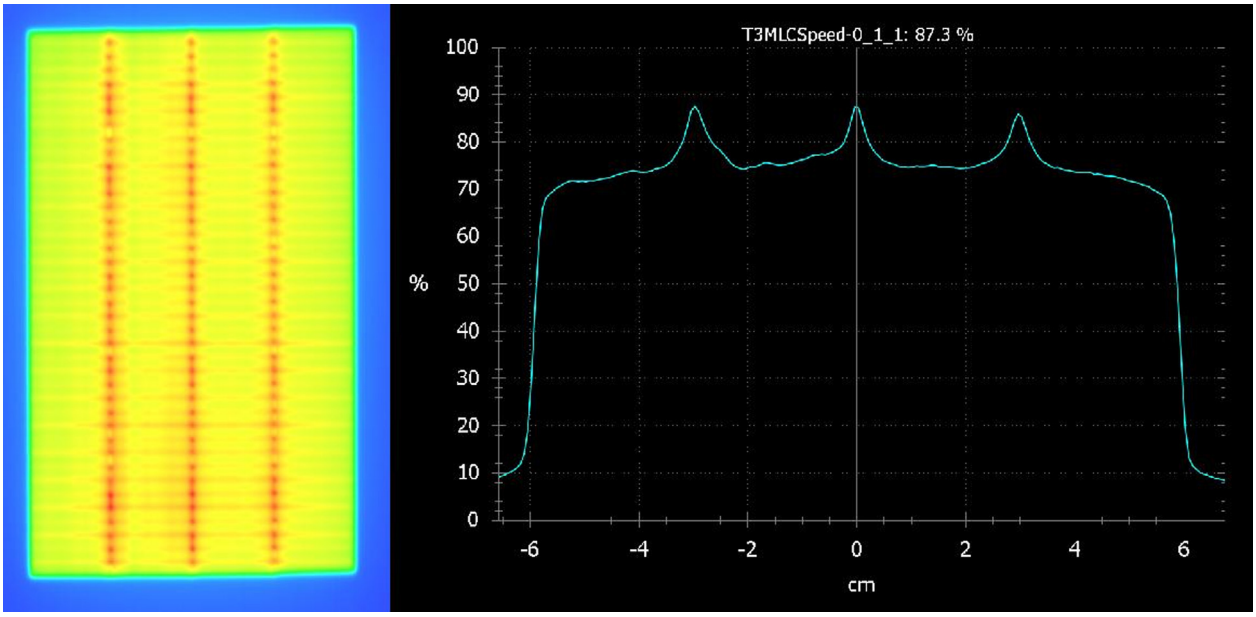


Fig. 16 – The image obtained on EPID and evaluated using the Portal Dose Prediction Software to evaluate accurate control of leaf speed during RapidArc delivery.

4.5. *RapidArc delivery accuracy:*

At delivery level, RapidArc plans are transferred by DICOM-RT communication to the 4D treatment console of the Varian linear accelerator. Here, the actual treatment parameters are determined and transferred to the various system controllers. Particularly, the MLC controllers verify every 50 ms the position of the leaves with respect to expected, previous and following positions as well as the agreement of delivered dose. The linear accelerator controllers check, with the same frequency and logic, the angular position of the gantry and the dose rate. Whatever discrepancy should be detected by the controllers would generate immediate beam off interlock and the delivery would be interrupted.

As per the expectation the result obtained showed that the RapidArc plans are transferred by DICOM-RT to treatment console and is delivered as per the plan and the interlock showed up during the discrepancy.

5. Conclusion

The delivery of RapidArc requires several advanced technologic capabilities: variable dose rate, variable gantry speed, and dynamic MLC during gantry rotation. Commissioning and acceptance procedures of RapidArc must therefore address the reliability and accuracy of these parameters. In this study, we designed procedures to achieve the following: (1) test MLC positional accuracy, (2) assess the accuracy of variable dose-rate, and (3) evaluate the accuracy of MLC leaf speed. The above tests verify all these parameters and prove that the linear accelerator is capable of performing RapidArc accurately.

As the measurements are done on film as well as EPID using Omni Pro Accept software for film analysation while PDIP and EPIQA are used to analyze the EPID fluences, the measurements done in all the three modalities showed the same results. This proves that the further QA can be done using EPID.

Conflict of interest

None declared.

Financial disclosure

None declared.

Acknowledgements

The authors acknowledge Dr. Rajesh Jeganathan, Managing Director, Billroth Hospitals Ltd., Chennai, India; Shiyama Swaminathan, Medical Physicist, Billroth Hospitals Ltd., Chennai, India and Dr. Padmanabhan Loganathan, Clinical Oncologist, Billroth Hospitals Ltd., Chennai, India.

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