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Analysis of Commissioning Parameters and its Validation of O-Ring Gantry Based Medical Linear Accelerator Halcyon™ for Improved Radiotherapy Technique

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ABSTRACT

Introduction: Popularly, teletherapy (telecobalt/LA) equipment is based on a C-arm gantry system. Recently, a fast O-ring gantry system introduced a medical linear accelerator (LA) to smoothen the workflow of treatment of cancer patients because of the increasing trend of the number of cancer cases over the past few years. This study aimed to analyze the commissioning parameters and validation of the O-ring gantry-based LA for improved radiotherapy techniques.

Material and Methods: Three-dimensional (3D) radiation field analyzer (RFA) used to commission Halcyon™ LA. It is used for measuring percent depth dose (PDD), profiles, and output factors.

Results: TPS data was validated by comparing it with our measured data. Plans per the TG-119 protocol showed good agreement between treatment planning systems (TPS) calculated and measured doses. For patient-specific, QA plans showed good agreement with gamma evaluation criteria.

Conclusion: Commissioning and validation of O-ring gantry system Halcyon™ LA was performed successfully.

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Introduction

Understanding of radiation started way back in 1895 with the discovery of X-rays (named due to their unknown nature) by Wilhelm Rontgen. It was followed in 1896 by Henri Becquerel, who observed similar rays emitted naturally by uranium salt; later, Marie Curie named it radioactivity. Since the discovery of X-rays, ionizing radiation has been used for the treatment of cancer patients. Initially, low kilo voltage (KV) energy was used, and then moved to megavoltage (MV) with telecobalt & medical linear accelerator (LA).

Popularly teletherapy (telecobalt/LA) equipments are based on a C-arm gantry system. Conventional C-arm gantry system-based LA has been used for the past few decades and has the advantage of its ability to modulate fluence by introducing a multileaf collimator (MLC) as a key component with variable dose rate and gantry speed. Recently, a fast O-ring gantry system introduced medical LA to smoothen the workflow of treatment of cancer patients because of the increasing trend of the number of cancer cases over the past few years. It can be called a true image-guided radiotherapy (IGRT) system, as before treatment mandatory to perform image verification [1,2].

Our hospital is the first government institute in India to procure Halcyon™ medical linear accelerator. We have an installed Halcyon™ V 3.0 bold model (M/s Varian Medical System, Palo Alto, CA) medical LA O-ring gantry system. It comes with a 6MV flattening filter-free (FFF) beam with a jawless design. This system has seamless patient throughput due to the newly designed dual-layer stacked and staggered MLC, having two banks named proximal and distal. These MLCs have reduced transmission and 114 leaves (29 pair /bank on proximal, 28 pair /bank on distal) producing leaf effect of 5 mm at isocenter for treatment of patients, as both the banks within offset with respect to each other by 5 mm, high dose rate (800 cGy/min), higher MLC speed (5 cm/s), four

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gantry rotation per minute (4 RPM) and capable of producing maximum 28 x 28 cm^2 field size for clinical use [3,4]. Unlike conventional LA, it has no light field. The MV imager panel equipped with amorphous silicon (aSi) 1200 detector panel fixed at a distance of 154 cm from the source has a physical size of 43 × 43 cm2 with a 28 × 28 cm2 iso-centric projection. Dose rates 9 cGy/min and 15 cGy/min are available for imaging. It is equipped with a beam stopper which shields primary radiation and eventually reduces the shielding requirement of primary barriers. It is mandatory to perform daily machine performance check (MPC) checks before starting treatment [5].

Sophisticated and advanced radiotherapy treatment techniques for cancer patients are becoming more popular. With increase degree of complexity for these techniques, the quality control of dose delivery needs to be assured. It can be assured if the treatment planning system (TPS) is properly commissioned or validated, and verification is performed through proper end-to-end (E2E) testing [6].

This study aims to analyze the commissioning parameters and validation of the Halcyon™ O-ring gantry-based LA for improved radiotherapy techniques. A new experience to commission a ring gantry for clinical use as it has no light field, a mechanical distance indicator, and limited accessibility inside the bore for water phantom placement.

Materials and Methods

Equipment

Tissue phantom ratio (TPR) phantom with farmer type ionization chamber (IC) 0.6 cm^3 by PTW, Freiburg Germany inserted into groove used for measuring $TPR_{20/10}$. 0.6 cm^3 IC (with and without buildup cap) respectively used for patient plane leakage measurement and in combination with slab phantom for various MLC tests.

Relative dosimetry

Three-dimensional (3D) radiation field analyzer (RFA) beam scan (PTW, Freiburg Germany) with semiflex 3D (0.07 cm^3) ionization chambers (PTW, Freiburg Germany) as reference and field chamber used for measuring percentage depth dose (PDD), beam profiles, and output factors (OF). Halcyon™ LA has a 100 cm diameter bore size, so we need an RFA which can fit inside the bore during measurement or a system in which the phantom can be detached from the water tank, ultimately providing an easy and shorter phantom setup time. All measurements were performed with MEPHYSTO software (PTW, Freiburg, Germany).

Analysis of acquired data

The PDDs and dose profiles were measured and compared with the reference beam profiles (RBPs). Analysis of measured depth dose profiles for FFF beam performed as per recommendations of atomic energy regulatory board (AERB) task group recommendations.

- TPR20/10 measurement
- The charge was collected at 20 cm and 10 cm depth for 10*10 cm^2 field size to verify beam energy.
- Surface dose measured and compared with TruebeamTM medical LA nominal flattened photon beam energy (due to Halcyon™ having only 6FFF beam energy).
- Field size is the separation between the inflection points (IP), which is derived per its mathematical definition. And for practical purposes, it is approximated as the midpoint of the steepest part of the high dose gradient region of the beam profile.
- Symmetry is measured as International Electro-Technical Commission recommends (IEC 60976, 2008).

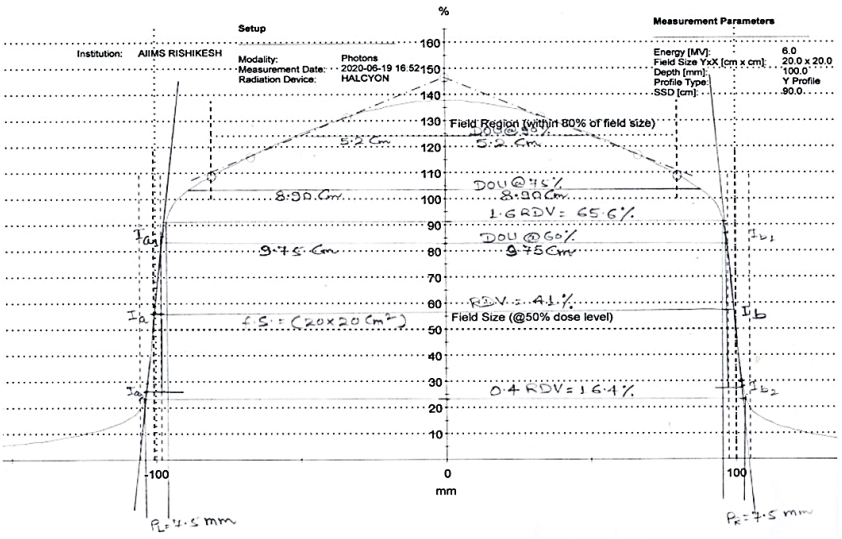

Figure 1. Depth dose profile of 6 MV-FFF beam to analyse beam parameter at SSD=90 cm, d=10cm and field size=20*20 cm^2

- Off-axis ratio was measured at ±3 cm lateral distance from the central axis at 10 cm depth for 10*10 cm² field size.
- Lateral distance from the central axis on either side of the beam profiles at 90%, 75%, and 60% dosage points were measured along the major axis for assessing degree of unflatness.
- The reference dose value (RDV) is the dosage value at the Inflection points (IP), which are points determined at 1.6 and 0.4 times the RDV (i.e., 80% and 20%), respectively. The lateral distance between the 1.6 RDV and 0.4 RDV points on either side of the profile [7], as depicted in figure (1), is known as the radiation beam penumbra.

Safety checks, output, radiation leakage, and dosimetric characteristics of the dual layer MLC system including transmission, dosimetric leaf gap, tongue and groove effects performed. Rapid arc delivery test, MV imaging test, couch transmission factor, etc., were also measured. Halcyon™ LA geometry presents a challenge as it has O-shape geometry, no light field, mechanical distance measuring device, hence adopting an image-guided approach to perform quality assurances. Mechanical test performance is relative to treatment isocenter derived from irradiation of EBT gafchromic film, EPID imaging, or other phantom-based radiation measurements. For laser verification, a QUASAR™ Penta-Guide Phantom was placed and set at the virtual isocenter position, and the required longitudinal shift to treatment isocenter was performed; the image was acquired with an electronic portal imaging device (EPID), necessary shifts were performed, and it was the laser deviation from the radiation isocenter. Gantry and collimator angle accuracy was checked by exposing an EBT3 gafchromic film at different angles. For different tests of MV imaging quality assurance, gafchromic film, quart phantom, catphan, las vegas phantom, and small object detection tools were used [8,9].

Results

Mechanical tests

Due to the non-presence of the light field, a new image-guided strategy was adopted to perform mechanical tests with the help of the gafchromic film and electronic portal dosimeter (EPID) system. Laser accuracy measured <1mm.

Output consistency check and Tissue Phantom Ratio ($TPR_{20/10}$) measurement

Output consistency was checked three times a day for the stability of beam output. A maximum deviation of 0.97% was observed. Output at different static gantry angles was performed, and results are shown in table (1). Quality Index ($TPR_{20/10}$) measured value was 0.626, and energy stability (quality index) for available photon energy 6MV FFF at different times in a day was within ±1%.

Percentage depth dose (PDD) and beam profiles measurement

PDD at a depth of maximum dose (D_{max}) and 100 mm depth for sizes 2x2 cm², 4x4 cm², 6x6 cm², 8x8 cm², 10x10 cm², 20x20 cm², 28x28 cm² field sizes acquired. The crossline and inline profiles were analyzed manually. The reference dose value (RDV) was 41% on the percentage dose axis on the beam profile, with the degree of unflatteness (DoU) at 60%, 75%, and 90% analyzed for inline and crossline beam profiles. Their values were 9.8 cm, 8.90 cm, 5.20 cm (both sides), and 9.75 cm, 8.90 cm, and 5.20 cm (both sides), respectively. Penumbra was analyzed for inline and crossline beam profiles; their values were 7.5 mm (left and right) and 8.0 mm (left and right), respectively, for 20*20cm² field size with 90 cm SSD at 10 cm depth. Table (2) summarizes penumbra measurements for various field sizes. Figure (2) shows RFA setup and chamber position verification through EPID on Halcyon™. Figure (3), figure (4), and figure (5) respectively show measured percentage depth dose, beam profiles, and output factors. The measured data was well in agreement with reference pre-configured beam data.

Table 1. Output at static gantry angles

Gantry angle (°)	Output reading	% Deviation	Tolerance
0 (Ref)	0.2834	0.0000	±3 %
90	0.2843	0.3909	±3 %
180	0.2852	0.5810	±3 %
270	0.2854	0.6880	±3 %

Table 2. Penumbra in measured beam profiles for different field sizes

Field Size	Penumbra Left (cm)	Penumbra Right (cm)
2cm*2cm	0.48	0.46
4cm*4cm	0.50	0.50
5cm*5cm	0.53	0.58
8cm*8cm	0.58	0.55
10cm*10cm	0.60	0.60
20cm*20cm	0.75	0.75
28cm*28cm	0.88	0.85

Surface dose

International Electrotechnical Commission (IEC 60976) defines the surface dose as the dose at a depth of 0.5 mm. It was measured for field sizes 2x2 cm², 4x4 cm², 6x6 cm², 8x8 cm², 10x10 cm², 20x20 cm², 28x28 cm². Percent surface dose measured 69.5% for maximum field size 28x28 cm² with semiflex 3D (0.07cm³) volume chamber.

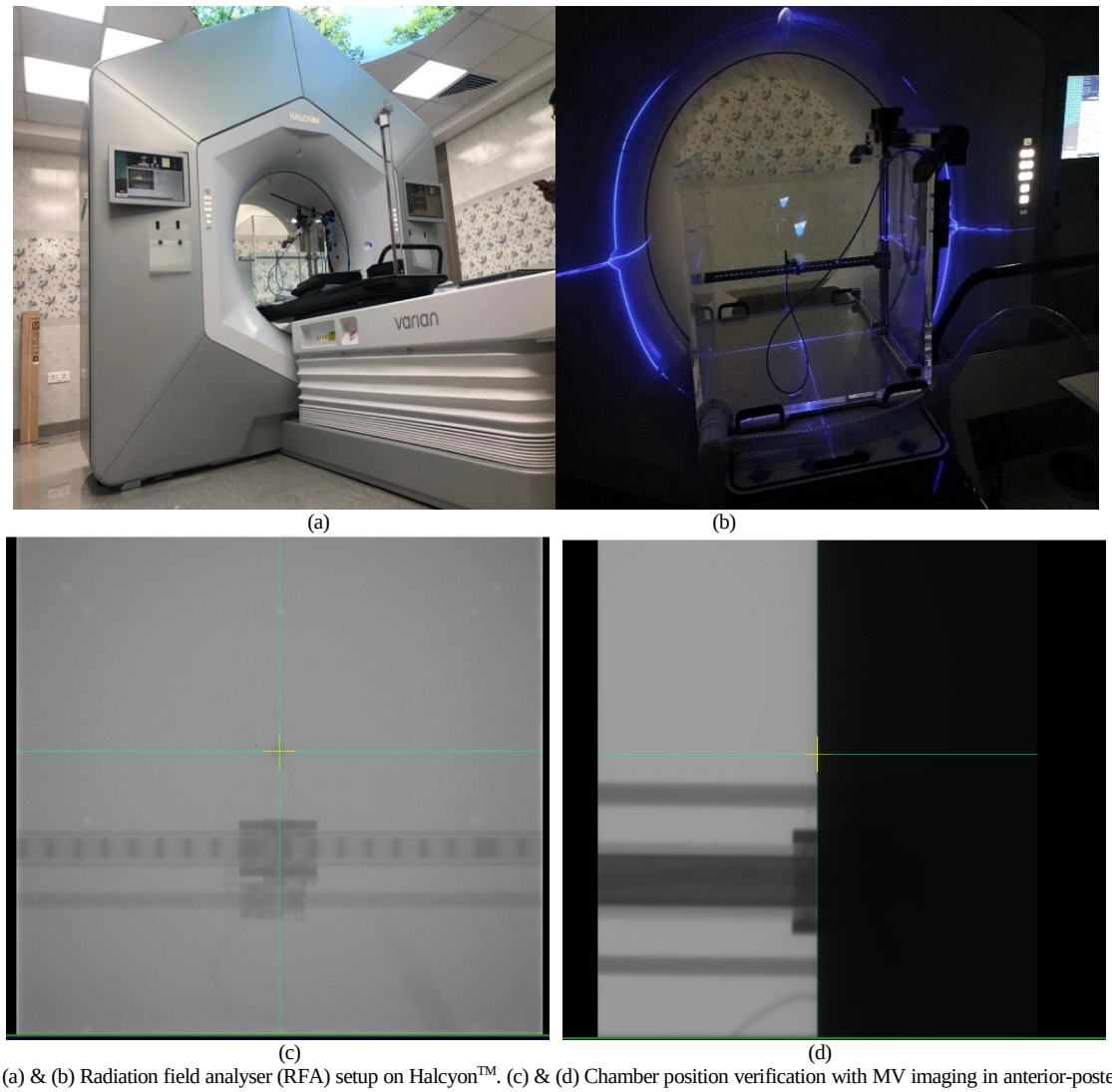

Figure 2. (a) & (b) Radiation field analyser (RFA) setup on Halcyon™. (c) & (d) Chamber position verification with MV imaging in anterior-posterior (AP) and lateral setup.

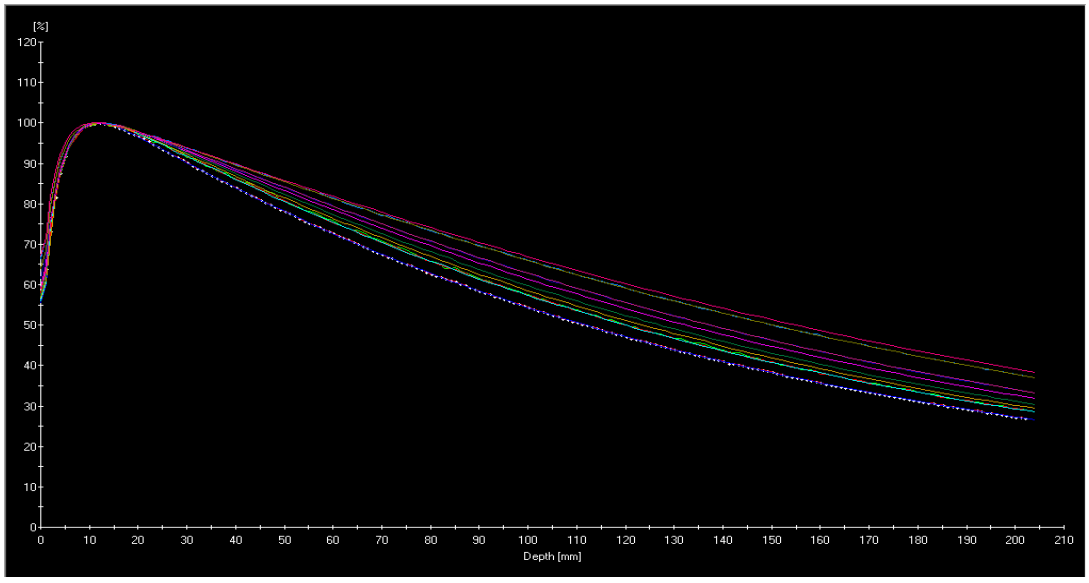

Figure 3. Measured percentage depth dose (PDD) curve for 6 MV-FFF beam at SSD=100 cm.

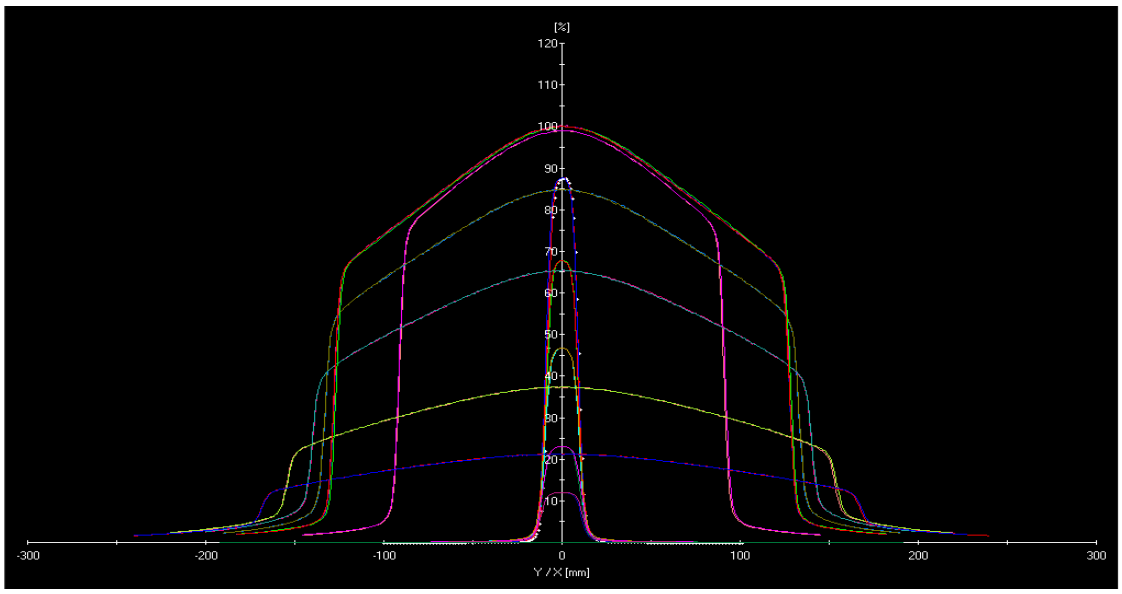

Figure 4. Measured depth dose profile (MBP) curve for 6 MV-FFF beam at SSD=90 cm for various field sizes starting from 2*2 cm² to 28*28 cm²

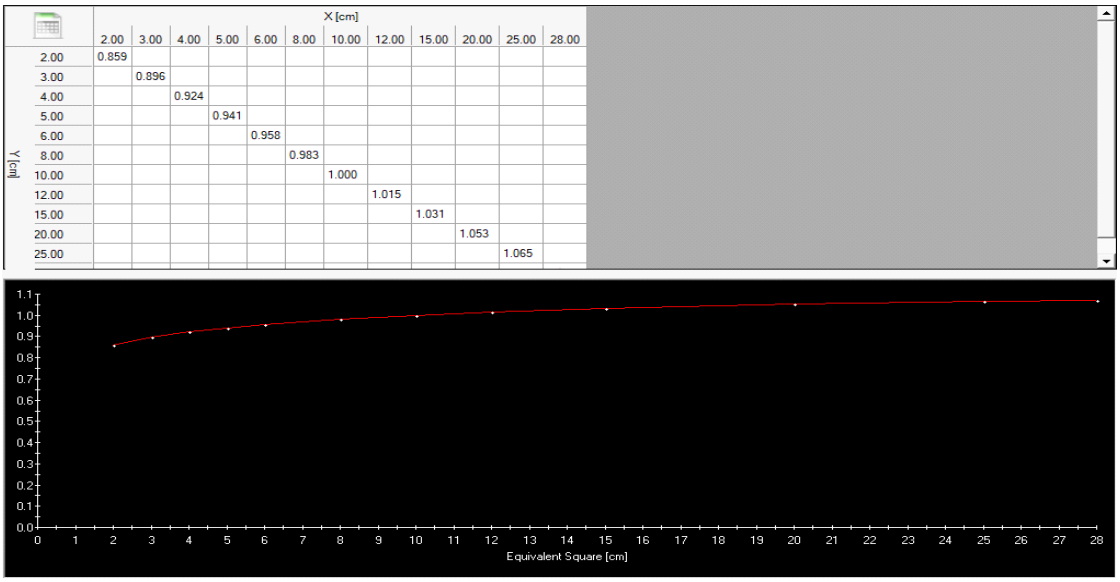

Figure 5. Measured output factor (OF) for 6 MV-FFF beam

Multi leaf collimator (MLC) tests

Maximum photon leakage radiation through MLCs: (i) For proximal bank at Dmax and 10 cm depth were 0.40% and 0.44%. (ii) For distal bank at Dmax and 10 cm depth were 0.30% and 0.43%. (ii) For combined at D_{max} and 10 cm depth were 0.35 % and 0.40%. Excellent agreement (0.01 cm) between TPS and measured dosimetric leaf gap (DLG) was found. Figure (6) shows the result of the dosimetric leaf gap (DLG) measurement for Halcyon™ dual-layer MLC. The picket fence test result showed an average value of 0.9 mm. The MLC leaf position accuracy and reproducibility both were within 0.5 mm. The tongue and groove effect was 0.04% and 0.05%, respectively, for proximal and distal banks. Figure (7) shows the picket fence image performed with EPID and the picket fence image with intentional leaf-end position errors performed with EPID, respectively. Table (3) shows the static picket fence test result.

Table 3. Static Picket-Fence Results

Gantry angle (degree)	Maximum deviation (mm)	Tolerance (mm)
0 (Reference)	0.27	1
90	0.25	1
180	0.26	1
270	0.26	1

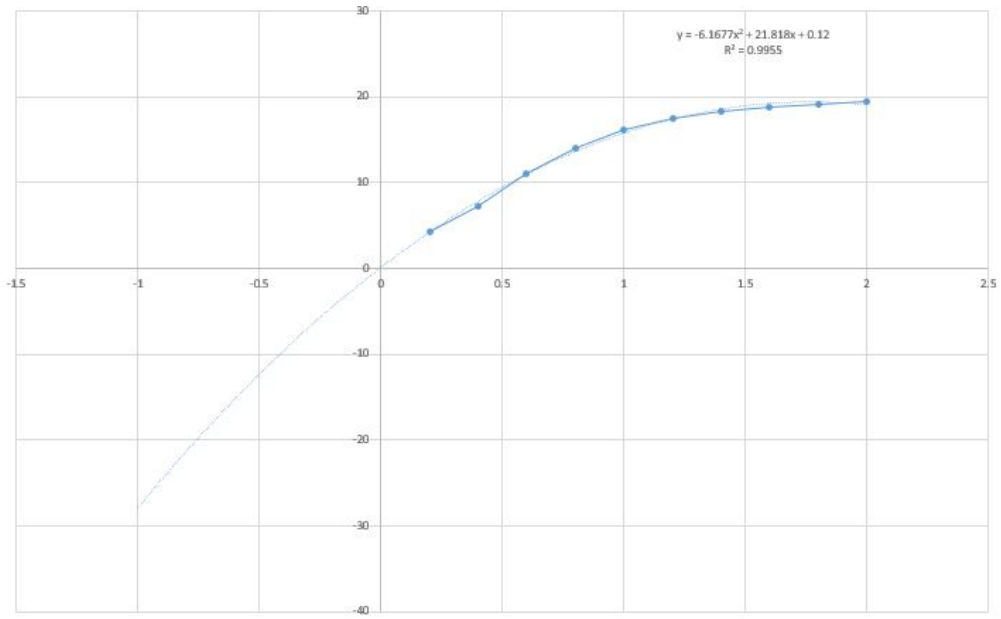

Figure 6. Dosimetric leaf gap (DLG) measurement for Halcyon™ dual layer MLC

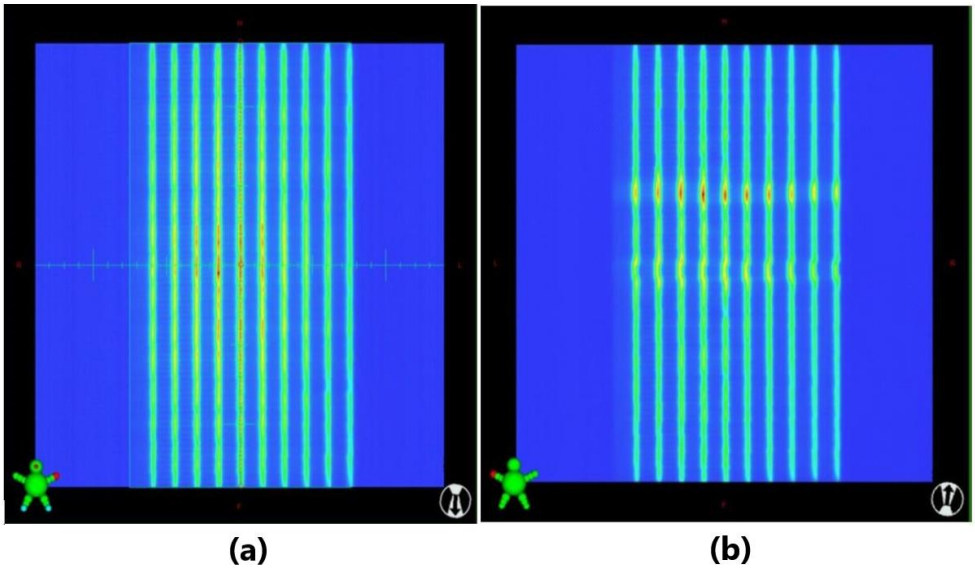

Figure 7. a) Picket fence image performed with EPID & b) Picket fence image with intentional leaf-end position errors performed with EPID

Megavoltage (MV) imaging isocenter accuracy

The accuracy of the MV imaging isocenter is paramount as it is to be used to verify the patient setup before dose delivery. The coincidence of the radiation isocenter and MV imaging isocenter was checked and it was within <1mm diameter

Patient plane leakage measurement

Measurement was performed with a farmer-type ionization chamber (0.6 cm^3) by PTW with a buildup cap. In the bore gantry system, as the couch moves inside the bore no couch rotation is possible and few points are outside the patient plane; it is possible to measure only 8 out of 24 points. In addition, all values were <0.01%.

Rapid Arc performance QA

DMLC dosimetry, picket fence test versus gantry angle (static case), picket fence test during the rapid arc, picket fence during rapid arc with intentional errors, accurate control of dose rate and gantry speed during rapid arc delivery, accurate control of leaf speed during rapid arc delivery test performed. For the DMLC dosimetry test, the maximum deviation was 0.60% for 270^0 with respect to the reference 0^0 gantry angle. For the picket fence test versus gantry angle (static case), the picket fence test during rapid arc maximum deviation was found to be 0.27 mm and 0.39 mm, respectively. For the picket fence, during rapid arc with intentional errors, the wider leaf pair and the shifted leaf pair were visualized.

For accurate control of dose rate and gantry speed during rapid arc delivery, deviation of the corrected reading of each region of interest (ROI) [diff(x)%] value was 0.90%, 0.08%, and the average of absolute difference [diff(abs)%] was 0.49%, 0.34% respectively. For accurate control of leaf speed during rapid arc test delivery deviation of the corrected reading [diff(x)%] value was 1.90% and the average of absolute difference [diff(abs)%] was 0.85%.

Intensity modulated radiation therapy (IMRT)/volumetric arc therapy (VMAT) commissioning

The goals specified by TG-119 were achieved in all test cases. Gamma evaluation shows that with 3%, 3mm dose difference and distance to agreement (DTA) criteria, points passed by 100%, whereas for criteria of 2%, 2mm points passed by 99% to 100% except for 92% for multi-target (VMAT_MT) case. Figure (8) shows the setup of slab phantom with an ion chamber inserted into the groove and the treatment plan created in Eclipse TPS version 16.1. Figure (9) shows the results of gamma (ϒ) analysis for IMRT and VMAT plans performed on electronic portal dosimetry (EPID) and result of the standardized test cases shown in table (4).

End-to-end (E2E) verification and patient specific quality assurance (QA)

E2E tests performed on slab phantom starting from acquiring computed tomography (CT) image, plan generation, image verification, and dose delivery for all the available treatment techniques. A smooth workflow started from CT acquisition to dose delivery for all plans observed, and the dose difference was within <3% for all cases. Patient-specific QA was performed with point dose verification and fluence verification method; the result was within respective tolerances.

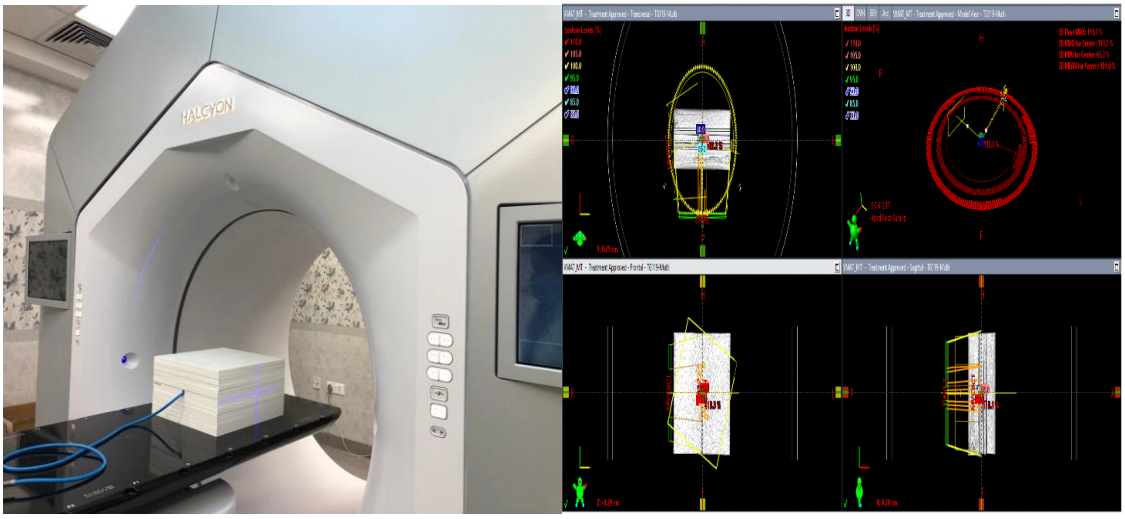

Figure 8. VMAT plan for multi target case as per TG-119 recommendation

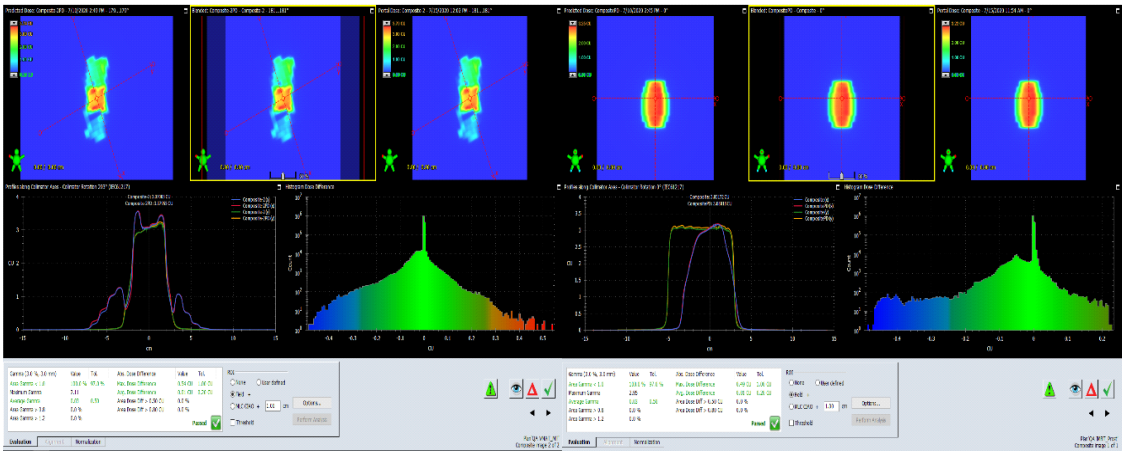

Figure 9. Gamma evaluation for IMRT and VMAT plans of multi target cases as per TG-119 recommendation

Table 4. Result of tests performed as recommended by AAPM TG-119

S.No.	Plan ID	TPS Dose (Gy)	Measured Dose (Gy)	% variation
1	AP-PA C Shape	4.00	4.08	1.80
2	IMRT C Shape	1.75	1.77	1.14
3	IMRT_HN	1.77	1.77	0.00
4	IMRT_MT	1.78	1.78	0.00
5	IMRT_Prostate	1.99	2.01	1.00
6	VMAT C Shape	2.05	2.11	2.90
7	VMAT_HN	1.79	1.81	1.10
8	VMAT_MT	2.11	2.06	2.40
9	VMAT_Prostate	1.96	2.01	2.50

Discussion

In this study, we performed all pre-requisite QA before validating the O-ring gantry system. In this regard American association of physicists in medicine (AAPM) task group-100 (TG-100) report provides a guideline regarding the application of risk analysis methods to radiation therapy quality management. Many errors in radiation oncology are caused by problems with workflow and process rather than malfunctions with hardware or software. To effectively allocate limited QM resources and achieve optimal safety and patient care quality, a methodical comprehension of the probability and therapeutic consequences of potential malfunctions during radiation is required. TG-100 has approached these problems broadly. Through the RT planning and delivery process, a framework for creating quality management (QM) activities has been developed, based on estimates of the probability of recognised failures and their clinical outcome. A particular radiotherapy procedure necessary for "intensity modulated radiation" has been selected by the Task Group. The Task Group has chosen a specific radiotherapy process required for "intensity modulated radiation therapy (IMRT)" as a case study. To show the RT community that these techniques could lead to more effective and efficient ways to improve the safety and quality of our treatment operations, TG-100 used contemporary risk-based analysis tools to this intricate RT process [10]. Teo PT et al. (2019) provided risk analysis techniques for the Halcyon™ LA acceptance testing and commissioning process using the TG-100 framework. They demonstrated how the risk assessment methodology suggested in the TG-100 study, when applied to the full acceptance testing and commissioning (ATC) procedure of a Halcyon™ LA, might serve as a model for enhancing the features of the Halcyon™ LA's design. Failure modes and effects analysis (FMEA) was carried out in accordance with the AAPM TG-100 protocol's instructions. Quality control and failure mode analysis (FMEA) were used to reduce the failure modes (FMs) in the Halcyon machine's ATC process. Particular FMs that arise from the variations between the vendor's ATC recommendations and the present conventional protocols, as well as the difficulties in executing the ATC because of the newly highlighted ring-gantry design and novel linac characteristics [11].

To confirm that the patient is receiving the recommended dosage from the system, a water phantom offers accurate beam data and beam model visualisations. Data measured in accordance with Eclipse TPS requirements for Halcyon™ LINAC. The measured data and the reference beam data (RBD) supplied by the vendor agreed well. Gao S et al. (2019) investigated the viability of using an ionisation chamber array (ICA) and a one-dimensional water scanner (1DS) in lieu of a three-dimensional water scanning system (3DWS) for the Varian Halcyon-Eclipse Treatment Planning System (TPS) acceptance testing and commissioning verification. A 1DS, an ICA, ionisation chambers, and an electrometer were used to measure the beam data. Commissioning and acceptance testing are carried out concurrently by comparing the measured data with profiles and percentage-depth-dose (PDD) pre-configured in TPS. This study suggested that 1Ds can use to accept and verify the halcyon system; this type of RFA is an alternative to 3Ds, especially in resource-limited countries (middle and low-income countries) due to their cost effectiveness [12]. In this study we have used 3D RFA for relative dosimetry measurements.

Halcyon™ medical LA system comes with pre-configured reference beam data (RBD), resulting in shorter commissioning and validation time than conventional LA. De Roover R et al. (2019) demonstrate that the international commissioning requirements of AAPM MPPG 5. a and AAPM TG-119 are met by a fast-rotating O-ring linac and its pre-configured TPS. E2E readings on human phantoms that were diverse fell within tolerable clinical bounds [13]. However, the AAPM TG-106 study demonstrates that reference beam data provided by the same manufacturer for the same equipment may vary. Since commissioning beam data is used as a reference and eventually used by treatment planning systems, the purpose of the TG-106 report is to support a certified medical physicist in measuring the beam data, confirming a portion of it prior to use, or for periodic quality assurance measurements. To prevent dosimetric and patient treatment errors that could result in unfavorable radiation results, the data that is gathered needs to be of the highest caliber. Therefore, it is crucial to carry out the commissioning and beam data validation with great care. Hence it is essential to carefully perform

commissioning and validation of the beam data, as any deviation of beam data during the commissioning and validation process leads to a potential risk of injury. Already incidents reported regarding this lead to a fatal consequence of under-dosing and overdosing on patient treatment. TG-106 report also emphasizes the emerging trend in Monte Carlo simulation techniques in photon and electron beam commissioning [14].

Netherton T et al. (2019) study shows that the volume averaging effect of a large vs. small for 10*10 cm2 field (depth = 10 cm) yielded a 0.2 cm difference in the penumbra. These differences in penumbra were small for large field sizes (>8*8 cm2). They also observed that for a 2*2 cm2 small field (because of lack of charge particle equilibrium, volume averaging effect, and source occlusion), using an ultra-volume chamber and small volume chamber penumbra difference of 0.2 cm was observed. Given that the penumbra difference is 10% of the field size, it is noteworthy. They come to the conclusion that comparing dose profiles computed in a TPS with those obtained from scanner measurements would not be appropriate in bigger volume chambers. Ultra-tiny chambers (diodes, diamond detectors) matched relative TPS beam profiles more precisely than small-volume chambers for small field sizes [15]. We have used a semiflex 3D chamber (0.07 cm^3) to measure PDDs, beam profile, and output factor. Technical Reoprt Series by International Atomic Energy Agency (IAEA TRS-398) (2000) International Codes of Practice for dosimetry of radiotherapy beams adopted. The document provides the necessary formulation for reference and relative dosimetry and the data required for their implementation.

IMRT plan integrity verification was a critical step for this machine to ensure the accuracy of treatment dose delivery because of its unique geometry from the conventional LA. The commissioning of intensity-modulated radiation therapy (IMRT) was carried out in accordance with the task group (TG)-119 procedure of the American Association of Physicists in Medicine (AAPM). IMRT commissioning: Multiple institution planning and dosimetry comparisons have been thoroughly reported by Ezzell GA et al. (2009); this work has generated quantitative confidence limits as baseline anticipated values for IMRT commissioning. To evaluate the overall precision of IMRT treatment planning and delivery, a series of test scenarios was created. Target and avoidance structure outlines are drawn inside rectangular phantoms for each test. This report concluded that any locally derived confidence limits that substantially exceed baseline values set by TG-119 might indicate the need for improved IMRT commissioning. It set a standard regarding what should be a reasonable and achievable standard for IMRT commissioning [16]. In present study, the measured dose was compared with the dose calculated on the active volume of the chamber with Eclipse TPS version 16.1 (M/s Varian Medical System, Palo Alto, CA). A good agreement was found between TPS planned dose and the measured dose. Standardized test cases were imported, planned, and dose delivered to determine the agreement between Eclipse TPS calculated dose and measured dose on the treatment delivery system (Halcyon™ LA O-ring system). E2E tests performed with slab phantom having ion chamber inserted into groove given for all the available treatment technique. Rapid arc performance and integrity tests were performed for each associated parameter with the help of a farmer-type ion chamber and EPID. All tests were within their respective tolerance limits; this proves that rapid arc can be performed with desirable accuracy.

The AAPM TG-218 guideline's recommendations for patient-specific quality assurance (PSQA) are followed; the report offers a thorough review with the goal of enhancing comprehension and uniformity of these procedures, as well as suggestions for approaches and tolerance limits in patient-specific IMRT QA. The goal of these recommendations for IMRT QA delivery strategies, data interpretation and dose normalization, γ analysis routine use, and tolerance limit selection was to identify discrepancies between calculated and measured doses using rigorous analysis techniques and a thorough comprehension of IMRT verification metrics. PSQA was carried out in this investigation using the point dose and fluence verification methods. The point dose measurement performed with slab phantom having ion chamber inserted into groove scanned, planned, placed on the couch, and dose delivered showed a good agreement between TPS planned dose and measured dose [17]. The EPID was used for the fluence verification approach. Gamma evaluation showed that with criteria of (3%,3mm) dose difference and distance to agreement (DTA) points passed by 100%, whereas for criteria of (2%,2mm) points passed by 99%-100% except for 92% for VMAT_MT case, which possibly due to sharp the dose gradient between high, intermediate and low planning target volumes [18].

Conclusion

The Halcyon™ fast-rotating O-ring gantry system was commissioned and validated. It fulfills the international commissioning codes of practice. With the appropriate choice of detector, all the measured commissioning parameters agreed with the TPS value. Good agreement between TPS calculated and measured dose of IMRT/VMAT plans, confirmed the treatment delivery quality. The E2E tests were successful, showing smooth workflow from CT scan acquisition to dose delivery. The commissioning and validation experience will be helpful to enhance the confidence and adapt the ring gantry-based LA for improved radiotherapy techniques in clinical applications.

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