

Experience and Suggestions on “Commissioning and QA Procedures” for Halcyon

Version 1.2

Contributors: MD Anderson Cancer Center University of Pennsylvania

Laurence Court	Dimitris Mihailidis
Peter Balter	Chris Kennedy
Song Gao	Ryan Scheuermann
Tucker Netherton	Lei Dong
Yuting Li	James Metz

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1. INTRODUCTION

This document is a report of the early experiences for commissioning and QA of the Halcyon™ treatment delivery system based on evaluations of non-clinical prototype versions of the system. We expect that the establishment of the clinical practice of commissioning and QA for the Halcyon treatment delivery system will be developed by the clinical community of users, based on collective experience and future reports and publications.

This information is provided to leverage the experience gathered during the evaluation of non-clinical Halcyon treatment delivery systems to assist new users who are approaching the system for the first time.

The commissioning and QA procedures reported in this document are largely based on the following The American Association of Physicists in Medicine (AAPM) reports:

- **AAPM TG-51 protocol for clinical reference dosimetry amended for FFF beam**
- **AAPM MPPG- 5.a Commissioning and QA of Treatment Planning Dose Calculations**
- **AAPM TG-119 on IMRT commissioning**
- **AAPM TG-142 report on Quality assurance of medical accelerators**

Other relevant documents are referred to in various Sections.

This document is written with recognition of the contents of the AAPM TG reports cited above, and describes procedures and methodologies suggested by those reports. To the extent that there are design features unique to this machine that may have relevance for commissioning and QA, these design features are described in more detail.

This document is based on the work of two USA-based institutions, University of Pennsylvania and MD Anderson Cancer Center, in collaboration with Varian. The two institutions used the recommendations from various AAPM reports for guidance in their approach to the commissioning and QA for the new treatment delivery system. Users in other geographic locations should consider taking into account similar reports from their respective professional and scientific societies.

This document is a reporting of work that was done and recommendations that were followed by the two institutions. This should be considered a 'works in progress' that enables the clinical community to eventually establish consensus recommendations for commissioning and QA of the Halcyon system. Mention of specific QA products or devices is not intended to be an explicit or implicit endorsement of those products. Technical information about the Halcyon product described in this document is subject to change.

Lastly, the contributors are providing this document as a courtesy, and are not to be held responsible for any omissions, errors, etc. in the document.

2. SAFETY CHECKS

Safety checks are performed to assure a safe environment for the staff and public. A basic set of checks is summarized in the table below.

TABLE 1: Safety Checks for Halcyon

System	Description
Door Interlock	Door open
Audio	One-way audio intercom
Video monitor	1 remote controlled camera with zoom
Radiation Monitor	Console flashing light
Radiation off at console	Radiation off button on console
Stop treatment with timer	Set time on console
Collision interlock - end of couch	Collision detector by the end of couch bottom
Collision interlock – bore	Collision detected with any item and the bore

3. RADIATION PROTECTION

The unit has a ring-mounted 6MV linac with a beam-stopper. The head leakage specification is 0.1% and the beam stopper is specified for 0.1% transmission of 6 MV. The user should refer to NCRP Report No. 151 for shielding calculations, vault evaluation and associated considerations. It is the user's responsibility to comply with all local shielding, and radiation safety/protection requirements. This may include measurements of head leakage as part of the acceptance testing of the unit. A radiation area survey is also needed upon successful installation of the unit before further commissioning measurements are acquired.

4. ABSORBED DOSE AT REFERENCE DEPTH

It is the user's responsibility to calibrate the unit with the approved calibration protocol for their location and ensure that it matches the reference setting in the Eclipse™ treatment planning system. In regions that use the AAPM TG-51 protocol the user is reminded to apply the TG-51 addendum for FFF beam [1, 2]. For protocols that allow calibration in water or plastic the recommended dosimetry medium is water and a tank of dimensions of at least 30x30x30 cm will be needed to cover the beam generated by the system. It is standard practice to use quality equipment with calibrations consistent with the local protocols that are not more than 2 years old shall be used. The meteorological equipment (thermometer and barometer) should also be of good quality and should have calibrations or inter-comparisons of not more than 1 year old. An example procedure based on TG-51 with reference values is presented below.

Example TG 51 procedure for the Halcyon

The IBA Blue Phantom 2 water tank was set up on the treatment table and a water-proof Exradin A12 farmer chamber was inserted for the output measurements. An ADCL-traceable, calibrated electrometer was used for measurements. The 100-cm water level SSD was set by adjusting the couch height to align the water surface with the isocenter crosshair in a lateral EPID image. Alignment of the ion chamber's measurement volume to machine isocenter was achieved using the Blue Phantom 2 central axis measurement utility, and verified with an anterior-posterior EPID image. Percent depth dose measurements were performed to determine the beam quality correction factor k_Q with and without the lead foil as described^{1,2}. The measurements showed that $PDD_{10}=63\%$ and 63.9% without and with lead foil, respectively. Equation (1) and Table I in [2] were used to calculate k_Q without lead (0.9974) and with lead (0.9962), resulting in a difference of 0.12%. The correction for change in radial beam profile over the chamber volume (P_{rp}) was 0.25%, calculated by averaging the profile scan results over the chamber length. The output calibration was measured at 10 cm depth and corrected to d_{max} using the clinical PDD_{10} for a $10 \times 10 \text{ cm}^2$ reference field at 100 SSD, as per TG-51. An adjustment of about 1% was made relative to the output established at installation. For safety considerations, the Halcyon is restricted to a limit of 5% adjustment of the dose output calibration at a time.

Important Note: The Halcyon system software requires that the user select one of three geometries for which 1 MU is normalized to 1 cGy, as described in the Appendix. The above example is for 100 SSD at d_{max} , with corresponding settings in the Eclipse. **It is extremely important that the selected calibration geometry and the settings in the Eclipse be the same, otherwise major treatment error can occur.**

¹Almond, P., et al., "AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams." Med. Phys. **26(9)**:1847-1870 (1999).

²McEwen, M., et al., "Addendum to the AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon beams" Med. Phys. **38**:5146-5166 (2011).

5. MECHANICAL AND RADIATION TESTS

Mechanical and radiation tests can be performed in accordance with recommendations from standard linac commissioning protocols and to the AAPM TG-142 or an equivalent safety protocol. The list below gives examples of methods to perform the recommended tests:

5.1. Delivery Component Mechanical Testing

Table Travel Indicator

- Measured with calibrated ruler over a travel range consistent with the magnitude of shifts expected in clinical practice.

Table Sag

- BB's attached to table and images taken at gantry angle 90 with various loadings.

Laser co-planarity and alignment with couch motion

- BB phantom with mechanical indicators aligned to lasers. Translate table for full range of laser projection. Observe run-out on phantom.

Virtual isocenter to machine isocenter shift

- BB phantom aligned to virtual isocenter using lasers. Move to isocenter position. Perform clinical 2D/2D match and record shift.

Isocenter size

- Winston-Lutz or Star-shot equivalent test (gantry and MLC rotation).

MV imager offset

- EPID images of BB phantom at cardinal gantry angles.

Coincidence of radiation/imaging/couch coordinates

- Observe run-out of BB under couch motion along expected beam axis in EPID images.

Digital gantry and collimator indicators

- Gantry method 1: Mark bubble level line on radiochromic film starshot.
- Gantry method 2: Observe run-out of BB under couch motion along expected beam axis in EPID images.
- Collimator: Image half beam block fields at cardinal collimator angles, use measuring tool to find actual angle.

MLC: alignment, speed, positioning accuracy, repeatability

- Vendor-provided test plans (picket fence at cardinal angles, MLC maximum speed test, etc.) analyzed with EPID/portal dosimetry and/or trajectory log file.

MLC dosimetric parameters: dosimetric leaf gap, transmission factor

- Vendor-provided test plans.

RapidArc Gantry speed/dose-rate/MLC speed tests

- Vendor-provide test plans analyzed with EPID/portal dosimetry and/or trajectory log file.

5.2. Radiation Testing

Beam performance tests:

- Backup monitor constancy
- Dose rate output constancy
- Beam profile constancy
- Energy check
- MU linearity
- Output/profile/dose rate change under gantry angle rotation

Details of how to perform these tests are not provided here but results of measurements conducted during the evaluation of the prototype systems are presented in the table below.

TABLE 2: Results of independent tests of Halcyon

Test	Independent measurement method and results
Isocenter size	Star-shots analysis: <ul style="list-style-type: none"> • Gantry rotation plane: 0.4 mm diameter • G-T plane: 0.30 mm diameter • Collimator rotation: 0.36 mm diameter
MV imager offset	BB cube/starshot: < 0.2mm
MLC position	Picket fence: < 0.5 mm
MLC reproducibility	Radiographic measurement: < 0.2mm
Y-field edge offset	Radiographic measurement: < 0.2mm
Collimator rotation offset	Radiographic measurement: < 0.2°
Gantry absolute/relative	Bubble level line marked on radiochromic film starshot: < 0.5 deg
Couch readouts	Ruler: < 0.5 mm over 20 cm travel distance
Couch Sag (200lb load)	3mm vertical, < 0.1° change in pitch
Virtual-to-isocenter distance	BB cube: < 0.5 mm
MLC dosimetric leaf gap	Proximal: 0.17 mm Distal: 0.18 mm
MLC transmission	Proximal: 0.44% Distal: 0.43% Combined: 0.007%
Dose rate constancy	Imaging dose rates <2% difference relative to treatment dose rate
MU linearity	2-4 MU < 4%, 5 MU and greater < 0.5% relative to 100 MU reference

Output/profile/dose rate constancy under gantry rotation	All readings < 1% difference compared to heads up gantry reading
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These results are within the stated tolerance of the MPC tests in Section 6.
Tests related to intensity modulated deliveries will be presented in subsequent paragraphs.

6. MACHINE PERFORMANCE CHECK (MPC)

Of importance is the provision and integration of the Machine Performance Check (MPC) procedure in Halcyon. The purpose of the MPC is to verify that the various machine parameters, radiation, mechanical and imaging, are within product specifications. Daily measurement using the MPC is a prerequisite prior to the clinical operation of the machine. However, it is not intended as a substitute of independent QA activities performed by medical physicists.

The MPC method is similar to that of the TrueBeam® system and has been reported in the literature (JACMP V18, p139-; Radiat Onc V10, p97-). Results of MPC measurement for this machine, has been compared with independent mechanical and radiation tests performed at the University of Pennsylvania and MD Anderson Cancer Center, as reported in other sections of this document.

The procedure for running the MPC, with the Varian Drum Phantom properly positioned, is detailed in the User Manual. Briefly, the MPC automatically sets various machine parameters and acquires 33 radiation images with the EPID. Based on these measurements, the MPC software performs analysis and verifies that the following items are within their respective tolerances:

- Isocenter size: ≤ 0.9 mm radius (Gantry and collimator isocenter accuracy)
- Isocenter projection (or MV Imager position) offset: ≤ 0.5 mm
- MLC leaf positioning accuracy: ≤ 0.6 mm
- MLC backlash: ≤ 0.8 mm
- Collimator rotational accuracy: $\leq 0.5^\circ$
- Y field edges: ≤ 1 mm
- Absolute gantry positioning accuracy: $\leq 0.5^\circ$
- Relative gantry positioning accuracy: $\leq 0.5^\circ$
- Relative couch positioning accuracy in all 3 axis: ≤ 0.5 mm
- Virtual to treatment isocenter couch shift accuracy: ≤ 2 mm
- Beam output change: ≤ 4 % (relative to Baseline¹ results)
- Beam uniformity change: ≤ 2 % (relative to Baseline results)
- Cumulative Gain Change in ion chambers for MU1 and MU2: $\leq 10\%$

¹ Before using the system clinically, it is required to perform a MPC run to establish a Baseline for beam changes.

If the measured results are within their respective tolerances, the console will show a “green check sign” icon. Otherwise the results of the MPC will need to be further reviewed.

The measured results can be reviewed in the “MPC Detail View” module, which provides more in-depth information about the acquired images and the associated analysis.

7. RADIATION BEAM CHARACTERIZATION

7.1. Background

The accuracy of the dose calculations in the Treatment Planning System (TPS) is essential for safe and effective dose delivery. At the time of this document, Varian provided only a preconfigured beam model for Halcyon in the Eclipse TPS and it is not user-adjustable. The built-in beam configuration includes the Analytical Anisotropic Algorithm (AAA) for final dose calculation, as well as the Multi-resolution Dose Calculation (MRDC) for IMRT and RapidArc® radiotherapy technology optimization, and the Fourier Transform Dose Calculation (FTDC) model for calculation of the MV imaging treatment field dose. If additional algorithms are added, then the commissioning process will need to be repeated for each algorithm that will be used clinically.

As the beam data is pre-configured, manual or automated entry into the TPS is not necessary. However, the users are responsible for validating that the dose calculations are sufficiently accurate. The following guidance documents were reviewed in the context of commissioning the Halcyon system:

- **AAPM Medical Physics Practice Guideline 5.a.: Commissioning and QA of Treatment Planning Dose Calculations – Megavoltage Photon and Electron Beams (MPPG5.a).** Treatments with Halcyon fall within the scope of this document in terms of geometry, dose calculation algorithm, MLC use and recommended tolerances. This report refers to the **IAEA TRS 430** report, which is also an appropriate guidance document.
- **Accelerator beam data commissioning equipment and procedures: Report of the TG-106 of the Therapy physics committee of the AAPM.** This report provides guidelines and recommendations on phantom and detector selection that are relevant to the device, as well as many practical hints that are useful when taking data.
- **IMRT commissioning: Multiple institution planning and dosimetry comparisons, a report from AAPM Task Group 119.** This document contains a series of test cases that can be executed for evaluating IMRT planning/delivery.

Additional details of the preconfigured beam model and algorithms can be found in Varian’s *Eclipse Photon Beam Model for Halcyon* document on MyVarian (my.varian.com), the *Eclipse Photon and Electron Algorithm Reference Guide*, and the *Instructions for Use*.

7.2. Example of Beam Dosimetric Characterization

Radiation beam dosimetry is validated against the TPS calculation during the machine commissioning processes.

1. Output determination: (a) Verification of Calibration (TG-51 protocol), (b) Verification of Monthly and Daily Constancy Values
2. Relative Dosimetric validations:
 - (a) Percent Depth Dose:

Blue2 water phantom, SSD = 90 cm, different field sizes (2 to 28cm).
For 10x10 field, PDD (10cm) = 61.4%±1%, $d_{max} = 1.3 \text{ cm} \pm 0.15 \text{ cm}$.
 - (b) Output Factor versus Field size:

Blue2 water phantom, SSD = 90 cm, different field sizes (2 to 28cm), depth =10 or 5 cm.
 - (c) Beam profiles:

Blue2 water phantom, SSD = 90 cm, different field sizes (2, to 28cm), depth: d_{max} , 5, 10, 20, 30 cm.
 - (d) Flatness and Symmetry:

Flatness and symmetry were calculated from in-plane (radial) and cross-plane (transverse) scans using the Wellhöfer scanning system.
 - (e) Off Axis Factor:

The data below is from in-water scans, an average of in-plane and cross-plane profiles, setup SSD = 90 cm. For the largest 28 × 28 cm² field and standard 10 × 10 cm² field, scans were taken at different depths, from 1.3 cm to 30.0 cm. The measurement result is also compared to the Eclipse treatment planning system (TPS) calculations; the agreement between the measurement and TPS calculation should be ≤ 1% within 80% of the field width. The TPS calculation data as follows²:

TABLE 3: 6MV FFF - Off-axis factor from TPS calculation, 90 cm SSD, 10x10 cm² field.

Depth(cm)	1.3	5	10	20	30
Distance (cm)					
0	1.000	1.000	1.000	1.000	1.000
1	0.994	0.993	0.993	0.993	0.994
2	0.978	0.977	0.976	0.977	0.979
3	0.950	0.947	0.945	0.948	0.954
4	0.894	0.895	0.897	0.906	0.918
5	0.074	0.160	0.490	0.827	0.867
6	0.029	0.052	0.092	0.179	0.513

TABLE 4: 6MV FFF - Off-axis factor from TPS calculation, 90 cm SSD 28x28 cm² field.*

Depth (cm)	1.3	5	10	20	30
Distance (cm)					
0	1.000	1.000	1.000	1.000	1.000

² This is with a pre-release version of the preconfigured beam model. Results may be slightly different with the commercial release of Eclipse 15.1.1.

1	0.994	0.995	0.995	0.996	0.997
2	0.981	0.983	0.985	0.988	0.990
3	0.959	0.962	0.966	0.972	0.977
4	0.929	0.936	0.943	0.952	0.960
5	0.897	0.906	0.915	0.929	0.940
6	0.875	0.879	0.888	0.903	0.916
7	0.842	0.850	0.860	0.877	0.892
8	0.808	0.817	0.828	0.849	0.866
9	0.780	0.785	0.795	0.817	0.838
10	0.745	0.752	0.762	0.784	0.808
11	0.714	0.718	0.726	0.751	0.776
12	0.679	0.682	0.689	0.715	0.744
13	0.137	0.597	0.645	0.677	0.710
14	0.044	0.085	0.373	0.635	0.674

(f) Beam profile versus gantry angle:

Beam profiles were measured using Sun Nuclear IC Profiler for four principle angles: 0°, 90°, 180°, and 270°.

(g) Dose-MU Linearity

(h) Inverse Square Law Check

(i) In Air Output versus Gantry Angle

(j) Buildup Region dose

7.3. Comments on the MPPG5.a document.

The authors recommend following all photon validation sections of the MPPG5.a document for any algorithms used to calculate the dose from treatment fields:

- Equipment: We recommend following the equipment guidance in the MPPG5.a and AAPM TG-106 documents.
- Basic dose algorithm validation (section 5 of the MPPG5.a)
 - Note - The MPPG5.a document refers to the modeling (physics) module (test 5.1). This does not apply to the Halcyon system/Eclipse combination. All TPS calculations should be done in the External Beam Planning module of Eclipse.
- Photon beams: heterogeneity correction validation. We used an anthropomorphic phantom (CIRS) for these tests, but any similar phantom is appropriate.
- Photon beams: IMRT/VMAT dose validation. This is an important component of the validation, especially given that all treatments with the Halcyon device use step and shoot, sliding window IMRT or VMAT. The MPPG guideline was followed.
- External review (test 7.5 of the MPPG): We performed a complete end-to-end test using the IROC lung and head phantoms. We strongly encourage this or an equivalent test

which is an important and independent validation of the performance of the Halcyon system.

- The results of MPPG tests performed are shown in the table below:

TABLE 5: Commissioning tests based on MPPG5.a. These are the tests that we ran – others may also be useful and/or necessary.

MPPG Tests	MPPG Tolerance	MDACC Result
I. Basic Dose Algorithm Validation		
TPS performance under calibration conditions	0.50%	0.3%
PDD comparison between TPS and Measurement	2%	0.9%
Off-axis factor comparison between TPS and Measurement	2%	0.7%
PDD and profile comparison of small square MLC-shaped fields	High Dose region: 2%	1.6%
PDD and profile comparison of small asymmetric MLC shaped fields	High Dose region 5% Penumbra: 3mm DTA** Low dose tail: 3% of maximum field dose	High Dose region 4.99% Penumbra: 2.45mm DTA** Low dose tail: 2.45% of maximum field dose
Point dose and profile comparison of large field with extensive MLC blocking		
Point dose and profile comparison of half-beam block at minimally anticipated SSD		
Point dose and profile comparison of oblique incident beam		
II. Heterogeneity Correction Validation		
Point dose comparison using CIRS Thorax Phantom – Treatment dose (AAA)	3%	1.07%
Point dose comparison using CIRS thorax Phantom – Imaging dose*	3%	3.74%*** (<0.1 cGy)
III. IMRT/VMAT Dose Validation		
PDD and profile comparison of very small field (2x2)	See above	2.2%****
IMRT/VMAT QA result	2%2mm, no pass rate tolerance	92.4%
IROC Phantom End-to-End test	5% of prescribed dose	2%

*This is an addition to the MPPG5.a suggestions.

**DTA: Distance to agreement.

***The average imaging dose difference between measurements and TPS calculation is - 0.07cGy.

****For 2x2 cm² field size, PDD measured by EDGE detector, the average difference between measurement and TPS is 3.9%. PDD measured by CC13 detector, the average difference is 0.4%.

7.4. Validation of imaging dose calculations

The imaging dose calculations (MV-MV, or MV-CBCT) uses the Varian FTDC algorithm which is different than the AAA used for treatment field dose calculations. This algorithm should be separately validated. The authors used an anthropomorphic phantom (CIRS phantom), and

compared calculations and measurements for all available imaging techniques (orthogonal imaging, MV CBCT, high-quality and low-dose techniques). Other phantoms could also be used. Tests can include a range of field sizes, isocenter positions, and measurements at points in regions where the imaging and treatment fields overlap, and outside the overlapped regions. The average imaging dose from MV low-dose and high-quality orthogonal imaging and low-dose and high-quality MV CBCT was measured as 1.52, 3.04, 3.62, and 7.28 cGy, respectively. Comparison of the TPS and measured doses should be quantified, including the expected dose differences when imaging is used for each treatment fraction of a standard treatment course (e.g. over 30 fractions). Quality assurance tests for the imaging system are discussed in a later section.

7.5. Absolute dose calibration

Absolute dose was measured using the protocols recommended in the **AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams**. For the FFF beams of we followed the recommendations in **Addendum to the AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon beams** (sections 4.K. and 5.C.7). SSD and ion chamber position in a water tank can be verified using the advice below.

7.6. Using a water tank.

A 3D scanning water tank is useful for PDD, profile, and output factor measurements, although 1D tanks and array detectors could be used for some of the tests (this is consistent with MPPG5.a). TG-106 contains much useful advice on water tank measurements. Although it can be a tight fit, the following tanks have been used successfully by the authors in conjunction with the Halcyon system.

- IBA Blue Phantom
- IBA Blue Phantom2
- Sun Nuclear 1D Scanner™

To avoid collision, some tanks might need to be rotated by 90 degrees before moving the couch to isocenter.

Note-A PTW MP3-M water tank will fit inside the Halcyon bore while positioned on top of the couch. The PTW MP3-M device was not utilized by these authors.

7.7. SSD Setup

The lack of a mechanical distance indicator and ODI means that new procedures are needed to check the SSD when using a water tank (1D or 3D). An SSD measurement technique developed by Varian, which uses imaging to check the SSD, will be covered in Varian's Halcyon Physics Training Course. We have compared the vendor-provided technique against various other approaches (e.g. using a brass cap on the ion chamber or a high-Z flotation device to show the water surface in MV images), and shown them to be all equally accurate. The vendor-provided technique is generally the fastest and can be performed without additional equipment. Attention must be paid to the leveling of the water tank to account for any slight sag in the couch.

7.8. Isocenter Setup

MV-EPID images of the ion chamber can be taken to verify isocenter position. A brass cap placed on the ion chamber can be used to better visualize the chamber during High-Quality imaging. If a brass cap is not available, delivering high MU (20-100) during integrated imaging is an alternate method.

8. ROTATIONAL DELIVERY (RAPIDARC) RELATED TESTS

As described in [1], the accuracy of DMLC positioning during gantry rotation was evaluated by comparison of static to dynamically delivered picket fence tests captured by the EPID. The effect of gantry rotation on MLC positioning accuracy was found to be negligible (<0.2mm).

It is critical to test the precise control of dose rate, gantry speed, and MLC speed for accurate delivery of Volume Modulated Arc Therapy (VMAT). Two methodologies previously described in the literature were used for evaluation: 1) Patterns of equivalent dose delivered under varying levels of dose rate, gantry speed, and MLC speed were captured by the portal imager, and normalized to an open-field image. Three VMAT test plans¹ provided by the vendor delivered dose rate levels from 128 - 800 MU/min, gantry speeds from 3.7 - 23 deg/s, and MLC speeds from 1 - 5 cm/s respectively. 2) Imaging of a couch-mounted fiducial marker at a known off-isocenter location by a narrow field defined by the MLC ("Snooker Cue") to assess angular accuracy of VMAT delivery². Portal images were acquired for dose delivered around four discrete gantry angles for 180 degree VMAT fields, delivered in both clockwise and counter-clockwise directions. Accurate delivery was indicated by the fiducial appearing in the center of the MLC aperture. In-house generated treatment plans were developed with varying degrees of MLC delay between control points to test system performance. Induced errors of one and two degrees were performed to demonstrate test sensitivity. Log files acquired at 20 ms frequency were analyzed as an additional check of VMAT accuracy. The maximum deviation for any pattern was 1.9% when normalized to open field. All "Snooker Cue" images show the fiducial located near the center of the MLC aperture. Log file analysis revealed maximum errors of 0.2 mm (MLC), 0.21 MU, and 0.09 degrees for any sample during delivery.

¹Ling, C., et al., "Commissioning and Quality Assurance of RapidArc Radiotherapy Delivery System." *IJROBP* **72(2)**:575-581 (2008).

²Van Esch A., et al., "Implementing RapidArc into clinical routine: A comprehensive program from machine QA to TPS validation and patient QA." *Med. Phys.* **38**:5146-5166 (2011).

9. IMAGING TESTS

Relevant guidance documents referenced during our evaluation are:

- **Quality assurance for image-guided radiation therapy utilizing CT-based technologies: A report of the AAPM TG-179**
- **Task Group 142 report: Quality assurance of medical accelerators**

The user may also refer to AAPM TG 104: **The Role of In-Room X-ray Imaging for patient Setup and Target Localization**. Although this report focuses on kV imaging, many of the suggestions and discussion are relevant to MV imaging.

9.1. Image registration and couch motions

The accuracy of the image registration and couch motions is crucial for the Halcyon system. Tolerances for remote-controlled couches can be found in **Task Group 142 report: Quality assurance of medical accelerators**. TG-179 provides guidance for testing the entire image acquisition, registration and position correction process. An independent test of this can be included in the end-to-end tests (discussed in Section 10). Additional, regular QA is also appropriate – the frequencies and tolerances are covered in TG 142.

9.2. Image quality

TG-142 also covers the image quality measurements and tolerances for imaging, including uniformity and noise, spatial resolution, scaling and geometric accuracy. TG-179 suggests that image quality tests (for CT) be performed monthly, eventually switching to a semi-annual basis after stability has been demonstrated. The authors support these suggestions for the Halcyon system. Commercial phantoms can be used to perform image quality control tests. We have used the CatPhan 500 phantom (The Phantom Laboratory, Salem, NY), although other phantoms are available. Many CT phantoms were designed for kV imaging QA, but can also be used for measuring baselines for MV imaging.

TABLE 6: Image Quality measurements and recommended acceptance criteria.

Contrast		Criteria: NA		
Test	Low Dose		High Quality	
	Measured	Status	Measured	Status
Low contrast	0	N/A	0	N/A
High contrast	4	N/A	4	N/A
Geometric Accuracy		Criteria: $\leq 0.05\text{cm}$		
Distance between two rods	Low Dose		High Quality	
	Avg Diff (cm)	Status	Avg Diff (cm)	Status
	0.015	Pass	0.003	Pass
Image Uniformity		Criteria: $\leq \pm 40\text{HU}$		
	Low Dose		High Quality	
	Average HU	Status	Average HU	Status
HU in ROI	3	Pass	13	Pass

9.3. Imaging dose

TG-179 suggests that each facility should evaluate the doses associated with each IGRT implementation so that this can be discussed with the radiation oncologist. Additionally, TG-142

suggests measuring the imaging dose baseline, and monitoring periodically. These suggestions are appropriate for the Halcyon system. Measurement of the MV imaging dose is discussed in Section 7, including the accuracy with which Eclipse models the dose.

9.4. Accuracy of CT numbers

CT number accuracy is only important if images are used for dose calculations – this is not the purpose of MV CBCT images taken by the Halcyon system so some variation is acceptable. The authors' experience is that the CT numbers are not necessarily accurate. CT number measurements can be used as one of the descriptors of image quality, so it is useful to measure a baseline, repeated periodically.

10. END-to-END TEST

MPPG5.a recommends performing a complete end-to-end test that involves scanning an anthropomorphic phantom, planning, delivery, and sending dosimeters out for external review. Because all treatments with the Halcyon system use IMRT/VMAT, end-to-end tests using an anthropomorphic thoracic phantom are also recommended. The phantom should be positioned using IGRT, not just setting the phantom up using lasers – in this way, the end-to-end test includes a test of the phantom imaging, registration and position correction process. If it is not possible to send dosimeters out for external review, the results of the end-to-end tests should be peer-reviewed by an independent Qualified Medical Physicist (as recommended by MPPG5a).

We irradiated the anthropomorphic head/neck and thoracic phantoms provided by IROC-Houston, and had excellent agreement dose calculations and independent measurement. Both end-to-end tests passed with an average dose ratio (measurement/TPS) of 0.99 and 0.97, and an average gamma passing rate (7%/4mm³) for film profiles of 99% and 98.8% for the head-and-neck phantom and the lung phantom, respectively.

11. PERIODIC QUALITY ASSURANCE FREQUENCY AND METHODS

The following example of a periodic QA schedule for Halcyon system and TPS was generated with the guidance of AAPM Task Group reports 142 and 179, MPPG5.a report, and consultation with Varian representatives. Methods for testing are generally similar to C-arm type linacs, with notable exceptions being mechanical testing as described above, and dose rate constancy testing. Variable dose rates are not selectable in Service mode except for the nominal delivery dose rates for treatment and imaging. Testing of clinically relevant dose rates for modulated treatments can be accomplished using the vendor-provided test plans for RapidArc delivery (i.e., dose rate and gantry speed test treatment plans).

³ Criteria used by IROC

- Halcyon Treatment Device
 - Daily:
 - Safety:
 - Door interlock beam off
 - Door closing safety
 - Audiovisual monitors
 - Radiation area monitor (if used)
 - Beam on indicator
 - Backup MU counter
 - Beam termination
 - Bore collision interlock
 - Couch collision interlock
 - Dosimetry:
 - Output constancy
 - Mechanical:
 - Laser localization
 - Virtual to machine isocenter vector check
 - Imaging
 - Phantom localization and repositioning with couch shift
 - Monthly:
 - Dosimetry:
 - Output constancy
 - Backup monitor constancy
 - Beam profile constancy
 - Mechanical
 - Gantry/collimator angle indicators
 - Treatment couch position indicators
 - Laser localization
 - MLC
 - Travel speed
 - Positioning accuracy
 - Imaging
 - Scale, distance, orientation accuracy
 - Uniformity, noise
 - High contrast spatial resolution
 - Low contrast spatial resolution
 - RapidArc
 - Vendor-provided test treatment plans
 - Annual:
 - Dosimetry:
 - Profile/symmetry change from baseline

- Output calibration (TG-51)
 - Spot check of field size dependent output factors
 - X-ray beam quality
 - MU linearity
 - Output constancy vs. dose rate/gantry angle
 - Dose rate constancy
- Mechanical
 - Collimator/gantry rotation isocenter
 - Coincidence of radiation and mechanical isocenter
 - Table top sag
 - Table angle
 - Table travel maximum range movement all directions
- Treatment Planning System (TPS)
 - Annual:
 - Follow recommendations from MPPG5.a
 - After performance or software upgrade of Halcyon
 - MU Calibration consistency check between Halcyon and TPS
 - Delivery and gamma analysis of selected modulated plan (IMRT / RapidArc) compared to baseline
 - After software upgrade of TPS
 - MU Calibration consistency check between Halcyon and TPS
 - Recalculation of selected modulated plans (IMRT / RapidArc) compared to baseline

12. SUMMARY

This document should be considered a 'work in progress' towards supporting the clinical community in establishing recommendations for commissioning and QA of the Halcyon system. The medical physicists and their radiation oncology colleagues at two institutions, University of Pennsylvania and MD Anderson Cancer Center, devoted significant efforts to evaluate the radiation, mechanical and imaging characteristics of this machine. As indicated throughout the document, the authors followed AAPM recommended protocols extensively, and where necessary new methodology was developed.

The studies at the two institutions were initially independent of each other; only after each team has completed all phases of its investigation, were the findings jointly discussed and compared. Varian provided assistance and technical information to facilitate their studies. This document is the results of these independent and collaborative efforts. Example results are from either of the two institutions.

13. Acknowledgements

The authors would like thank Clifton Ling, Pekka Uusitalo, Mu Young Lee, Magdalena Constantin, Petri Kokkonen and Juha Kauppinen for the assistance and support they provided during the evaluation work and preparation of the document.

APPENDIX I – MU Calibration

The MU calibration conditions are detailed on the Halcyon console in **System Administration** under the **Configuration** tab. MU calibration of the machine is restricted to three different geometries and associated dose rates:

- 100 SSD, dmax depth (1.3 cm), max dose rate 800 MU/min
- 95 SSD, 5.0 cm depth, max dose rate ~740 MU/min
- 90 SSD, 10.0 cm depth, max dose rate ~600 MU/min

The MU calibration geometry is configured both at the console and within the TPS when the system is delivered and the software is installed by Varian. Within Eclipse™, the calibration geometry and depth of normalization where 1 MU = 1 cGy is displayed in the **General** tab of the **Field properties** dialog, and in the **Parameters** field in **Beam Configuration** module.

Users should ensure that the console and the TPS are configured identically, and further confirmed by measuring the dose at a point for a simple plan (i.e., open 10cm x 10cm).

APPENDIX II – Imaging and dosimetric measurements.

- a. **Materials:** The authors made use of a test device (model XRV-124) from Logos System International [<http://www.logosvisionsystem.com/>] to verify the treatment-to-image isocenter coincidence in an end-to-end type procedure. A cone-shaped scintillator that converts the beam into two visible spots in the beam direction uses the intersection of all beam vectors to give the average isocenter position. **Methods:** CT-based planning to create the intended isocenter with 8 pencil beam fields (8 angles). Use onboard CBCT to align the Logos system (IGRT). Deliver 8 slit beams with Halcyon system. Analyze the “Isofocus”: The average deviation of all beam vectors closest to the cone Z-axis (the imaging center).

Results: See table below

TABLE 7: Treatment-to-image isocenter coincidence with Logos system

XRV-124 Iso Analysis						
					Target =	0 0 84.4
Gantry	X	Y	Z_net	Theta	Distance to Target	Gantry Angle Accuracy
180	-0.061	0.000	-0.64	89.82	0.6387	0.18
135	0.824	0.818	-1.07	134.79	1.5764	0.21
90	0.004	1.068	-0.64	179.78	1.2452	0.22
45	-0.480	0.483	0.20	44.81	0.7088	0.19
0	0.067	0.000	0.22	89.78	0.2274	0.22
315	0.424	0.421	-0.30	134.80	0.6672	0.20
270	0.005	1.140	-0.63	179.76	1.3015	0.24
225	-0.690	0.696	-0.66	44.76	1.1830	0.24
Average	0.01	0.58	-0.44	Ref=84.4	0.7262 mm	0.60 Avg Deviation
STD	0.47	0.44	0.45			0.72 1SD
MIN	-0.69	0.00	-1.07			
MAX	0.82	1.14	0.22			

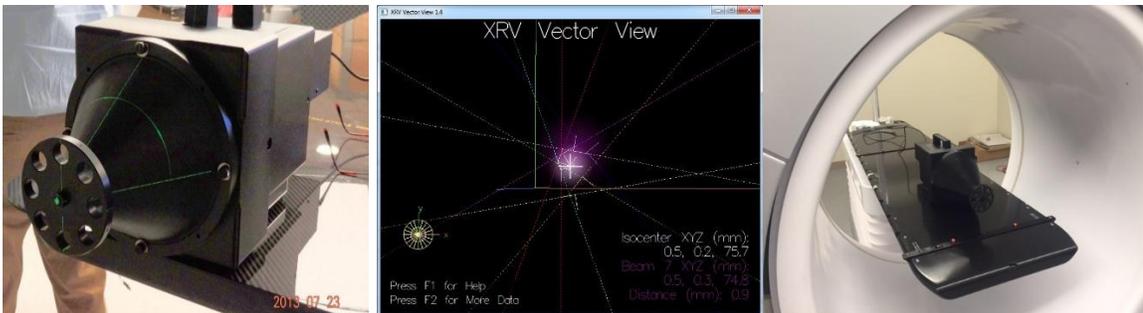


IMAGE 1: Logos System’s scintillation camera used for beam geometry measurements.

b. Star-shots testing

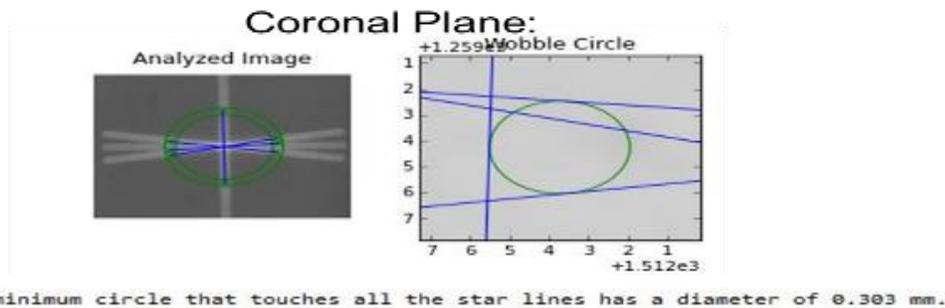
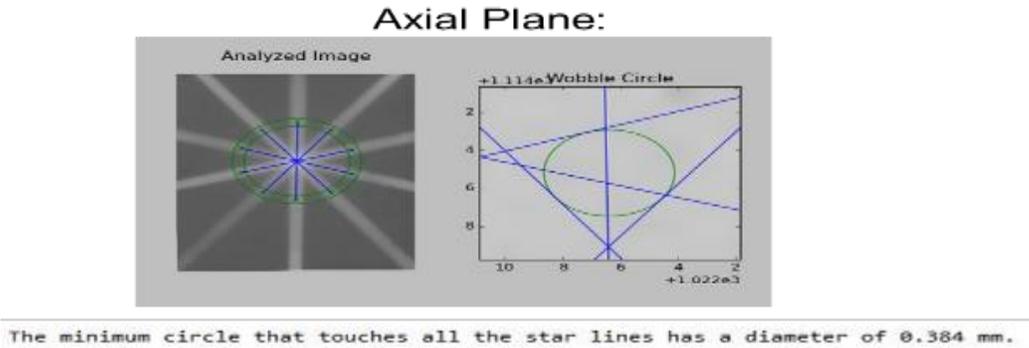


IMAGE 2: Star-shot testing results

c. Rotational delivery test results

In table 8 columns 1 and 2 show the dose deviation results for patterns of equivalent dose delivered to the EPID under varying levels of dose rate, gantry speed or MLC speed and normalized to an open field image. Log file results are shown in columns 3-5 for all tests, including Snooker Cue (SC).

TABLE 8: Dose deviations measured by EPID.

Test	Max-dose deviation %	Abs mean deviation	Max-MLC error (mm)	Max-MU error (MU)	Max- gantry error (deg)
Dose Rate	-0.774	0.414	0.20	0.08	0.06
Gantry speed	-0.917	0.409	0.14	0.07	0.07
MLC speed	1.9%	1.14%	0.15	0.08	0.06
SC No MLC delay	n/a	n/a	0.05	0.21	0.09
SC MLC delay	n/a	n/a	0.05	0.12	0.09
SC Large MLC delay	n/a	n/a	0.04	0.09	0.09

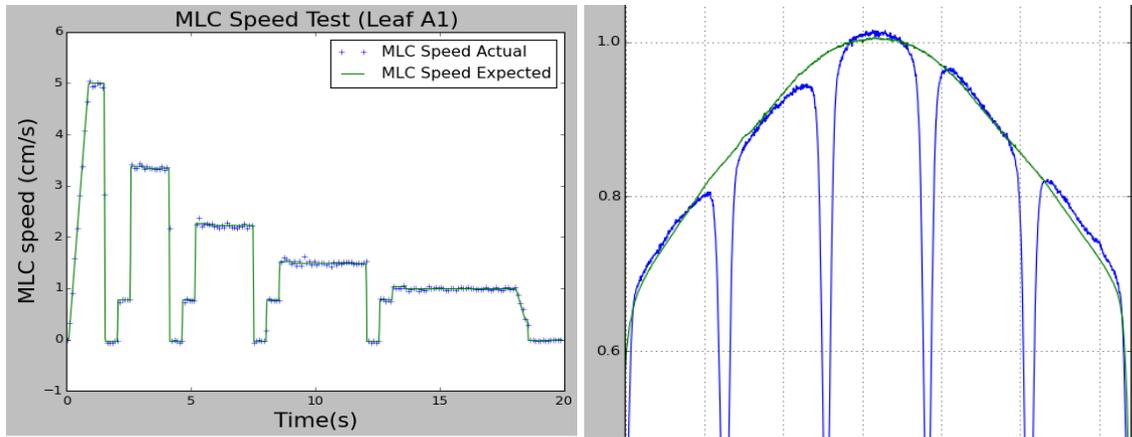


IMAGE 3: Log file results of expected and actual MLC leaf speed (A1) for the MLC speed test delivery. Speeds from 1-5 cm/s were tested (LEFT). Profile of EPID image for MLC speed test (blue) and open field image (green) (RIGHT)

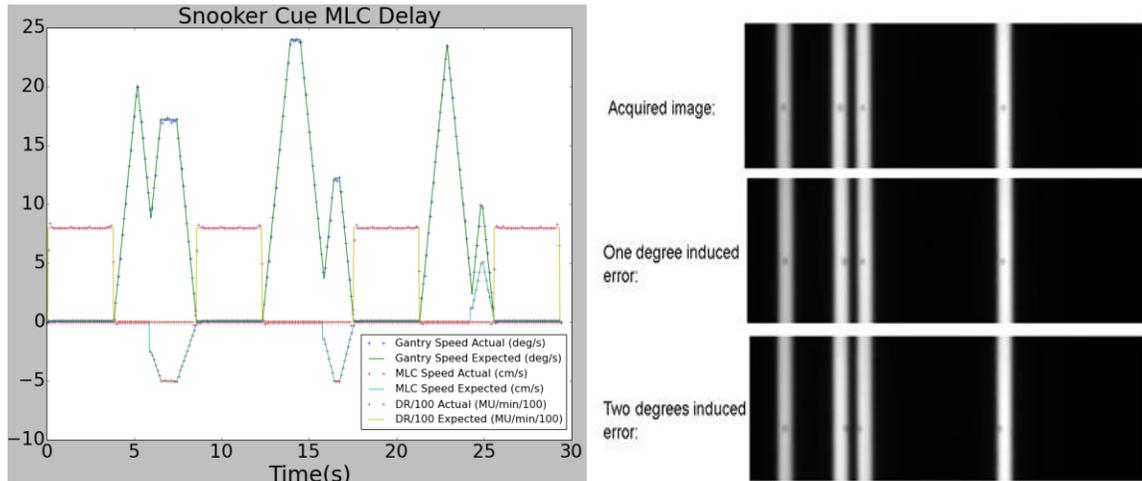


IMAGE 4: Log file results of expected and actual MLC leaf speed, gantry speed, and dose rate/100 for the MLC delay Snooker Cue test. MLC delay was chosen to result in rapid deceleration of MLC and gantry (LEFT). Representative acquired EPID images for Snooker cue test. Induced delivery errors of one and two degrees gantry angle were performed to demonstrate test sensitivity (RIGHT).

d. MLC alignment and positioning accuracy

Picket fence tests were created for single layer and double layer MLC configurations to assess the MLC alignment and position accuracy, for both fix-gantry-angle and rotational radiation delivery. Some of the most common measurement methods involve film dosimetry or portal dosimetry. The figure below shows a sample of results for the Picket fence tests: 1) Picket-fence test during RapidArc; 2) Static, gantry at 0;

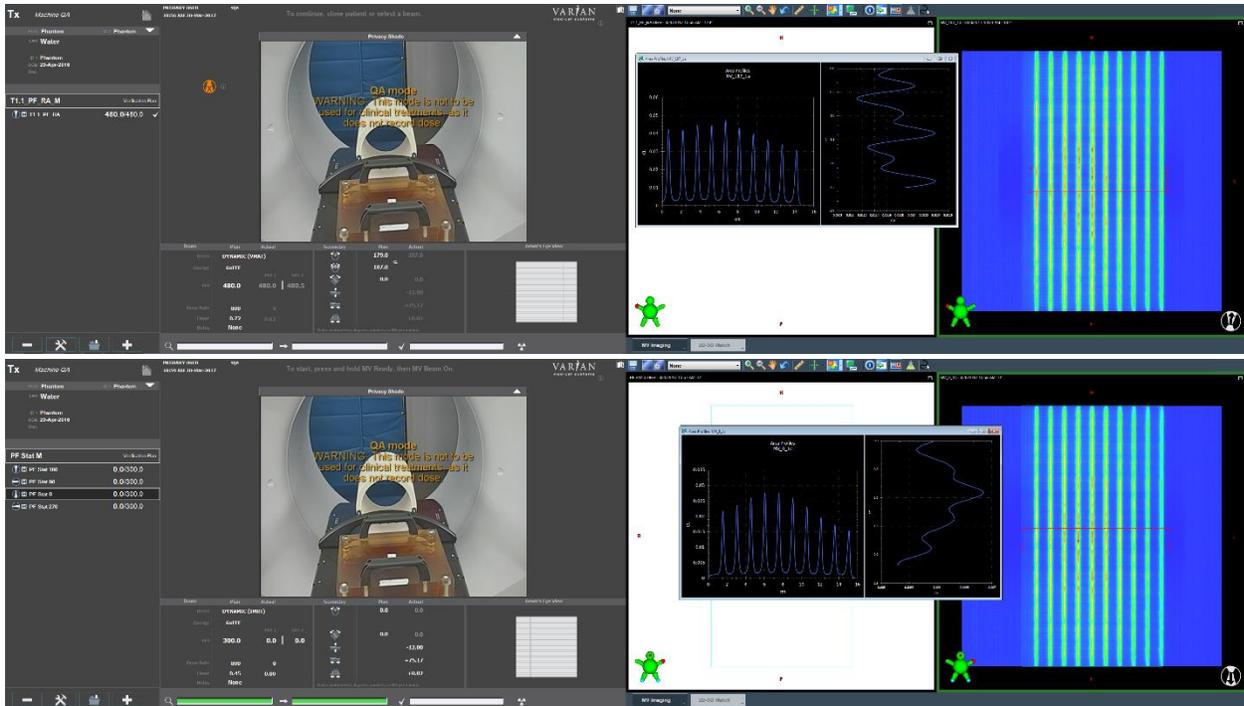


IMAGE 5: Picket-fence test arrangements.

e. MLC dosimetric parameters: leaf transmission factor and dosimetric leaf gap

TABLE 9: MLC leaf transmission, measured per layer and per bank for 2 different SSD values and depths. An external PTW Farmer ionization chamber has been used.

SSD [cm]	Depth [cm]	Prox A	Prox B	Dist A	Dist B	avr(A,B)-prox	avr(A,B)-dist
95	5	0.45%	0.44%	0.46%	0.45%	0.45%	0.45%
90	10	0.49%	0.48%	0.50%	0.49%	0.49%	0.49%

The dosimetric leaf gap is a parameter that is being used in the TPS to account for the radiation leakage through the rounded leaf ends. The traditional test used to measure the DLG is the sweeping gap test. MLC sweeping gaps (with sizes varying from 2 to 20 mm) in a single layer configuration can be used to determine the DLG by measuring the net charge accumulated at isocenter for each sweep, as indicated by an external ionization chamber.

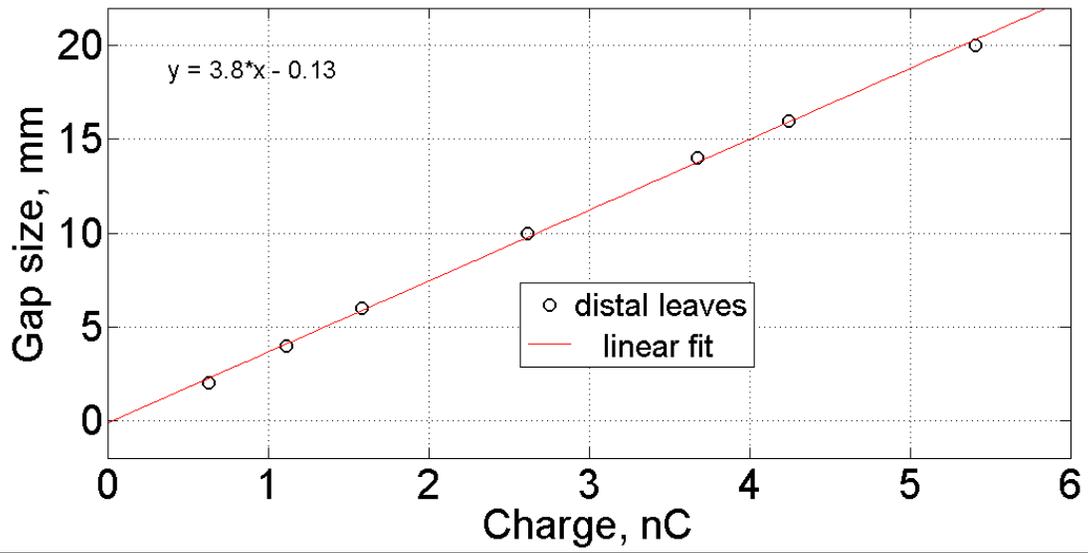


Figure 6: Dosimetric leaf gap (DLG) measurement for the distal leaves (single layer) using an external PTW Farmer ionization chamber. A DLG of 0.13 mm was found from the linear fit extrapolation of the accumulated charge versus sweeping gap size. A similar DLG value was found for the configuration corresponding to the proximal leaves.