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QUALITY ASSURANCE PROCEDURES IMPLEMENTATION FOR VARIAN TRUEBEAM

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A doctoral project submitted in partial
fulfillment of the requirements for the

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Abstract

Department of radiation oncology of Oncology Nevada updated its linear accelerator (LINAC) from Varian Clinac iX to a newer model known as Varian TrueBeam. The Varian TrueBeam LINAC includes 6x, 6xFFF (i.e., 6x without flattening filter known as flattening filter free), 10x, 10xFFF, 15x photon beams and 6e, 9e, 12e MeV electron beams. This system is also equipped with a 6 degree of freedom (DOF) couch, RapidArc, kV on board imager, MV portal imager and Cone Beam CT (CBCT) imaging. This system allows the clinical delivery of modern image guided radiation therapy (IGRT) modalities such as IMRT/VMAT, and SRS/SRT/SBRT. The periodic quality assurance (QA) tests of these systems include verification of the beam output and energy constancy, as well as beam profile constancy. These parameters are critical to ensure that patients receive quality care. The AAPM (American Association of Physicists in Medicine (AAPM) Task Group (TG) 142 recommends daily, monthly, and annual QA of the linear accelerators with predesignated tolerances for non-IMRT, IMRT, and SRS/SBRT treatment techniques. In the Oncology Nevada clinic, various devices are used for the periodic QA on the linear accelerators. These devices include, Machine Performance Check (MPC) IsoCal calibration phantom, Sun Nuclear Daily QA 3, Sun Nuclear IC Profiler, solid water phantom, and 1D water phantom. Daily QA tests are performed utilizing the Varian TrueBeam Machine Performance Check and Sun Nuclear Daily QA 3. This report will focus on the essential QA procedures performed on the Varian TrueBeam LINAC including daily QA in which the output constancy is compared to the baseline. Various safety and mechanical tests, as recommended by TG-142, will also be performed. The Sun Nuclear IC Profiler will be used for monthly QA to verify photon and electron beam profile constancy. Solid-water-based beam output and energy constancy checks will also be performed. Implementation of these QA procedures are part of the medical physicist’s tasks. By setting up those devices and implementing the measurement procedures, physicists perform the daily and monthly QA following the recommendations of the AAPM TG-142. Additional tests in the TG-142 protocol include the geometry isocenter, jaw position, Multileaf Collimator (MLC) position, couch lateral, longitudinal, vertical, rotation positions, daily output energy constancy check, beam profile constancy check, and beam output and energy constancy check. The goal of the project is to setup available equipment and implement measurement procedures in order to determine baseline values for both daily, monthly, and annual QA, which are required to fulfill TG-142 recommendations for LINAC QA and ensure patient care quality.

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Chapter 1. Introduction

1.1 Varian TrueBeam

Figure 1. Varian TrueBeam Linac

Figure 1 shows a picture of the Varian TrueBeam linear accelerator that has been installed at Oncology Nevada in Reno. The Varian TrueBeam system consists of a waveguide accelerator that can generate megavoltage x-ray (6MV, 6FFF, 10MV, 10FFF, 15MV) and electron beams (6, 9 and 12 MeV). The Varian TrueBeam is equipped with PerfectPitch 6DoF Couch, IGRT Couch Top, Gammex Micro+ Fixed Laser System (Green). TrueBeam Version 2.7 contains a kV imaging system, kV CBCT imaging system, and a megavoltage electronic imaging system (EPID). The TrueBeam LINAC is capable of performing TrueBeam RapidArc delivery.

Collimator controller, collimation heads, Y-jaws, X-jaws and multileaf collimator (MLC) are major components of the collimation system. This system can form different beam shapes to be delivered to the treatment targets. The collimation controller calibrates and initializes motion axes including the MLC, controls the Y-jaws and X-jaws motion and detects the jaw positions. The MLC includes two banks of movable tungsten leaves, each bank set consists of 60 leaves. Individual leaf position is controlled by the collimation controller and the MLC positions can be static or dynamic. The banks and leaves move along the X-jaws axis. The standard 120 MLC leaf has a thickness that is projected to be 5 mm at the isocenter. With this collimation system, one can create a maximum field size of up to 40 x 40 cm^2 for fixed field treatments, and a maximum of 40 x 32 cm^2 field for IMRT/VMAT treatments. MLC maximum and mean reproducibility, maximum and mean offset, and jaw offset and parallelism for X1, X2, Y1 Y2, and rotation offset are important quality assurance parameters to be checked daily or weekly.

The PerfectPitch 6DoF couch provides smooth motion in lateral, longitudinal, vertical, rotation, and pitch and roll adjustment. Pitch will tilt the couch up and down longitudinally, however, roll will tilt the couch up and down laterally. The pitch and roll rotations are within +/- 3.0 degrees. Couch lateral, longitudinal, vertical, rotation, pitch, roll and rotation-induced couch shift are important couch quality assurance parameters to be checked during the monthly QA.

1.2 Acceptance & Commissioning

The acceptance tests for the Varian TrueBeam include:

a. preliminary radiation survey,
b. site radiation survey,
c. collimator transmission,
d. x-ray leakage,
e. isocenter tuner record,

f. front pointer distance alignment verification,

g. field light alignment verification,

h. crosshair alignment,

i. gantry rotation,

j. collimator rotation,

k. couch rotation,

l. couch longitudinal, lateral, vertical PRO,

m. optical distance indicator.

n. PerfectPitch Couch pitch and roll PRO accuracy check,

o. MLC and jaws verification with collimation devices check,

p. radiation isocenter and beam stability verification.

q. energy and beam profile verification,

r. dosimetry verifications,

s. dynamic therapy,

t. RapidArc (VMAT) verification.

u. LaserGuard and collision protection system verification,

v. positioning unit (MVD, KVD and KVS),

w. Isocal and PRS positioning accuracy.

x. MV, kV and CBCT Imaging acquisition,

y. x-ray generator verification.

z. KVS collimator verification

The acceptance tests are similar to many monthly or annual mechanical quality assurance tests.

Commissioning of the TrueBeam LINAC includes the collection of data that are needed in the treatment planning system. These measurements were performed with a PTW 31021 Semiflex 3D ion chamber (0.070 cc active volume) for photon beams of 6X, 6FFF, 10X, 10FFF and 15X MV and included the percentage depth dose, PDD, along the central axis of the beams, from a depth of zero to a depth of 38 cm, for square field sizes of 3x3, 6x6, 10x10, 30x30, and 40x40 cm^2. Open field crossline profiles were measured for field sizes of 3x3, 6x6, 10x10 and 30x30 cm^2 at depths of d_{max}, 5, 10 and 30 cm. However, the open field inline profiles were measured for field sizes of 10x10 and 30x30 cm^2 at depths of d_{max}, 5, 10, and 30 cm. In all cases, a source-to-surface distance (SSD) of 80 cm was used for all photon energy measurements, The diagonal profiles were measured for a field size of 40x40 cm^2, using the depths of d_{max}, 10 and 30 cm. The SSD 80 cm data were converted to SSD 100 cm using software. For output factor measurements, the ion chamber (PTW 31021) was set at SSD of 95 cm, at a depth of 5 cm. Output factors were measured for all photon energies to compare with the TrueBeam Golden Beam data obtained from Varian's website. For the output factor measurements, field sizes were set to square fields of 3, 6, 10, 20, 30, and 40 cm^2 and rectangular field sizes of 3x20, 10x40, 30x3, and 40x10 cm^2.

For all electron beams (6, 9, and 12 MeV), measurements were performed at 100 cm SSD, by using the 5 different standard electron-cones (6x6, 10x10, 15x15, 20x20, and 25x25 cm^2). These measurements were completed at points along the central axis of the beams. For the PDD measurements, the PTW 31021 Semiflex 3D ion chamber was scanned at depths ranging from the water surface to Rp +10 cm. The in-plane and cross-plane profiles were measured with the ion chamber placed at depths of d_{max}: 6 MeV: 1.3 cm, 9 MeV: 2.1 and 2.8 cm: 12 MeV: With an open field (40x40 cm^2) setup, the ion chamber was set at 95 cm source to detector position and air cross-plane profiles were collected for comparison with Varian electron Monte Carlo (eMC) representative data for all energies (6, 9, and 12 MeV). For output factor measurements, the SSD was set at 100 cm for all standard electron cones. These factors were measured using the PTW 31021 Semiflex 3D ion chamber and the results were normalized to a 10x10 cm^2 reference electron cone at an SSD of 100 cm.

For small field dosimetry (square or rectangular fields from 1x1 to 2x40 cm^2), the Sun Nuclear Edge diode was used to measure output factors for 6X, 6FFF, 10X, 10FFF, and 15X MV, and the data were entered into the Eclipse treatment planning system. Additionally, 4x4 and 10x10 cm^2 square fields were measured as crossover factors. For MLC formed fields (1x1 cm^2, 2x2 cm^2, 3x3 cm^2, 4x4 cm^2, and 10x10 cm^2), the Sun Nuclear Edge Diode was used to measure output factors for photons. The PTW 31021 3D ion chamber was used to measure factors for 3x3, 4x4, 6x6, and 10x10 cm^2 fields. These commissioning data represented the baseline for the LINAC annual QA.

The LINAC commissioning measurements provide basic dosimetry data such as PDD, flatness and symmetry, Tissue-maximum ratio (TMR), and output factors. To perform the annual TG-51 calibration, commissioning data provide the gold standard to which the machine outputs are compared

1.3 AAPM TG-142 QA recommendation

Machine parameters, including dosimetric, mechanical and safety parameters, may be off from their initial values due to many reasons such as: machine misalignment, mechanical breakdown, parts malfunction and failure, operation accidents, major component change, and machine aging. Once the machine parameters are out of tolerance, the physicist needs to take action. Such action can be categorized as level 1 (inspection action), level 2 (scheduled action), and level 3 action (immediate action or stop treatment action or corrective action).

The AAPM TG-142 report was published in 1997. This literature recommends the quality assurance frequency and tolerance for LINACs. The report divides quality assurance tests into daily QA, monthly QA and annual QA in three different categories: dosimetry, mechanical and safety. The daily QA for stereotactic radiosurgery (SRS)/stereotactic body radiotherapy (SBRT) dosimetry includes photon and electron output constancy. Most of the dosimetry tolerances should not deviate by more than 3% from the baseline data. To fulfill daily QA recommendations, different clinics use different kinds of equipment. The commercially available devices include Beamchecker, and Sun Nuclear Daily QA3. The latest LINAC Model TrueBeam, Machine Performance Check (MPC) provided by the vender (Varian) is also an option to perform daily or weekly QA.

Monthly QA dosimetry checks and tests include, x-ray output constancy, electron output constancy, typical dose rate output constancy, photon beam profile constancy, electron beam profile constancy, and electron beam energy constancy. Mechanical checks include jaw position indicator and gantry/collimator indicator. To perform routine dosimetry output & energy constancy checks, the physicist can use a 1D water tank. MPCs can be used for some of the mechanical checks. The MPC will be discussed in Chapter 2.

AAPM Medical Physics Practice Guideline 8.a (MPPG 8a) was published in 2017. In section D of Dosimetry tests, the AAPM MPPG 8a gives the physicist an option to set up relatively simpler solid water-based monthly output & energy constancy checks for both photons and electrons based on the TG-142 recommendations. Also, the Sun Nuclear IC profiler is an option to perform monthly beam profile measurements. Profile measurements were compared with corresponding baseline data following the TG-142 monthly QA data.

Chapter 2. MPC & IsoCal Calibration

2.1 MPC phantom and setup

The Varian TrueBeam machine is equipped with a machine parameters self-test system known as the MPC. This machine performance check is used for daily and/or weekly verification of the functions of the linear accelerator and other accessories including couch, MLC and gantry. The results are evaluated by the physicist to verify that the critical parameters are within an acceptable/preset threshold. The MPC tests are fast and reliable and are typically used before the daily routine patient treatments. This system includes an IsoCal phantom, a MPC phantom mount, kV and MV imaging systems, and user interface and analysis software at the console. Figures 2 and 3 show the MPC phantom mount and IsoCal phantom in setup position for the Varian TrueBeam machine. The physicist/therapist fixes the isocenter calibration (IsoCal) phantom firmly to the couch top using a MPC phantom mount. At the LINAC control console, the physicist/therapist enters MPC mode and under the "**Tool**" tap, selects different checks to perform. MPC will follow the user instruction, per the tasks list assigned by the physicist/therapist, automatically acquire kV and MV images for different gantry and collimator position combination and for different couch longitudinal, lateral vertical, rotation positions. The acquired images are analyzed and displayed to evaluate the machine parameters. The MPC results will indicate if the measurement values are within the acceptable threshold.

Figure 2. MPC IsoCal phantom mount

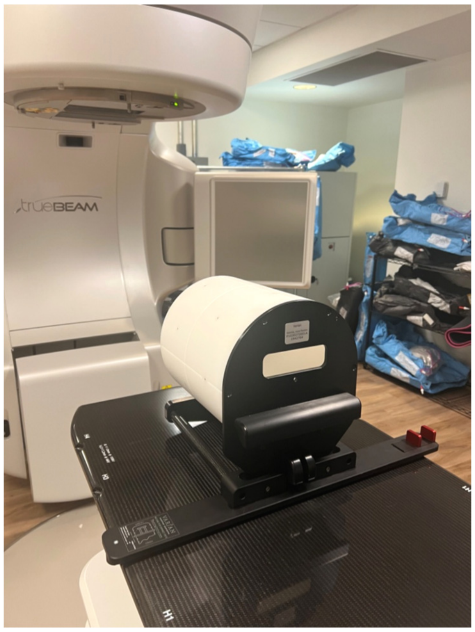


Figure 3. MPC IsoCal phantom setup at the couch top

The MPC can be operated either in the **console mode** or in the **offline mode**. The **console mode** runs on the LINAC treatment console which allows for rapid evaluation of various LINAC parameters including kV/MV images. The disadvantage of **console mode** is that all operations are performed at the console; thus, the evaluation cannot be performed during the routine daily treatment time since the console is occupied. The offline mode is used for detailed analysis of the MPC history data. The MPC software can be installed on different computers instead of the console computer and, as such, the physicist can perform MPC measurement data analysis without occupying the LINAC treatment console. Offline mode can also be used for measurement review and historical trend analysis. These tasks do not require any phantom set up or radiation.

In the LINAC console mode, the users' authority is set to three different groups: Therapist user, Physicist user, and Service user. The therapist group user can perform daily/weekly MPC tests. Specifically, the therapist can acquire checks, view checks, add checks and remove individual checks. The physicist group user can perform daily/weekly MPC tests, and administer (accept, decline, remove) MPC test results. Specifically, physicists can acquire checks, view checks, add ad-hoc checks, remove individual ad-hoc checks, remove scheduled checks, delete acquisitions, change MPC configurations and assign baseline data. Tasks such as scheduling MPC checks and establishing MPC baseline values for beam constancy checks, are part of the physicist's duties. It is also the physicist's responsibility to appoint MPC baselines at the suitable time (shortly after TG-51 calibration).

The Varian TrueBeam **Major Modes** interface allows the physicist/therapist to switch between different modes. The MPC mode, Treatment mode, Service mode, and System Administration mode are frequently used by the physicist. To perform daily/weekly MPC checks, the physicist/therapist starts from the Major Mode menu and logs in to the MPC mode.

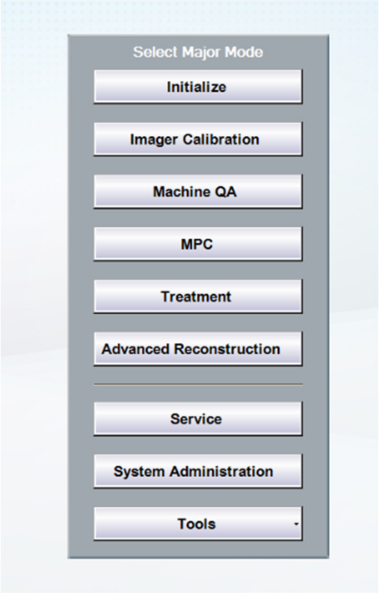


Figure 4. Varian TrueBeam Major modes

The **History review** window shows all MPC checks that have been performed previously. The checks status (**Pass/Warning/Fail)** of each individual MPC check is also shown in the **Review** window. For each MPC check, the **Pass/Warning/Fail** status is color coded: green means the MPC check results are within the preset threshold, orange indicates that the MPC check results are still within threshold but close to the threshold range limit, and red indicates that the MPC check results are out of threshold. The baseline MPC check is coded as gray. The physicist usually performs the TG-51 calibration after the LINAC acceptance or performs the TG-51 calibration during the annual quality assurance. Immediately after the TG-51 calibration, a complete set of MPC checks is performed by the physicist and this set of MPC tests are appointed as the baseline and thus serves as the reference value for future routine MPC checks. This baseline measurement is indicated in gray color in the **Review** window.

The MPC geometry check requires the physicist to appoint a couch reference position which is accomplished by positioning the IsoCal phantom at the LINAC isocenter. The physicist uses the vault laser (Figure 5) to set the IsoCal phantom at the isocenter and appoints this position as the couch reference position.

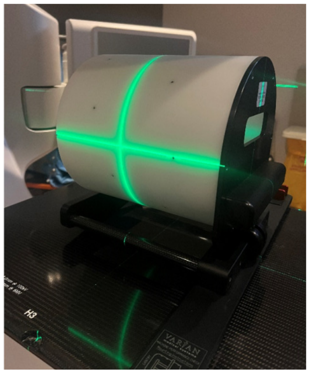


Figure 5. IsoCal phantom lineup per room laser

2.2 MPC baseline & QA measurement

The MPC checks include the beam constancy, geometry, enhanced couch, and enhanced MLC check. The beam constancy check uses 6MV photons to evaluate the beam change by obtaining 6MV test images and then comparing the test images to the baseline values. The MPC beam constancy usually evaluates the beam output constancy, beam center shift and beam uniformity parameters. The deviation of the test image from the baseline value is calculated and compared to the pre-set threshold. Beam and geometry checks evaluate the LINAC mechanical parameters including the treatment isocenter size, the coincidence of treatment isocenter with the kV/MV imaging isocenter, kV/MV imaging systems positioning accuracy, the gantry and collimator rotation angle positioning accuracy, the LINAC jaws and MLC leaves positioning accuracy, the MLC leaf positioning reproducibility, and the 6 DOF couch positioning accuracy. The enhanced couch check evaluates couch rotations up to 180° positioning accuracy.

MPC uses EPID to evaluate beam constancy. During the image acquisition, the gantry angle is set to 0°, the field size is set to 18 x 18 cm^2, and the 6MV beam is imaged with EPID. The ratio of the baseline image and the measured image is then calculated. Instead of comparing the whole 18 x 18 cm^2 images, only images of field size 13 x 13 cm^2 are used to perform the ratio calculation. The reason is that, at the corner of the field, the images might be uneven, thus the corners of the images are cropped. The output change is the ratio calculated in the center area of the imager. The uniformity change is determined by measuring the maximum variation between two images. The beam center shift is evaluated by measuring the relative field center shift compared to the baseline image.

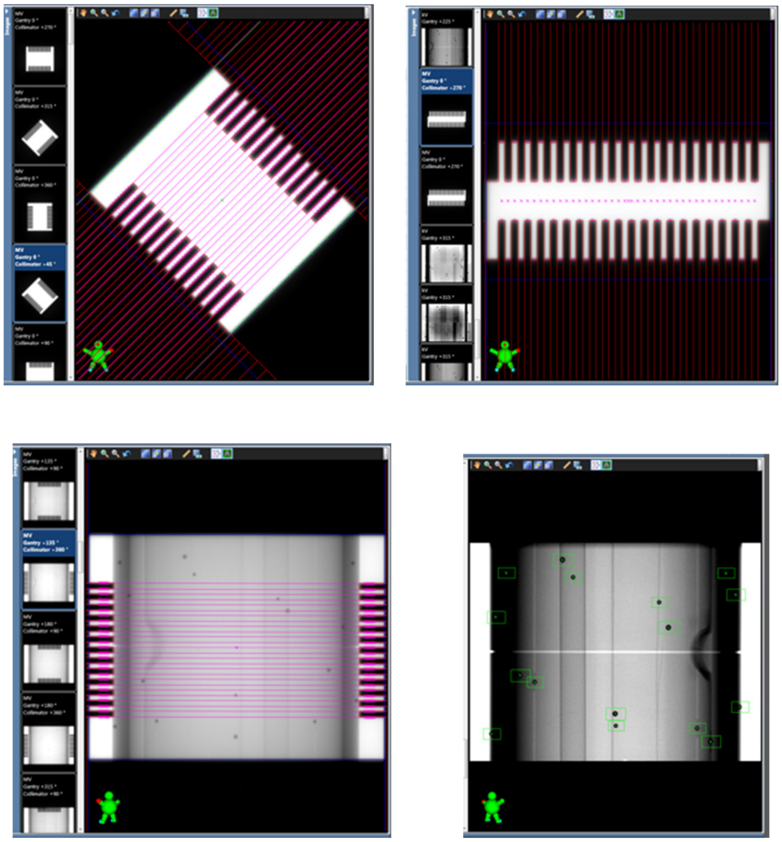
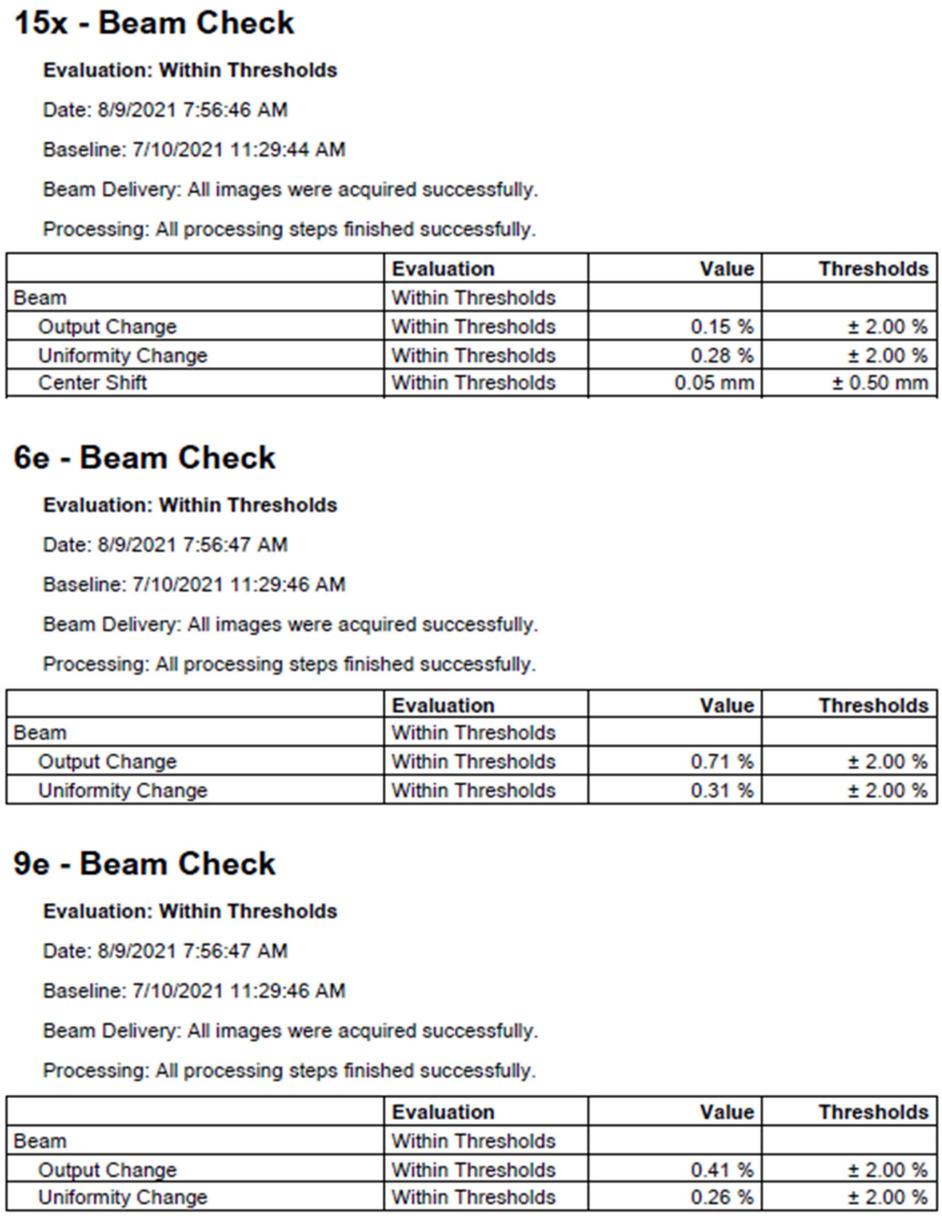


Figure 6. MPC kv/MV images for couch, gantry, collimator combination.

15X, 6 MeV, and 9 MeV beam constancy results with respect to baseline are shown in Figure 7.



15x - Beam Check

Evaluation: Within Thresholds

Date: 8/9/2021 7:56:46 AM

Baseline: 7/10/2021 11:29:44 AM

Beam Delivery: All images were acquired successfully.

Processing: All processing steps finished successfully.

	Evaluation	Value	Thresholds
Beam	Within Thresholds		
Output Change	Within Thresholds	0.15 %	± 2.00 %
Uniformity Change	Within Thresholds	0.28 %	± 2.00 %
Center Shift	Within Thresholds	0.05 mm	± 0.50 mm

6e - Beam Check

Evaluation: Within Thresholds

Date: 8/9/2021 7:56:47 AM

Baseline: 7/10/2021 11:29:46 AM

Beam Delivery: All images were acquired successfully.

Processing: All processing steps finished successfully.

	Evaluation	Value	Thresholds
Beam	Within Thresholds		
Output Change	Within Thresholds	0.71 %	± 2.00 %
Uniformity Change	Within Thresholds	0.31 %	± 2.00 %

9e - Beam Check

Evaluation: Within Thresholds

Date: 8/9/2021 7:56:47 AM

Baseline: 7/10/2021 11:29:46 AM

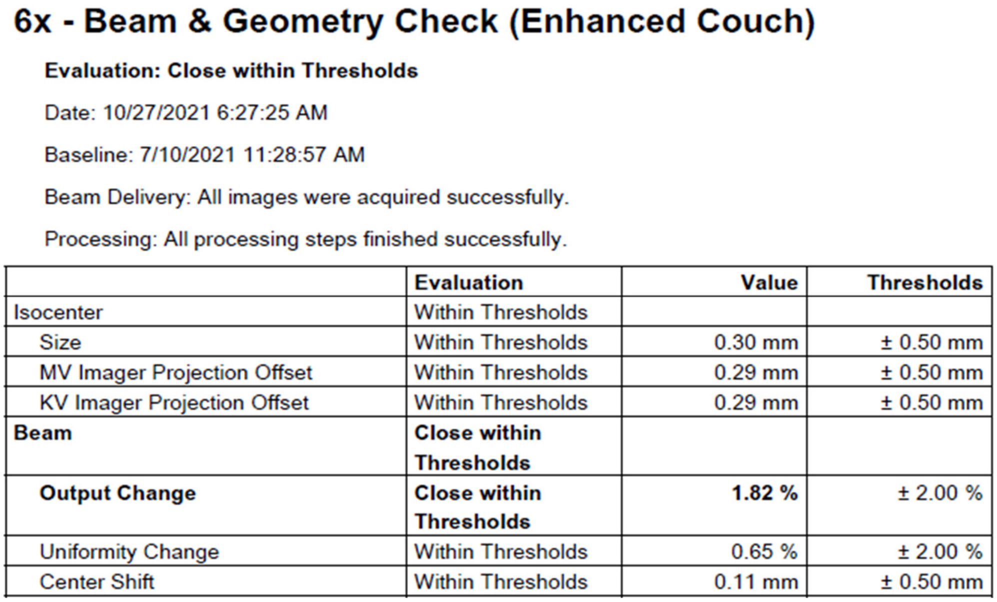
Beam Delivery: All images were acquired successfully.

Processing: All processing steps finished successfully.

	Evaluation	Value	Thresholds
Beam	Within Thresholds		
Output Change	Within Thresholds	0.41 %	± 2.00 %
Uniformity Change	Within Thresholds	0.26 %	± 2.00 %

Figure 7. Photon & Electron Beam Check results

The MLC can rotate 360˚, and this rotation axis is defined as the beam axis. The intersection of the beam axis over the gantry rotation axis is defined as the treatment isocenter. The treatment isocenter is calculated by acquisition MV images with the gantry set at different angles. Specifically, the gantry angles are set to 0, 45, 90, 135, 180, 225, 270, and 315˚. The largest distance between the beam axis from the ideal isocenter under the full gantry rotation is set as the isocenter size. The kV and MV imager offsets of the treatment isocenter projection are critical parameters for image-guided radiation therapy (IGRT). The maximum distance of the imager isocenter from the projection of the treatment isocenter is set as the imager projection offset. These offset values can be used to correct the imager isocenter using IsoCal calibration. Beam and geometry checks for 6X photons are shown in Figure 8



6x - Beam & Geometry Check (Enhanced Couch)

Evaluation: Close within Thresholds

Date: 10/27/2021 6:27:25 AM

Baseline: 7/10/2021 11:28:57 AM

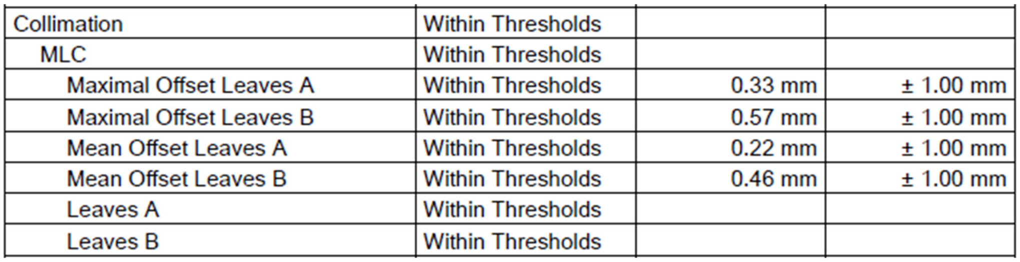
Beam Delivery: All images were acquired successfully.

Processing: All processing steps finished successfully.

	Evaluation	**Value**	**Thresholds**
Isocenter	Within Thresholds		
Size	Within Thresholds	0.30 mm	± 0.50 mm
MV Imager Projection Offset	Within Thresholds	0.29 mm	± 0.50 mm
KV Imager Projection Offset	Within Thresholds	0.29 mm	± 0.50 mm
Beam	**Close within Thresholds**		
Output Change	**Close within Thresholds**	**1.82 %**	± 2.00 %
Uniformity Change	Within Thresholds	0.65 %	± 2.00 %
Center Shift	Within Thresholds	0.11 mm	± 0.50 mm

Figure 8. Geometry Check results

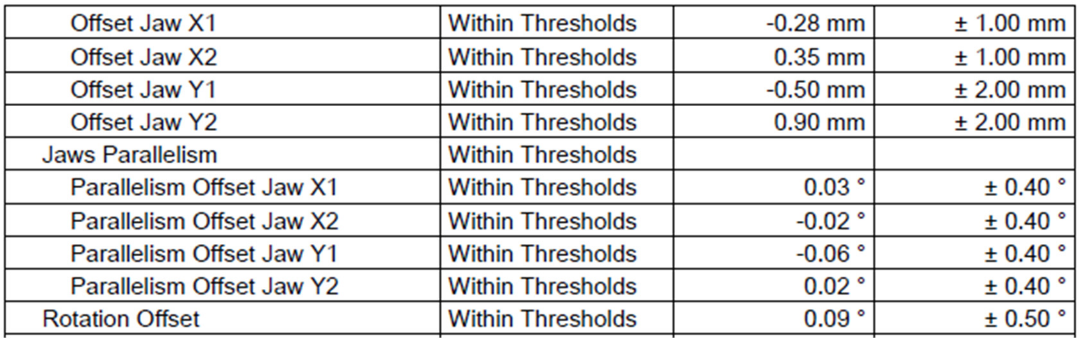
The collimation positioning accuracy is measured by using the field evaluations with the gantry set to 0˚. The software measures the MLC leaf tip position to the MLC center line distance. Reproducibility is measured in a similar manner, but with the MLC leaves approaching the same nominal position from opposite sites. For a standard 120 MLC configuration, all leaves are measured (Figure 9).



Collimation	Within Thresholds		
MLC	Within Thresholds		
Maximal Offset Leaves A	Within Thresholds	0.33 mm	± 1.00 mm
Maximal Offset Leaves B	Within Thresholds	0.57 mm	± 1.00 mm
Mean Offset Leaves A	Within Thresholds	0.22 mm	± 1.00 mm
Mean Offset Leaves B	Within Thresholds	0.46 mm	± 1.00 mm
Leaves A	Within Thresholds		
Leaves B	Within Thresholds		

Figure 9. MLC Check results

Jaw offset and parallelism is measured with an 18 x 18 cm^2 field (Figure 10)



Offset Jaw X1	Within Thresholds	-0.28 mm	± 1.00 mm
Offset Jaw X2	Within Thresholds	0.35 mm	± 1.00 mm
Offset Jaw Y1	Within Thresholds	-0.50 mm	± 2.00 mm
Offset Jaw Y2	Within Thresholds	0.90 mm	± 2.00 mm
Jaws Parallelism	Within Thresholds		
Parallelism Offset Jaw X1	Within Thresholds	0.03 °	± 0.40 °
Parallelism Offset Jaw X2	Within Thresholds	-0.02 °	± 0.40 °
Parallelism Offset Jaw Y1	Within Thresholds	-0.06 °	± 0.40 °
Parallelism Offset Jaw Y2	Within Thresholds	0.02 °	± 0.40 °
Rotation Offset	Within Thresholds	0.09 °	± 0.50 °

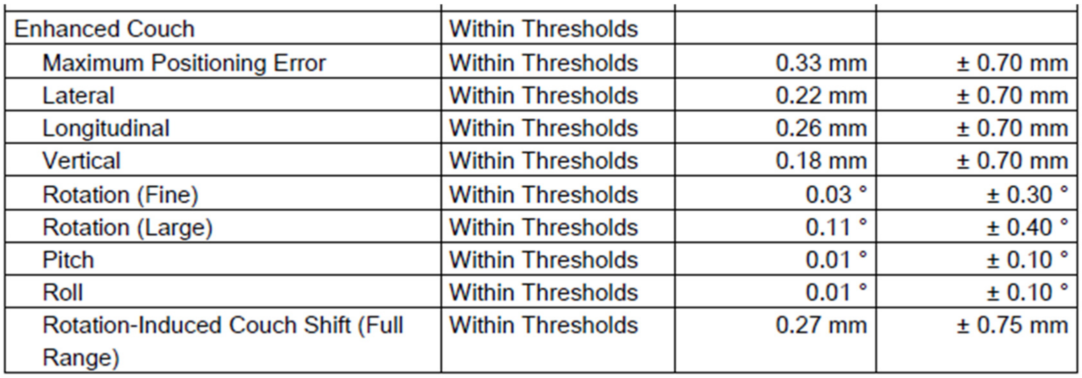
Figure 10. Jaw Check results

With the gantry angle set at 0˚, the angle between the couch vertical axis and the beam axis is evaluated as the gantry absolute positioning accuracy (Figure 11). The difference between the angle determined by the MV imaging system and the nominal gantry angle is evaluated as the gantry relative positioning accuracy (Figure 11). This series of MV images are acquired with the gantry angle set to 0˚, 45˚, 90˚, 135˚, 180˚, 225˚, 270˚ and 315˚. This gantry position accuracy check is comparable to the TG-142 gantry indicator quality assurance recommended as part of the monthly mechanical checks.

Gantry	Within Thresholds		
Absolute	Within Thresholds	-0.16 °	± 0.30 °
Relative	Within Thresholds	0.10 °	± 0.30 °

Figure 11. Gantry Check results

Couch positioning accuracy is determined by measuring the nominal couch shift distance to the couch reference position appointed by the physicist (Figure 12). This MPC check is comparable to the TG-142 couch indicator quality assurance recommended as part of the monthly mechanical checks.



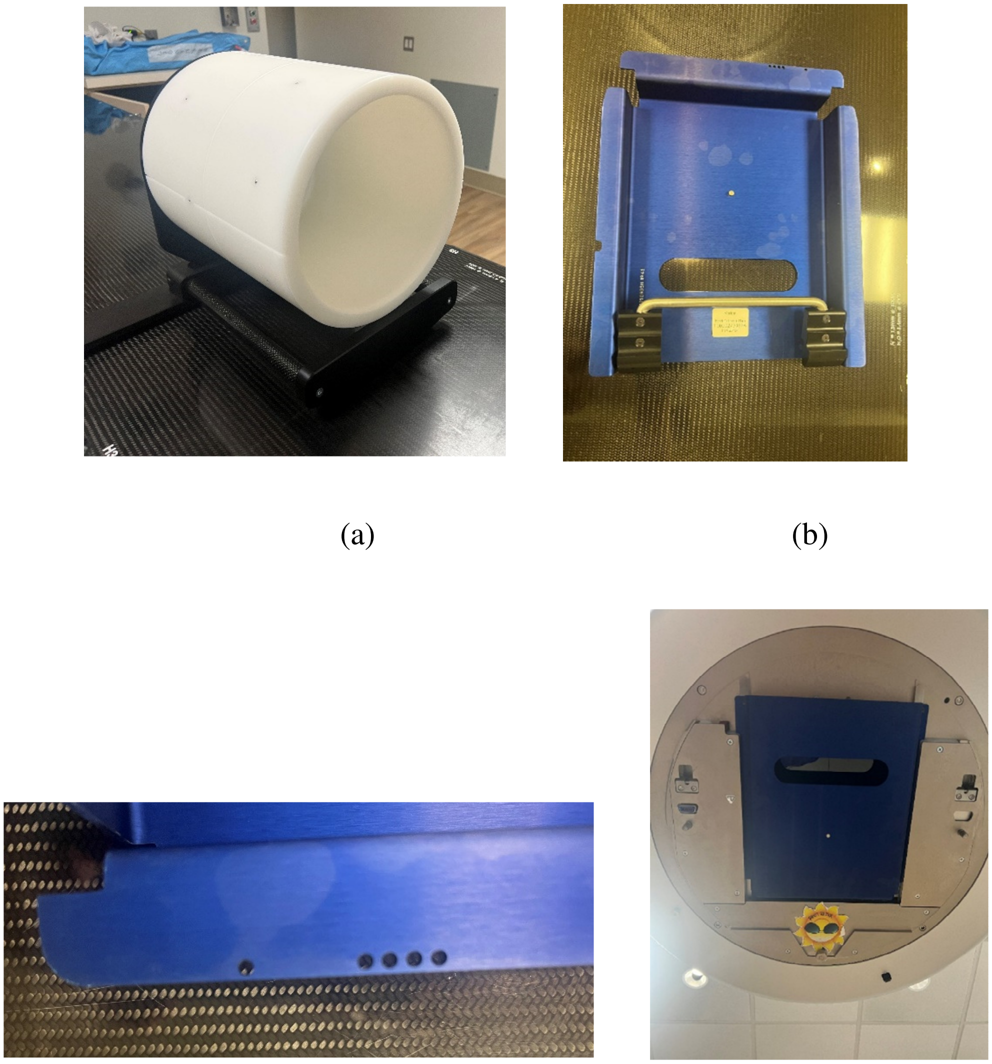
Enhanced Couch	Within Thresholds		
Maximum Positioning Error	Within Thresholds	0.33 mm	± 0.70 mm
Lateral	Within Thresholds	0.22 mm	± 0.70 mm
Longitudinal	Within Thresholds	0.26 mm	± 0.70 mm
Vertical	Within Thresholds	0.18 mm	± 0.70 mm
Rotation (Fine)	Within Thresholds	0.03 °	± 0.30 °
Rotation (Large)	Within Thresholds	0.11 °	± 0.40 °
Pitch	Within Thresholds	0.01 °	± 0.10 °
Roll	Within Thresholds	0.01 °	± 0.10 °
Rotation-Induced Couch Shift (Full Range)	Within Thresholds	0.27 mm	± 0.75 mm

Figure 12. Enhanced Couch Check results

In general, the MPC checks implement the mechanical checks for gantry positioning accuracy, couch positioning accuracy, collimation jaw positioning accuracy, MLC positioning accuracy and position reproducibility, and beam output constancy check. These mechanical and dosimetry quality assurance measurements fulfill the daily and monthly TG-142 QA recommendations for SBRT/SRS treatment LINACs.

2.3 Isocenter Calibration & Verification

The equipment used for isocenter calibration and verification is shown in Figure 13.


(a) (b)

(c) (d)

Figure 13. IsoCal phantom & plate. (a) IsoCal Phantom mounted at the couch top (b) partial transmission plate (c) plate code (d) Gantry angle 180º shows IsoCal Phantom and plate

For the MPC isocenter check, if the kV/MV imager projection offset is out of tolerance, an IsoCal calibration/reverification is performed to correct the offset. The IsoCal phantom is a polyoxymethylene 24 cm long cylinder in which the outer surface is embedded with 16 tungsten BBs as imaging objects. There are five grooves with four located along the cylinder longitudinally, and the fifth groove circling around the middle of the phantom in the axial plane. These five grooves are used to align the phantom to isocenter using the vault laser. The BBs distribution pattern allows them to be imaged as an independent check of the gantry angle. The phantom holder is mounted to the top of the couch using half circle notches on both sides to firmly lock the holder to the couch.

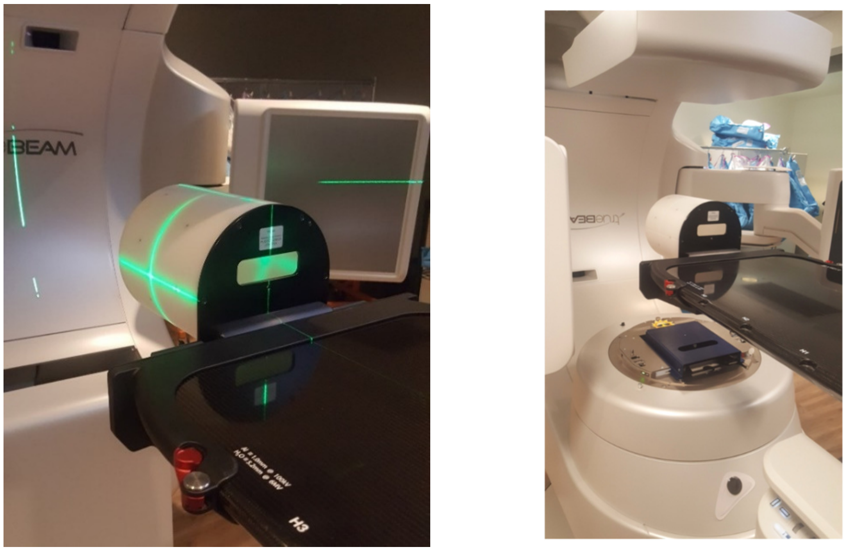
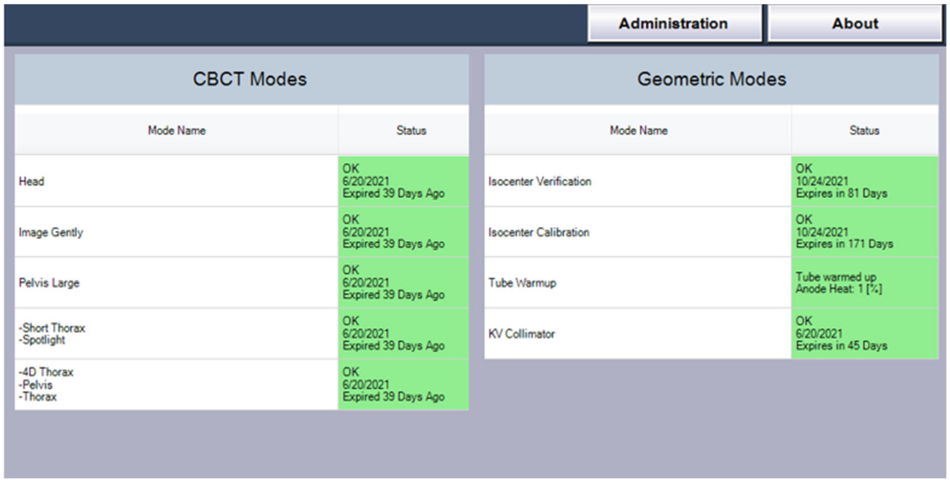


Figure 14. IsoCal setup for Isocenter calibration

The partial transmission plate is a 3mm thick aluminum plate. The plate is locked into the LINAC accessory interface mount. The transmission for 6 MV is 85%. This plate is coded to make sure that when the physicist runs the IsoCal calibration and verification, the plate is in position. Also, during treatment, if the code shows up, the LINAC will know the plate is still in position and will prevent routine treatment until the plate is removed.

The isocenter calibration uses 6MV for geometric calibration and it calibrates the MV and kV detector arms to the radiation isocenter and calculates the corrections to the longitudinal and lateral of both MV and kV imagers for each gantry angle. When performing the isocenter calibration, the partial transmission plate is placed into the gantry head MV collimator interface mount. The IsoCal phantom is then set up to the top of the couch using the vault laser (Figure 14). The physicist then logs in to **Imager Calibration** mode from the LINAC major mode, under the **Geometric Modes** (Figure 15). The physicist can then click “Isocenter Calibration” to perform the calibration. The entire isocenter calibration procedure is automatically performed. This process includes a series of image acquisitions up to 120 kV or MV over 360 combinations of gantry, and collimator rotations. The acquisition results are processed in real time and displayed; thus the physicist can review the acquired image and adjust the kV/MV arms. The physicist usually accepts the adjustment to the kV/MV arm parameters. The system will calibrate the kV/MV arms to minimize the offset between the imaging isocenter and the treatment isocenter. An isocenter verification is always performed after the isocenter calibration (Figure 16).



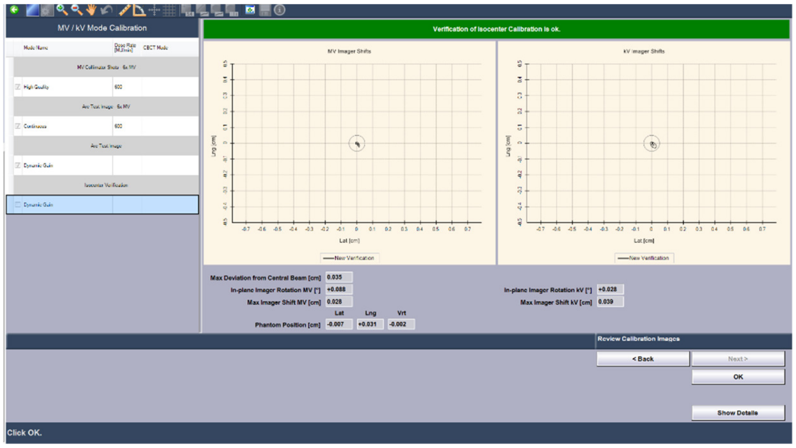
CBCT Modes

Mode Name	Status
Head	OK 6/20/2021 Expired 39 Days Ago
Image Gently	OK 6/20/2021 Expired 39 Days Ago
Pelvis Large	OK 6/20/2021 Expired 39 Days Ago
-Short Thorax -Spotlight	OK 6/20/2021 Expired 39 Days Ago
-4D Thorax -Pelvis -Thorax	OK 6/20/2021 Expired 39 Days Ago

Geometric Modes

Mode Name	Status
Isocenter Verification	OK 10/24/2021 Expires in 81 Days
Isocenter Calibration	OK 10/24/2021 Expires in 171 Days
Tube Warmup	Tube warmed up Anode Heat: 1 [%]
KV Collimator	OK 6/20/2021 Expires in 45 Days

Figure 15. Linac Imager calibration mode. Illustrates Isocenter Calibration and Isocenter Verification options.



Mode Name	Dose Rate [MU/min]	CBCT Mode
☑ High Quality	600	
☑ Continuous	600	
☑ Dynamic Gain		
☐ Dynamic Gain		

Verification of Isocenter Calibration is ok.

Max Deviation from Central Beam [cm] 0.035
In-plane Imager Rotation MV [°] +0.088
Max Imager Shift MV [cm] 0.028
Phantom Position [cm] Lat -0.007 Lng +0.031 Vrt -0.002
In-plane Imager Rotation kV [°] +0.028
Max Imager Shift kV [cm] 0.039

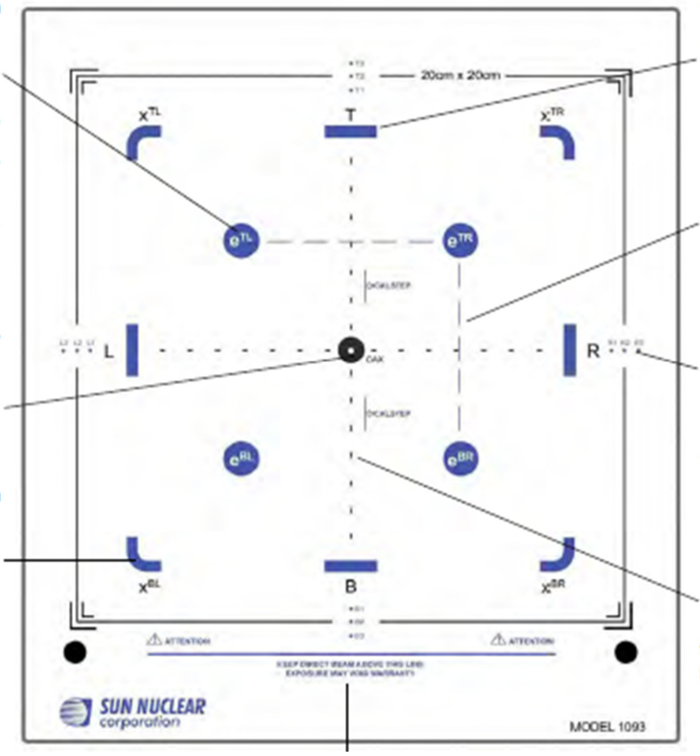
Click OK.

Figure 16. Isocenter verification results

Chapter 3. Daily QA3 & IC Profiler

3.1 Sun Nuclear Daily QA3

The Daily QA3 device includes 13 primary fully guarded vented ion chambers: one parallel plate CAX ion chamber is located at the center of the field; four primary rectangular shaped ion chambers are located along the X and Y axes 8 cm from the center, another four photon ion chamber detectors are located at each of the four corners (each chamber is 11.3 cm from the center). In all cases, the ion chamber volume is 0.3 cm^3 and the parallel plate separation is 4 mm. Four electron (e-Energy) detectors are located diagonally 5.6 cm from the center. Each e-Energy ion chamber has a volume of 0.6 cm^3 and the parallel plate separation is 4 mm. For the electron ion chamber detectors, attenuation is accomplished by disks embedded at the top left (0.216-inch iron), bottom right (0.216-inch copper), and bottom left (0.216-inch aluminum). These different attenuation densities provide a range of buildup depth permitting one exposure electron energy check. The inherent buildup over the primary ion chambers is 0.74 cm of acrylic (effective buildup ~0.84 g/cm^2). The buildup for the CAX chamber is acrylic buildup 1.0g/cm^2, for the top right it is air/acrylic buildup 0.2 g/cm^2, for the top left it is Fe/acrylic buildup 3.0 g/cm^2, for the bottom right it is Cu/acrylic buildup 4.3 g/cm^2, and for the bottom left it is Al/acrylic buildup 0.7 g/cm^2. There are 12 secondary diode detectors for penumbra detection which are located along the X and Y axes straddling the 20 cm light field mark. These detectors detect the edges of the 20 x 20 cm^2 field to measure the light-radiation field coincidence. The inherent buildup over the diode is acrylic 0.77 cm (effective buildup ~ 0.88 g/cm^2). The light field alignment is 20 x 20 cm^2. The locations of the detectors are shown in Figure 17.



Four e-Energy ion chambers (blue) with built-in attenuators labeled e^{TL} (electron, top left), e^{TR}, e^{BL}, e^{BR}. Attenuating disks of different densities embedded in top plastic provide a range of buildup depth, permitting single exposure e-Energy checks.

One parallel plate ion chamber (black) at Central Axis (CAX).

Four X-Energy ion chambers (blue) located along corners of a 16 cm square labeled X^{TL} (photon, top left), X^{TR}, X^{BL} and X^{BR}.

Four rectangular ion chambers (blue) 8 cm from CAX along X and Y axes labeled T (top), B (bottom), L (left), and R (right).

Blue dashed lines for calibration alignment.

Twelve diode detectors marked with small blue circles along X and Y axes straddling 20 cm light field mark. These diodes detect the edge of a 20 x 20 cm field to measure light-radiation coincidence.

Black X and Y lines to align with collimator crosshairs. A light field size locater is provided for a 20 x 20 cm field.

Figure 17. Daily QA3 phantom

There is one temperature sensor located near the device electronics that must not be exposed to radiation. There are 5 radiation-insensitive thermistors located near each X-Energy ion chamber and CAX ion chamber. The pressure sensor is a temperature compensated on-chip bipolar operational amplifier and thin film resistor network. The internal temperature/pressure measurement is adjusted to user temperature and pressure correction. Locations of the temperature sensors are shown in Figure 18.

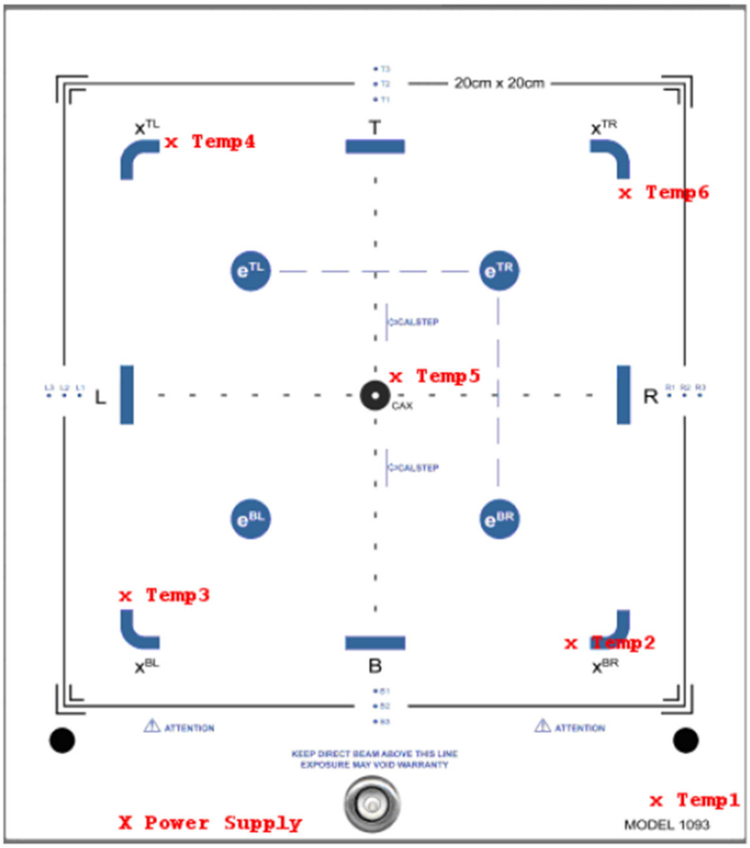
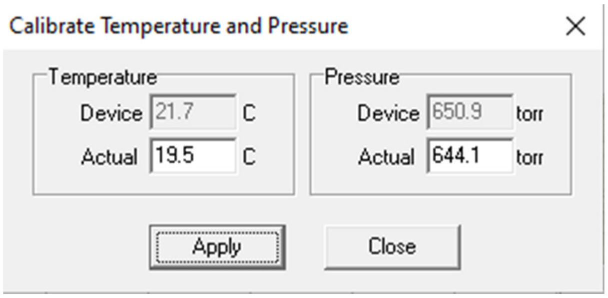


Figure 18. Daily QA3 temperature sensor distribution

A temperature and pressure calibration is required to finalize the calibration of the Daily QA3 phantom (Figure 19).



Temperature Device 21.7 C
Temperature Actual 19.5 C
Pressure Device 650.9 torr
Pressure Actual 644.1 torr

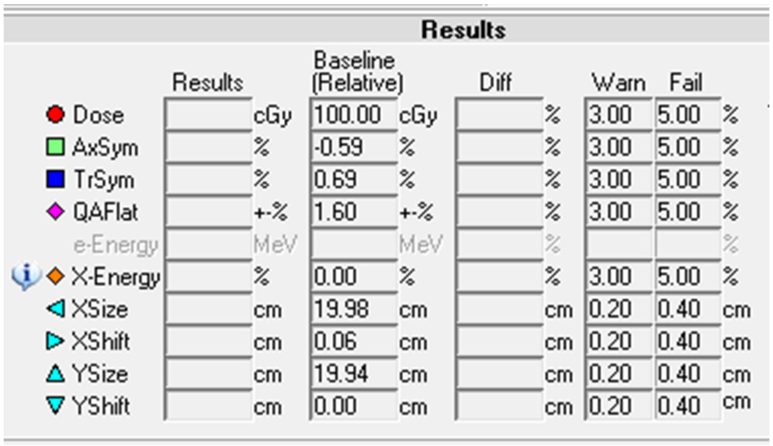
Figure 19. Daily QA3 temperature and pressure calibration

To calibrate absolute dose for the Daily QA3 phantom, the physicist sets up a 10x10 cm^2 field with a 5cm buildup (Figure 20). The intrinsic build up water equivalent for the daily QA3 is 0.74 cm, thus the total depth is 5.74cm. Per data book, for 6X MV, at 5.74 cm, the PDD is 82.6%. Therefore, 100 monitor units (MU) deliver a dose of 82.6 cGy and therefore 82.6 cGy is entered into the system as the absolute dose factor.

Figure 20. Daily QA3 absolute dose calibration

3.2 Daily QA3 Baseline

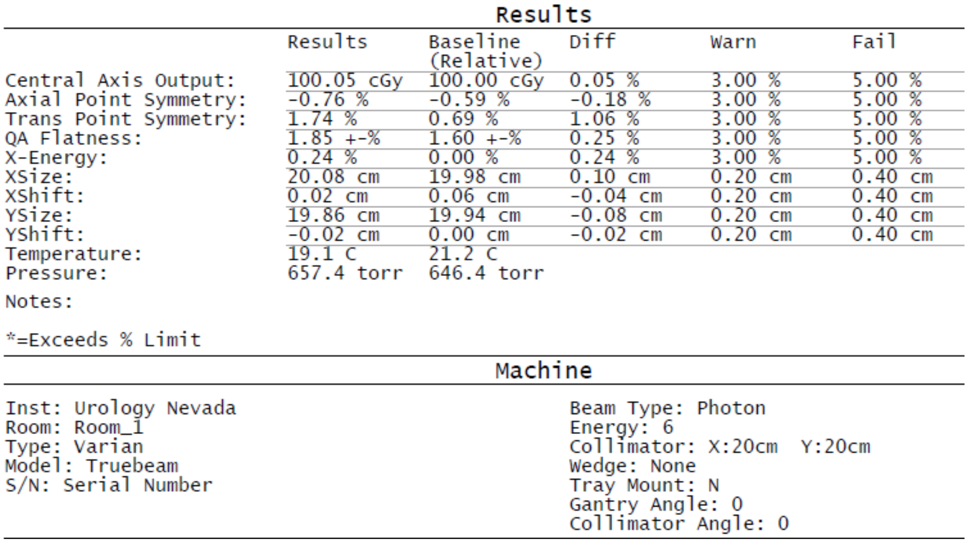
After the annual QA or TG-51 calibration, the physicist needs to perform the baseline measurement using the Sun Nuclear Daily QA3 device. From the Daily QA3 software menu, select Setup > Baseline QA template, select any photon/electron energy (i.e., 6x) and then reset the baseline. Setup the field size (20 x 20 cm^2) and press the star button to accept the dose. At the LINAC side, the physicist logs in to service mode, selects the photon/electron energy (i.e., 6x), and delivers 100 MU. At the pop-up menu at the Daily QA3 device, enter the baseline dose “100 cGy”, and delivered dose “100 cGy” and record the result. The baseline value for 6x photon energy is now set. The physicist can return to QA mode and perform a QA measurement to confirm the baseline results (Figure 21).



Results

	Results		Baseline (Relative)		Diff		Warn	Fail	
● Dose		cGy	100.00	cGy		%	3.00	5.00	%
🟩 AxSym		%	-0.59	%		%	3.00	5.00	%
🟦 TrSym		%	0.69	%		%	3.00	5.00	%
◆ QAFlat		+-%	1.60	+-%		%	3.00	5.00	%
e-Energy		MeV		MeV		%			%
ℹ ◆ X-Energy		%	0.00	%		%	3.00	5.00	%
◁ XSize		cm	19.98	cm		cm	0.20	0.40	cm
▷ XShift		cm	0.06	cm		cm	0.20	0.40	cm
△ YSize		cm	19.94	cm		cm	0.20	0.40	cm
▽ YShift		cm	0.00	cm		cm	0.20	0.40	cm

(a)

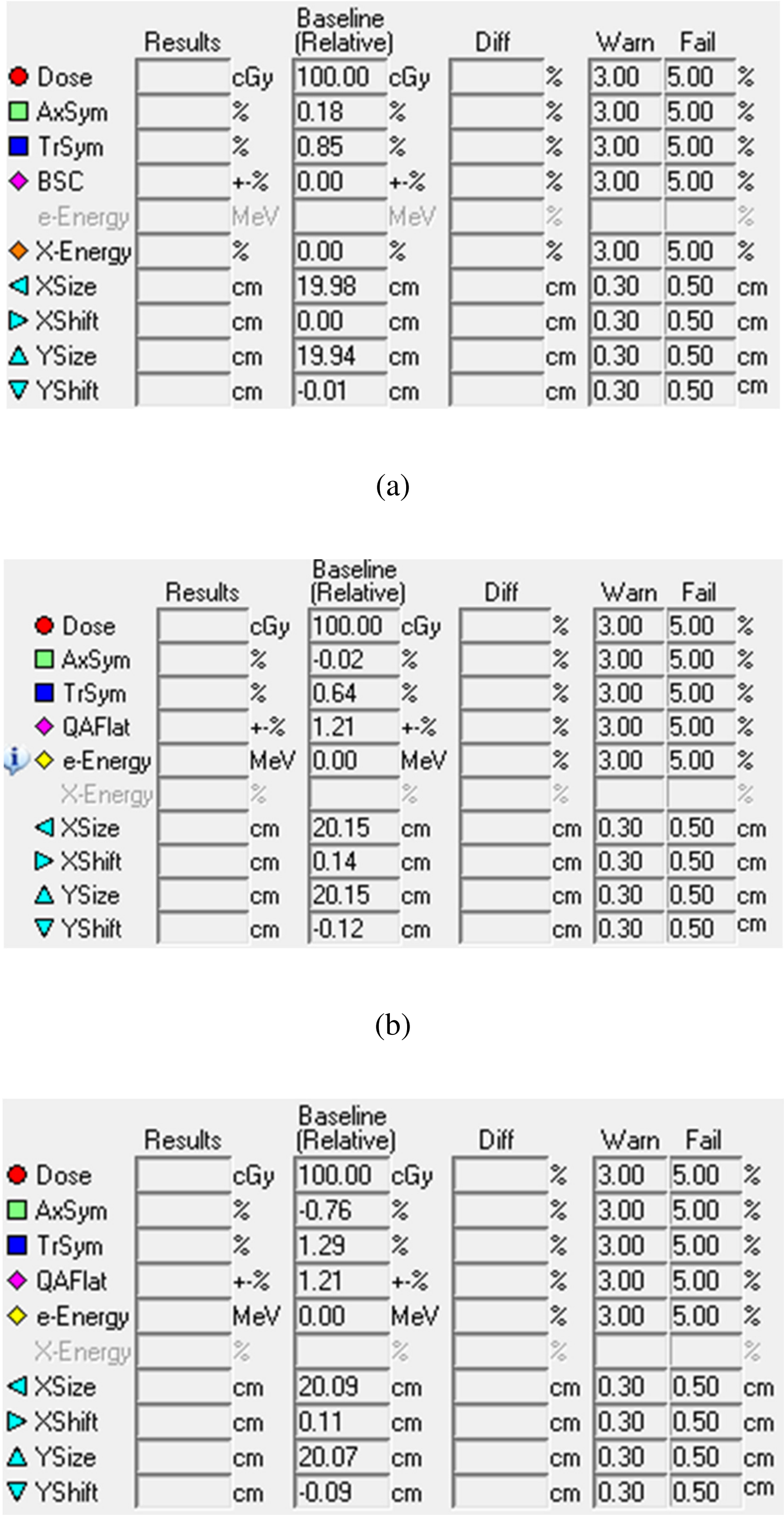


```
                                   Results
                        Results      Baseline     Diff         Warn         Fail
                                     (Relative)
Central Axis Output:    100.05 cGy   100.00 cGy   0.05 %       3.00 %       5.00 %
Axial Point Symmetry:   -0.76 %      -0.59 %      -0.18 %      3.00 %       5.00 %
Trans Point Symmetry:   1.74 %       0.69 %       1.06 %       3.00 %       5.00 %
QA Flatness:            1.85 +-%     1.60 +-%     0.25 %       3.00 %       5.00 %
X-Energy:               0.24 %       0.00 %       0.24 %       3.00 %       5.00 %
XSize:                  20.08 cm     19.98 cm     0.10 cm      0.20 cm      0.40 cm
XShift:                 0.02 cm      0.06 cm      -0.04 cm     0.20 cm      0.40 cm
YSize:                  19.86 cm     19.94 cm     -0.08 cm     0.20 cm      0.40 cm
YShift:                 -0.02 cm     0.00 cm      -0.02 cm     0.20 cm      0.40 cm
Temperature:            19.1 C       21.2 C
Pressure:               657.4 torr   646.4 torr
Notes:

*=Exceeds % Limit
                                   Machine
Inst: Urology Nevada                              Beam Type: Photon
Room: Room_1                                      Energy: 6
Type: Varian                                      Collimator: X:20cm  Y:20cm
Model: Truebeam                                   Wedge: None
S/N: Serial Number                                Tray Mount: N
                                                  Gantry Angle: 0
                                                  Collimator Angle: 0
```

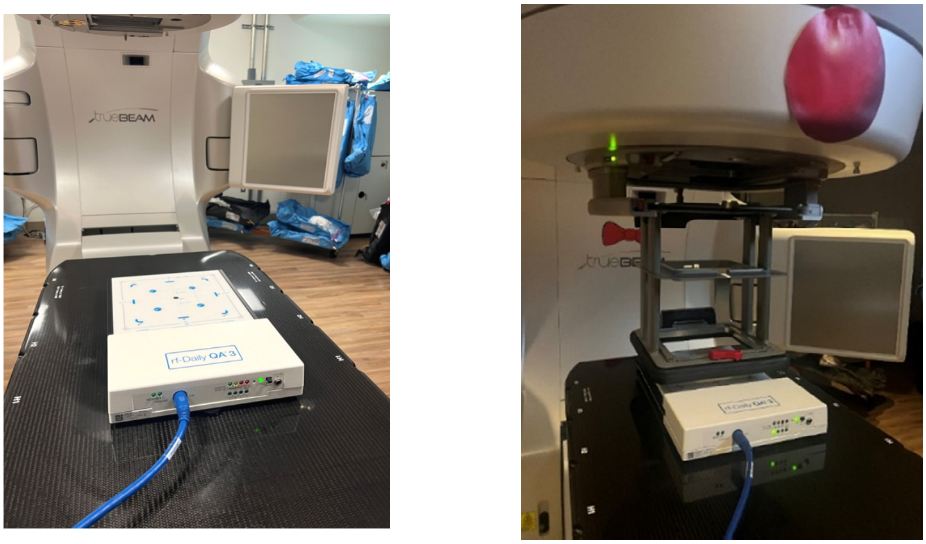
(b)

Figure 21. 6MV baseline and verification. 6MV baseline value (a) 6MV confirmation (b)



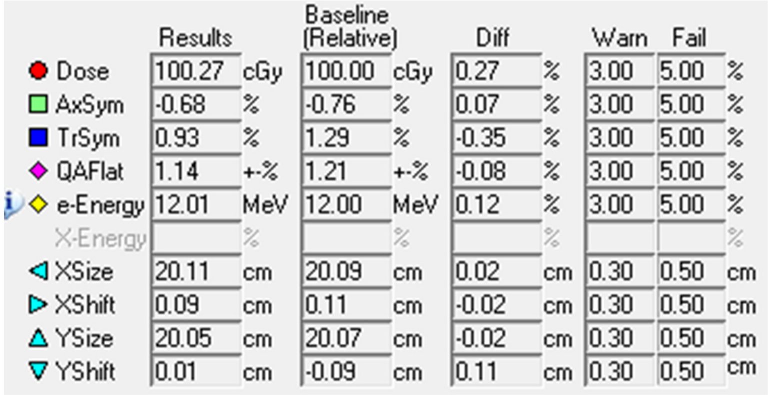
3.3 Daily QA3 routine measurement

For routine photon beam QA measurements: log in to Service Mode at the TrueBeam console. At the therapist computer, launch the "**Daily QA3**" software by double clicking the "**Daily QA3**" icon. After the background measurement is done, click on the 1st Energy (6x photon) to perform the QA procedure. The setup for a 6x photon beam is 100 MU, dose rate of 500 MU/min, (1200 MU/min for the FFF beam), and a field size of 20x20 cm^2. Click "**Start**" to begin the QA measurement and wait for the 6x photon beam to be delivered. At the TrueBeam console, switch to Service Mode and deliver 100 MU to the daily QA3 phantom. After the beam is delivered, the results are analyzed by comparing the measurement with the baseline. If the deviation is within the tolerance, the "Results" bar color will be green, and the therapist can record that day's measurement by clicking on "**Record Pass**". The software will move to the next photon energy, 6xFFF, and the therapist will repeat the operation for all photon energies. When the measurements for all photon energies are done, the therapist will install a 20x20 cm^2 electron cone to prepare for the electron energy measurement. The electron energy measurements are identical to those for the photons with the exception of the addition of the electron cone. Figure 23 shows a typical daily QA measurement setup for photon and electron measurements.



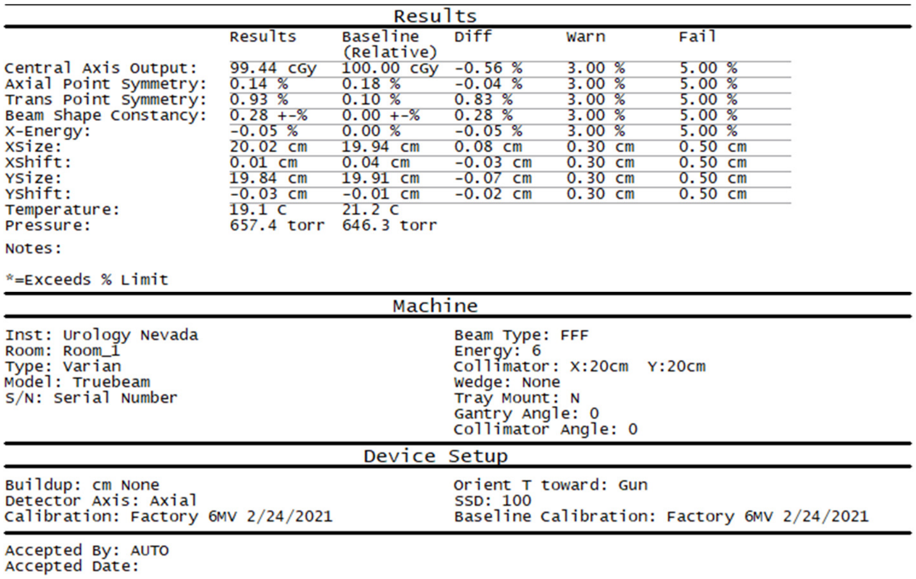
(a) (b)

Figure 23. Daily QA3 baseline setup view. (a) photon (b) electron. SSD is set to 100 cm.



	Results		Baseline (Relative)		Diff		Warn	Fail	
● Dose	100.27	cGy	100.00	cGy	0.27	%	3.00	5.00	%
🟩 AxSym	-0.68	%	-0.76	%	0.07	%	3.00	5.00	%
🟦 TrSym	0.93	%	1.29	%	-0.35	%	3.00	5.00	%
◆ QAFlat	1.14	+-%	1.21	+-%	-0.08	%	3.00	5.00	%
◇ e-Energy	12.01	MeV	12.00	MeV	0.12	%	3.00	5.00	%
X-Energy		%		%		%			%
◁ XSize	20.11	cm	20.09	cm	0.02	cm	0.30	0.50	cm
▷ XShift	0.09	cm	0.11	cm	-0.02	cm	0.30	0.50	cm
△ YSize	20.05	cm	20.07	cm	-0.02	cm	0.30	0.50	cm
▽ YShift	0.01	cm	-0.09	cm	0.11	cm	0.30	0.50	cm

Figure 24. 12MeV routine QA results



```
                                   Results
                        Results    Baseline    Diff        Warn        Fail
                                   (Relative)
Central Axis Output:    99.44 cGy  100.00 cGy  -0.56 %     3.00 %      5.00 %
Axial Point Symmetry:   0.14 %     0.18 %      -0.04 %     3.00 %      5.00 %
Trans Point Symmetry:   0.93 %     0.10 %      0.83 %      3.00 %      5.00 %
Beam Shape Constancy:   0.28 +-%   0.00 +-%    0.28 %      3.00 %      5.00 %
X-Energy:               -0.05 %    0.00 %      -0.05 %     3.00 %      5.00 %
XSize:                  20.02 cm   19.94 cm    0.08 cm     0.30 cm     0.50 cm
XShift:                 0.01 cm    0.04 cm     -0.03 cm    0.30 cm     0.50 cm
YSize:                  19.84 cm   19.91 cm    -0.07 cm    0.30 cm     0.50 cm
YShift:                 -0.03 cm   -0.01 cm    -0.02 cm    0.30 cm     0.50 cm
Temperature:            19.1 C     21.2 C
Pressure:               657.4 torr 646.3 torr

Notes:

*=Exceeds % Limit
                                   Machine
Inst: Urology Nevada                           Beam Type: FFF
Room: Room_1                                   Energy: 6
Type: Varian                                   Collimator: X:20cm  Y:20cm
Model: Truebeam                                Wedge: None
S/N: Serial Number                             Tray Mount: N
                                               Gantry Angle: 0
                                               Collimator Angle: 0
                                 Device Setup
Buildup: cm None                               Orient T toward: Gun
Detector Axis: Axial                           SSD: 100
Calibration: Factory 6MV 2/24/2021             Baseline Calibration: Factory 6MV 2/24/2021

Accepted By: AUTO
Accepted Date:
```

Figure 25. 6xFFF baseline values vs routine QA results

The Sun Nuclear Daily QA3 is capable of performing routine daily QA measurements. The measured results will show information as output, flatness, symmetry, energy, and light-radiation coincidence. The Daily QA3 can also provide photon/electron beam quality trends over a period. This device is an important tool to fulfill TG-142 recommendations for LINAC QA.

3.4 Sun Nuclear IC Profiler

The IC profiler package includes IC profiler device, power data interface and power/data cable (25m). The power data interface (PDI) 3.0 powers up the Sun Nuclear IC profiler and communicates measurement data between the IC profiler and the host computer. The PDI 3.0 uses a 25 m long power and data cable that can be connected to the device in the treatment room with the PDI 3.0 located at the control console. The cable runs through a data tunnel between the vault and the control console (Figure 26).

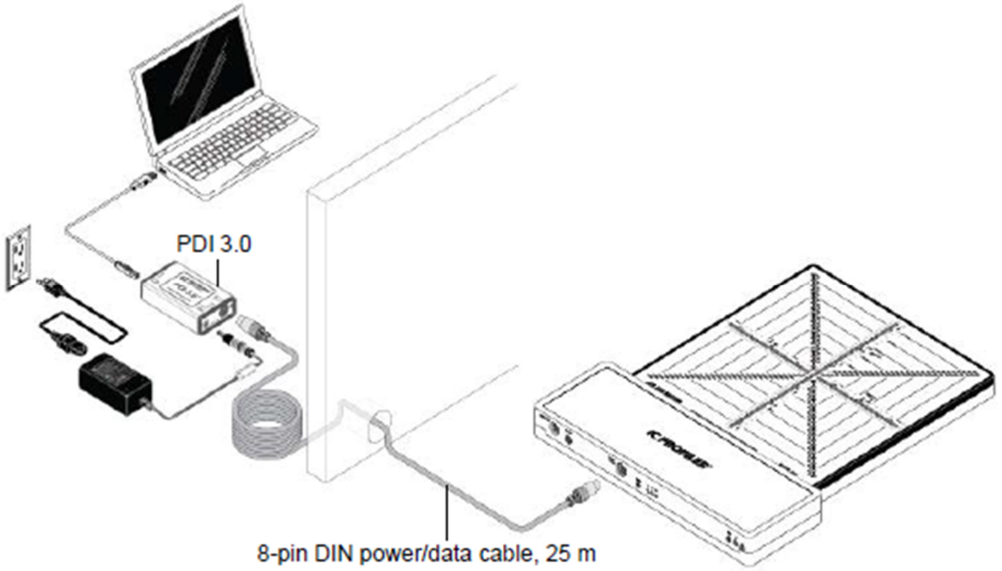


Figure 26. IC profiler hardware connection

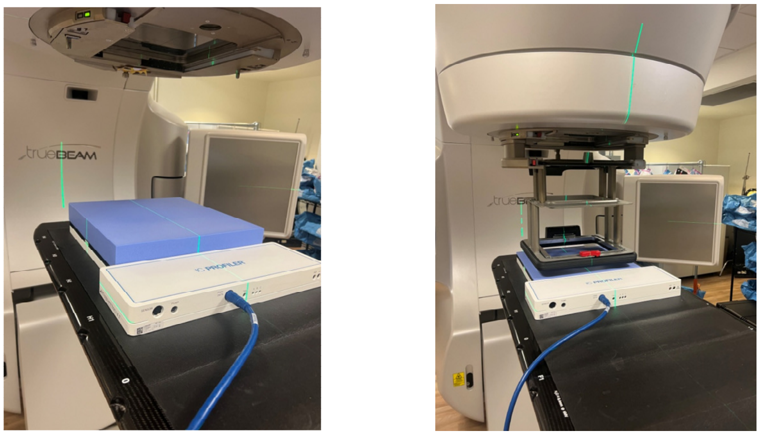
The IC Profiler consists of 251 modified parallel plate ion chambers. The array is located along the X and Y axes and two diagonals (positive diagonal 45˚ between coordinate axes, negative diagonal 135˚ between coordinate axes). There are 63 ion chambers along the X axis, 65 ion chambers along the Y axis, 63 ion chambers along the positive diagonal and the remaining 63 ion chambers are along the negative axis. The ion chambers are spaced 5 mm apart. The maximum active measurement field is 32 x 32 cm^2. The volume of each ion chamber is 0.046 cm^3. The inherent buildup to detector surface is 0.94 cm/g^2 and the inherent backscatter is 0.94 cm/g^2. When the IC profiler software is launched, for each detector, a background correction factor is needed for precise measurement. Thus, a 20s background measurement is performed automatically. If the profile measurements last for a long time, the physicist can manually collect background to ensure the background factor for the detectors are updated, at the software. **Tool > Collect Background** will fulfill this task. The physicist can manually set background collection times from 10 to 600 seconds.

Absolute dose calibration will provide dose calibration factors to the equipment. This is accomplished by selecting **Tools > Calibrate Dose**, which opens the dose calibration dialog box. Click "**Add**" to add dose to the current calibration list. Then click "**Set as Default**" to set this dose calibration factor as the default value. The absolute dose calibration is suggested to be performed annually. The setup for absolute dose calibration was accomplished with a 5 cm solid water buildup. Since the intrinsic water equivalent for the IC profiler is 0.875 cm water, the total depth is 5 + 0.875 cm. The other dosimetric parameters were: 100 cm SSD, 6 MV, 100 MU. Per data book, the PDD at depth of 5.875 cm is 82.3% and, as such, delivery of 100 MU to the IC profiler with 5cm solid water buildup results in an actual dose value of 82.3 cGy. This value is entered as the absolute dose factor.

Temperature and pressure of the room/vault were determined for correction of the absolute dose rate measured by the IC profiler. The IC profiler should be connected to the power and remain in the treatment room for one hour to reach temperature equilibrium.

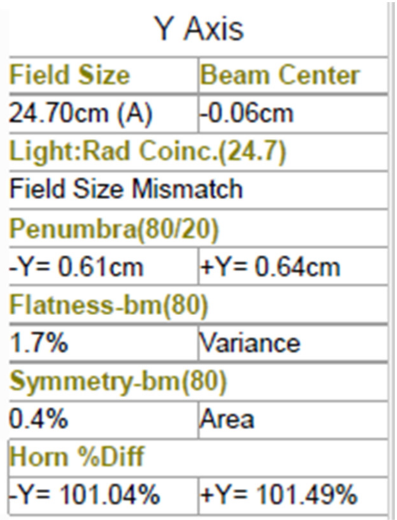
3.5 Sun Nuclear IC Profiler baseline

To collect the baseline data, the measurement was performed with the IC profiler using a setup with an SSD of 100 cm, and a field size of 25 x 25 cm^2 for all photon energies. These measurements were performed with a 5 cm thick solid water buildup material placed on the top of the IC profiler phantom. For all 6 MeV and 9 MeV electron energy measurements, a 0.5 cm thick solid water was added to the top of the IC profiler phantom. For 12 MeV beam profile measurements, acquisitions were repeated with an additional 1.5 cm thick solid water buildup material for comparison (Figure 27).



(a) (b)

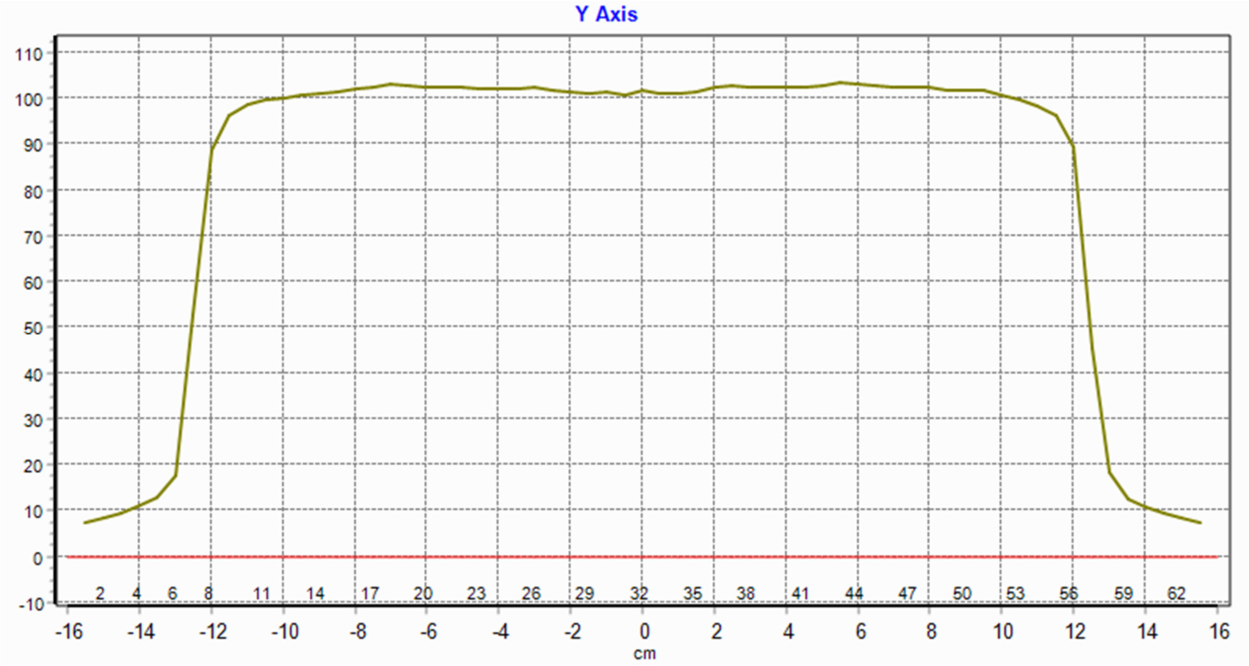
Figure 27. IC profiler baseline measurement setup. For a field size of 25x25 cm^2, (a) solid water 5 cm build up for all photon energies, (b) setup with 25x25 cm^2 cone, and a 0.5 cm solid water build up for all electron energies.



Y Axis

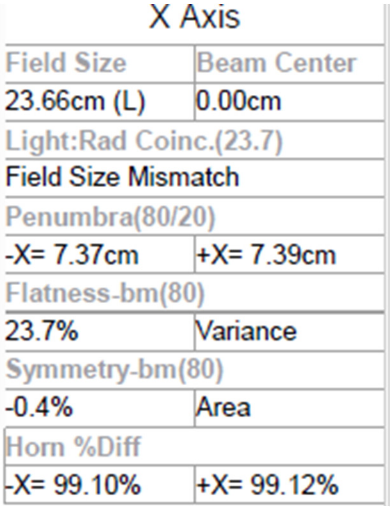
Field Size	Beam Center
24.70cm (A)	-0.06cm
Light:Rad Coinc.(24.7)	
Field Size Mismatch	
Penumbra(80/20)	
-Y= 0.61cm	+Y= 0.64cm
Flatness-bm(80)	
1.7%	Variance
Symmetry-bm(80)	
0.4%	Area
Horn %Diff	
-Y= 101.04%	+Y= 101.49%

(a)



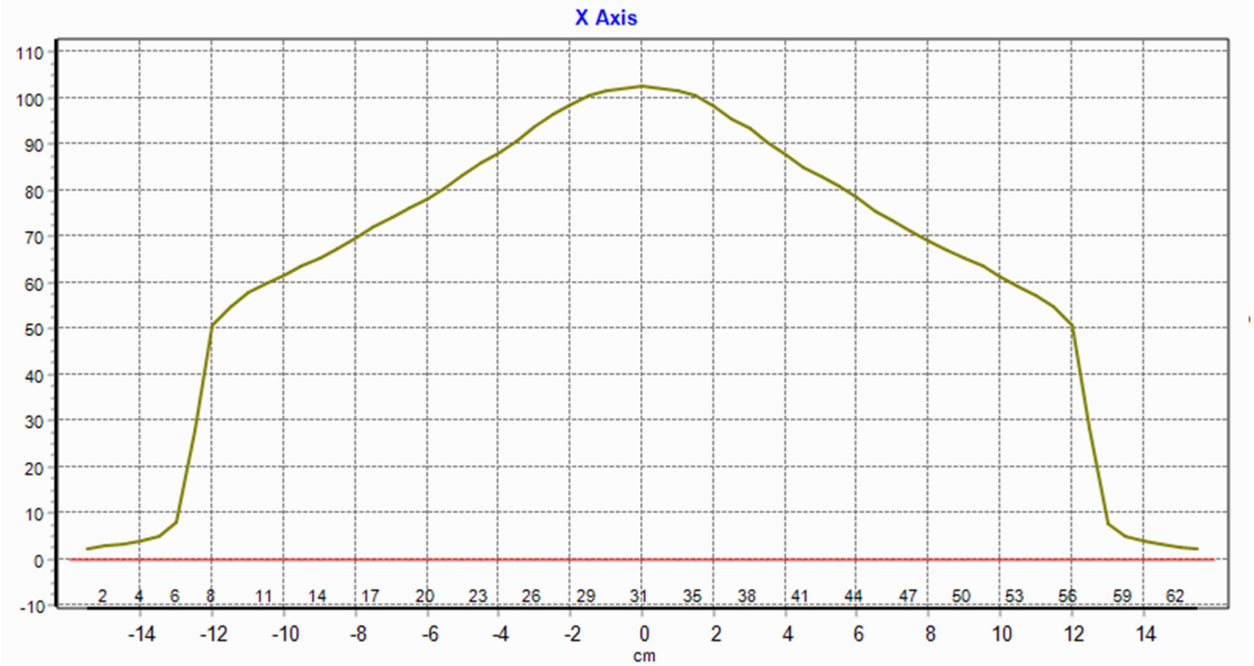
(b)

Figure 28: 6x beam profile baseline. (a) results and (b) beam profile image.



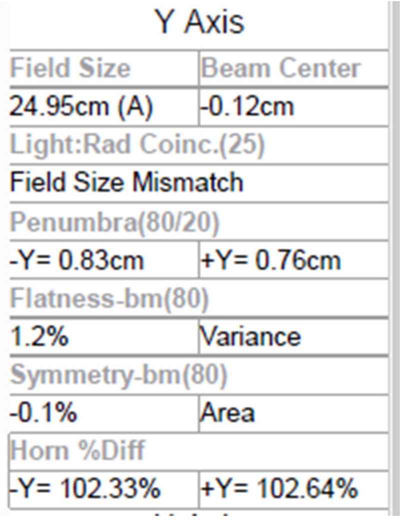
X Axis	
Field Size	Beam Center
23.66cm (L)	0.00cm
Light:Rad Coinc.(23.7)	
Field Size Mismatch	
Penumbra(80/20)	
-X= 7.37cm	+X= 7.39cm
Flatness-bm(80)	
23.7%	Variance
Symmetry-bm(80)	
-0.4%	Area
Horn %Diff	
-X= 99.10%	+X= 99.12%

(a)



(b)

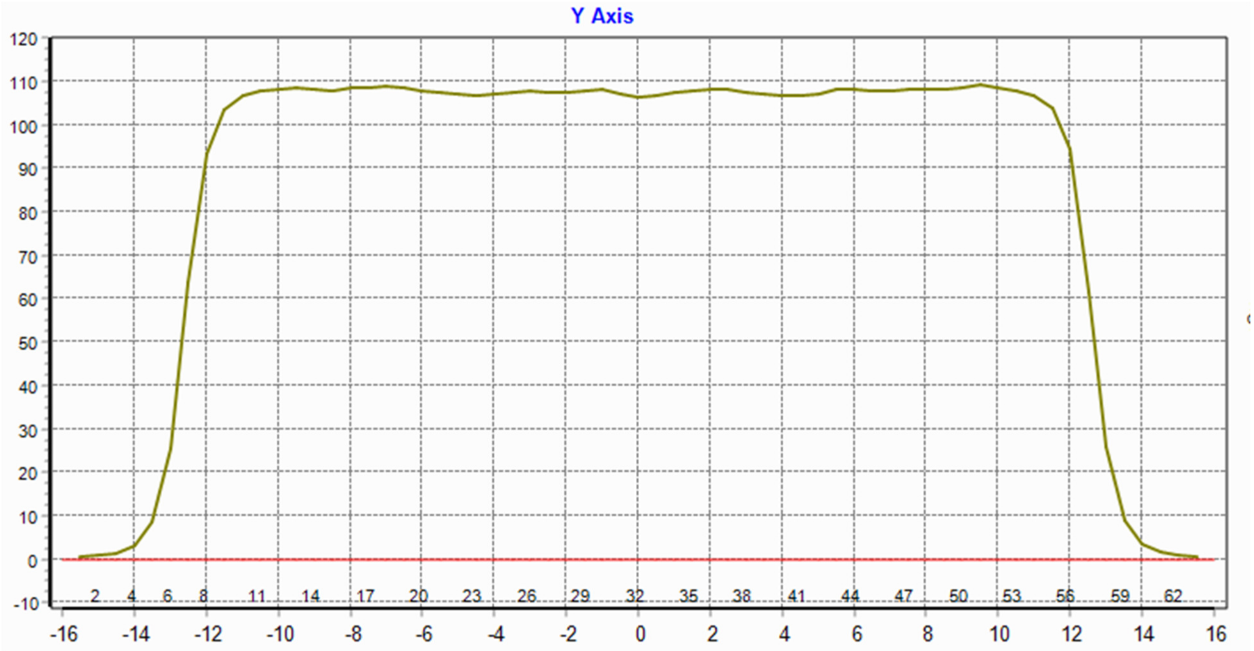
Figure 29: 10xFFF beam profile baseline. (a) results and (b) beam profile image.



Y Axis

Field Size	Beam Center
24.95cm (A)	-0.12cm
Light:Rad Coinc.(25)	
Field Size Mismatch	
Penumbra(80/20)	
-Y= 0.83cm	+Y= 0.76cm
Flatness-bm(80)	
1.2%	Variance
Symmetry-bm(80)	
-0.1%	Area
Horn %Diff	
-Y= 102.33%	+Y= 102.64%

(a)



(b)

Figure 30: 9MeV beam profile baseline. (a) results and (b) beam profile image.

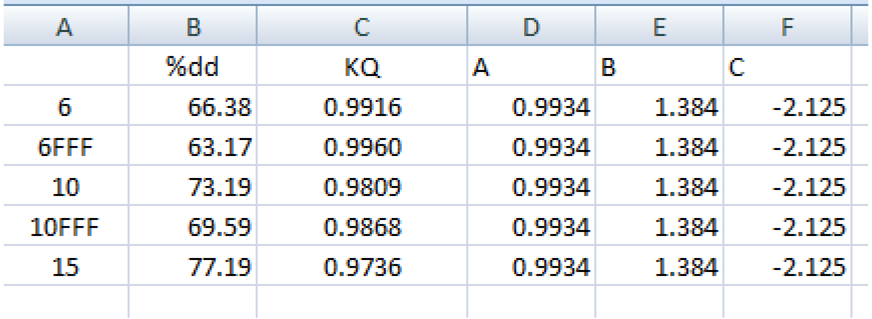
The standard beam profile for a photon beam is measured with a water-tank setup at a

10 cm depth. To use an IC profiler, a 5 cm thick solid water buildup was chosen for all photon energies instead. This was done since the consistency of the beam profile was evaluated and compared to the baseline data collected with a similar setup. For the 12 MeV electron beam, comparisons between the profile measured with 0.5 and 1.5 cm thick solid water buildup demonstrated that the results were the same and, as such, 0.5 cm buildup was chosen for all electron energies. The profile measurements provided dosimetric information such as field size, beam center, light/radiation coincidence, penumbra, flatness, and symmetry. After each annual QA or beam steering, the baseline needs to be examined and possibly re-measured and reset.

Chapter 4. Output & Energy Checks

4.1 Water Phantom Output TG 51 Calibration

Traditional output & energy constancy checks are performed with a Standard Imaging 1D water tank setup or using the 3D water tank setup, after the annual QA. For the TG-51 measurements, an Exradin A19 water-proof ion chamber was used. The inner cavity radius of this ion-chamber (r_{cav}) is 3.05 mm. The ion-chamber was calibrated by an Accredited Dosimetry Calibration Laboratory (ADCL) which provided a calibration factor (ND_W^{Co-60}) of 4.884E+07 Gy/C. The electrometer was a Max 4000, with a correction factor (P_{elec}) of 1.000 nC/rdg. The TG 51 measurement conditions were as follows: 10 x 10 cm^2 field size, 100 cm SSD, with the point of measurement at 10 cm depth in water. The dose delivery was set to 100 MU. For 6x photons, Kq was calculated to be 0.9916 using the parameters (A, B, C and %dd) found in the TG-51 addendum. Similarly, the Kq values for 6xFFF, 10x, 10xFFF, and 15x were calculated and the values are listed in column C of Figure 31. The 3D water setup for the TG-51 calibration is shown in Figure 32.



A	B	C	D	E	F
	%dd	KQ	A	B	C
6	66.38	0.9916	0.9934	1.384	-2.125
6FFF	63.17	0.9960	0.9934	1.384	-2.125
10	73.19	0.9809	0.9934	1.384	-2.125
10FFF	69.59	0.9868	0.9934	1.384	-2.125
15	77.19	0.9736	0.9934	1.384	-2.125

Figure 31. K_q value for TG 51 calibration

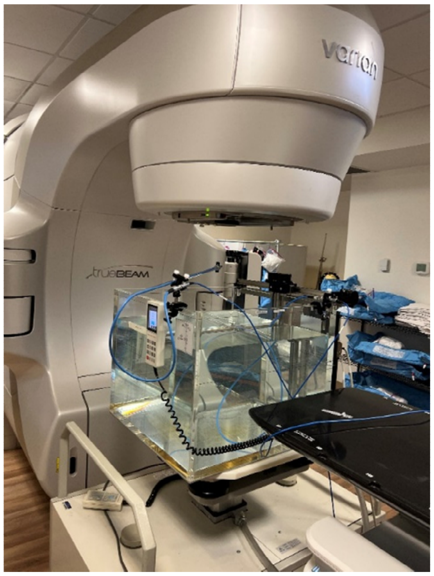


Figure 32. 3D water phantom setup for TG 51 calibration

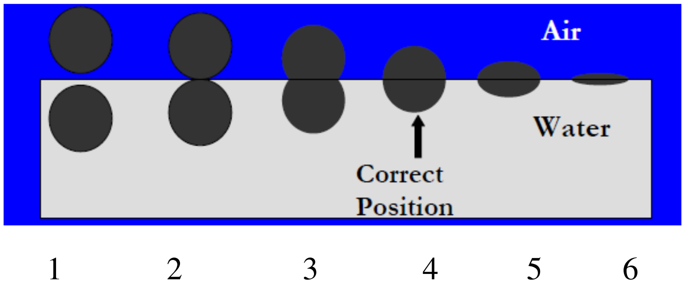


Figure 33. ion chamber position for TG 51 calibration

Once the water phantom setup was completed, the ion chamber was positioned at 10 cm depth for the precise TG-51 measurement. To setup the ion-chamber origin, the physicist observes the ion chamber from the side of the water tank and visualizes the tip of the chamber and its reflection in the water at the same time as shown in Figure 33. By adjusting the position of the ion-chamber, to match with its reflection, a full circle is formed indicating that half of the chamber is in the water and half is outside the water. Figure 33 shows the image of the ion-chamber and its reflection at several different positions. The water tank setup and the ion chamber positioning may be time consuming, but if not performed correctly, it could introduce positioning errors.

Once the setup was complete, the TG-51 formulation and correction parameters were used to determine the output. The five key equations are shown below.

$$D_w^Q = M k_Q N_{D,w}^{^{60}\mathrm{Co}} \quad \text{(Gy).}$$

(1)

$$M = P_{\mathrm{ion}} P_{\mathrm{TP}} P_{\mathrm{elec}} P_{\mathrm{pol}} M_{\mathrm{raw}} \quad \text{(C or rdg),}$$

(2)

$$P_{\mathrm{TP}} = \frac{273.2 + T}{273.2 + 22.0} \times \frac{101.33}{P},$$

(3)

$$P_{\mathrm{pol}} = \left| \frac{(M_{\mathrm{raw}}^{+} - M_{\mathrm{raw}}^{-})}{2 M_{\mathrm{raw}}} \right|,$$

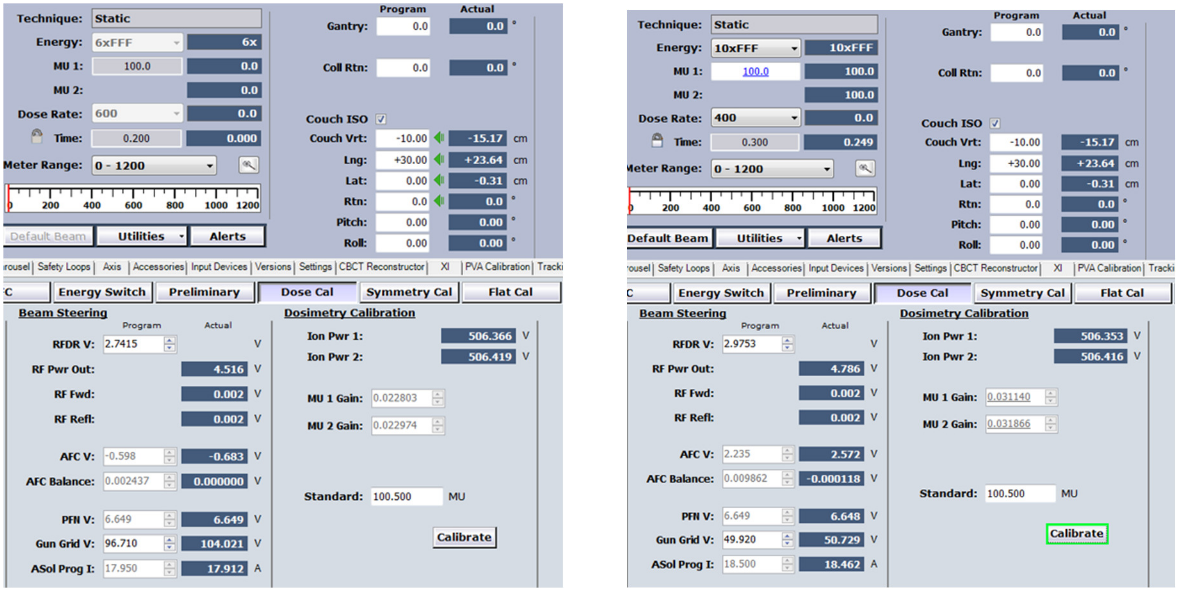
(4)

$$P_{\mathrm{ion}}(V_H) = \frac{1. - V_H / V_L}{M_{\mathrm{raw}}^{H} / M_{\mathrm{raw}}^{L} - V_H / V_L}.$$

(5)

For photon TG-51 calibration, 6xFFF was used as an example. Equation 1 was used to calculate the dose to water at the specific conditions. M is the electrometer reading corrected by P_{ion}, P_{pol} and P_{tp}. On the calibration day, the temperature was 18.9˚C and the pressure was 87.2 kPa. The standard temperature and pressure are 22˚C and 101.33 kPa. Per equation 3, the P_{tp} correction factor was 1.150.

The ion-chamber was calibrated at the ADCL with +300V bias, thus the $M_{\mathrm{raw+}}$ was set at +300V and the chamber was exposed to 100 MU radiation. One repeat reading was taken to verify the reproducibility of the data. The final data was the average value for M_{raw+}. To calculate P_{pol} (the polarity correction factor), the bias voltage was set to -300V to obtain M_{raw-} (average of two readings). In this calibration measurement, the M_{raw+} reading was 11.42, and the M_{raw-} reading was 11.44, thus the P_{pol} per Equation 4 was found to be 0.9991. To calculate the P_{ion} correction factor, the bias voltage was set to +150V and the average of two readings was taken as M_{low} raw. P_{ion} is the recombination correction factor, per Equation 5, V_h= +300V, V_{low}=150V, Mhighraw = 11.44nC, M_{low}raw= 11.37nC, thus the P_{ion} was calculated to be 1.0062. The fully corrected M was calculated as M= $M_{raw}*P_{tp}*P_{elec}*P_{ion}*P_{pol}$, and thus the final value for the 6x photon beam was M= 13.22 nC. The dose to water at 10 cm depth was determined from $M*Kq*ND^{Co\text{-}60}{}_{w}$ and was equal to 64.32 cGy. The dose per MU at 10 cm depth in water was 0.643 cGy/MU. The clinical value for %DD at 10 cm depth water phantom for SSD setup is 63.5%, thus the dose/MU at d_{max} was 0.643/0.635 = 1.013cGy/MU. The Varian TrueBeam needs to be calibrated to 1.000 ±0.02 cGy/MU at d_{max} and, as such, the measured output was within tolerance.



(a)

Field	Program	Actual	
Technique:	Static		
Energy:	6xFFF	6x	
MU 1:	100.0	0.0	
MU 2:		0.0	
Dose Rate:	600	0.0	
Time:	0.200	0.000	
Meter Range:	0 - 1200		
Gantry:	0.0	0.0	°
Coll Rtn:	0.0	0.0	°
Couch ISO	☑		
Couch Vrt:	-10.00	-15.17	cm
Lng:	+30.00	+23.64	cm
Lat:	0.00	-0.31	cm
Rtn:	0.0	0.0	°
Pitch:	0.00	0.00	°
Roll:	0.00	0.00	°

Beam Steering

	Program	Actual	
RFDR V:	2.7415		V
RF Pwr Out:		4.516	V
RF Fwd:		0.002	V
RF Refl:		0.002	V
AFC V:	-0.598	-0.683	V
AFC Balance:	0.002437	0.000000	V
PFN V:	6.649	6.649	V
Gun Grid V:	96.710	104.021	V
ASol Prog I:	17.950	17.912	A

Dosimetry Calibration

Ion Pwr 1: 506.366 V
Ion Pwr 2: 506.419 V
MU 1 Gain: 0.022803
MU 2 Gain: 0.022974
Standard: 100.500 MU

(b)

Field	Program	Actual	
Technique:	Static		
Energy:	10xFFF	10xFFF	
MU 1:	100.0	100.0	
MU 2:		100.0	
Dose Rate:	400	0.0	
Time:	0.300	0.249	
Meter Range:	0 - 1200		
Gantry:	0.0	0.0	°
Coll Rtn:	0.0	0.0	°
Couch ISO	☑		
Couch Vrt:	-10.00	-15.17	cm
Lng:	+30.00	+23.64	cm
Lat:	0.00	-0.31	cm
Rtn:	0.0	0.0	°
Pitch:	0.00	0.00	°
Roll:	0.00	0.00	°

Beam Steering

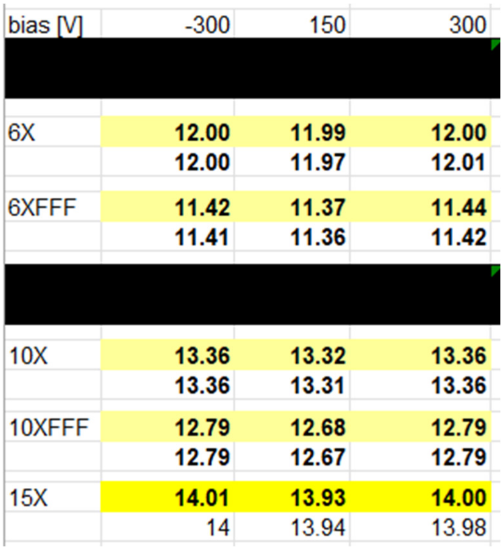
	Program	Actual	
RFDR V:	2.9753		V
RF Pwr Out:		4.786	V
RF Fwd:		0.002	V
RF Refl:		0.002	V
AFC V:	2.235	2.572	V
AFC Balance:	0.009862	-0.000118	V
PFN V:	6.649	6.648	V
Gun Grid V:	49.920	50.729	V
ASol Prog I:	18.500	18.462	A

Dosimetry Calibration

Ion Pwr 1: 506.353 V
Ion Pwr 2: 506.416 V
MU 1 Gain: 0.031140
MU 2 Gain: 0.031866
Standard: 100.500 MU

Figure 34. TG 51 calibration interfaces. 6x FFF (a) and 10xFFF (b)

For all photon energies, the TG-51 data is shown in Figure 35:



bias [V]	-300	150	300
[redacted]	[redacted]	[redacted]	[redacted]
6X	12.00	11.99	12.00
	12.00	11.97	12.01
6XFFF	11.42	11.37	11.44
	11.41	11.36	11.42
[redacted]	[redacted]	[redacted]	[redacted]
10X	13.36	13.32	13.36
	13.36	13.31	13.36
10XFFF	12.79	12.68	12.79
	12.79	12.67	12.79
15X	14.01	13.93	14.00
	14	13.94	13.98

Figure 35. TG-51 calibration photon data

The equations for electron calibration using the TG-51 formalism are shown below:

$$D_w^Q = M P_{gr}^Q \, k'_{R_{50}} k_{ecal} \, N_{D,w}^{60Co} \quad (\mathrm{Gy}). \tag{6}$$

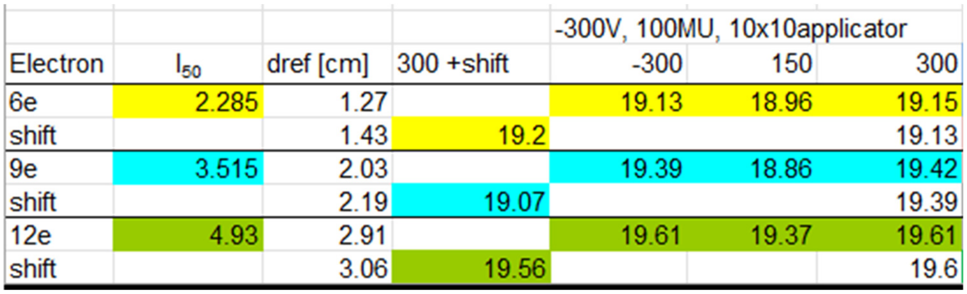
$$M = P_{ion} P_{TP} P_{elec} P_{pol} M_{raw} \quad (\mathrm{C\ or\ rdg}), \tag{7}$$

$$P_{gr}^Q = \frac{M_{raw}(d_{ref} + 0.5 r_{cav})}{M_{raw}(d_{ref})} \ (\text{for cylindrical chambers}), \tag{8}$$

For electron TG 51 calibration, 9 MeV electrons are used as an example. For a 9 MeV beam, from clinical water scanning data, I_{50} = 3.515 cm, R_{50} = 1.029 *I_{50}-0.06, thus R_{50} is 3.557 cm. The reference depth for 9 MeV electrons (d_{ref}) = 0.6*R50 - 0.1, and is equal to 2.03 cm. For the ion chamber model used in this calibration, kecal is 0.906. k'R_{50} is 1.0167. Equation 6 was used to calculate the dose to water at the specific conditions. M is the electrometer reading corrected by P_{ion}, P_{pol} and P_{tp}. On the calibration day, the temperature and pressure were 18.9˚C, and 87.21 kPa, respectively. The standard temperature and pressure are 22˚C and 101.33 kPa. Per equation 3, the P_{TP} correction factor was 1.150. The 10 x 10 electron cone was used for the TG-51 calibration.

The ion chamber was calibrated at the ACDL with +300V bias, thus the M_{raw+} was set at +300V, and the water phantom was exposed to 100 MU twice to obtain a mean value for M_{raw+}. To calculate the P_{pol}, the bias voltage was set to -300V and two readings were averaged. In this calibration measurement, the M_{raw+} readings were 19.39 and 19.42 nC. From equation 4, the P_{pol} was calculated as 0.9992. To calculate the P_{ion} correction factor, the bias voltage was set to +150V to obtain two readings (M_{rawlow}). The P_{ion} correction factor (1.0031) was found by substituting the following values into equation 5: V_h = +300V, V_{low} = 150V, $M_{rawhigh}$ = 19.42 nC and M_{rawlow}= 18.86 nC. The fully corrected M was calculated from $M = M_{raw}*P_{tp}*P_{elec}*P_{ion}*P_{pol}$ and was found to be 22.99 nC. The ion chamber was then moved to a depth of 2.19 cm (d_{ref} + 0.5 r_{cav}) and two readings were acquired (mean = 19.07 C). From equation 8, P^{Q}_{Gr} was found to be 0.982. The dose to water at d_{ref} (depth = 2.03 cm) was calculated from $M*K_q*ND_W^{Co-60}*$ P^{Q}_{Grad} and was found to be 1.016 Gy. Therefore, the dose per MU at d_{ref} in the water phantom was 1.016 cGy/MU. The clinical value for %DD at d_{ref} in a water phantom for an SSD setup is 100%, thus the dose/MU at d_{max} was 1.016cGy/MU. Since the Varian TrueBeam needs to be calibrated to 1.000cGy/MU at d_{max}, the measured 9 MeV electron output was within the acceptable tolerance (± 2%).

For all electron energies, the TG-51 data is shown in Figure 36:



				-300V, 100MU, 10x10applicator		
Electron	I_{50}	dref [cm]	300 +shift	-300	150	300
6e	2.285	1.27		19.13	18.96	19.15
shift		1.43	19.2			19.13
9e	3.515	2.03		19.39	18.86	19.42
shift		2.19	19.07			19.39
12e	4.93	2.91		19.61	19.37	19.61
shift		3.06	19.56			19.6

Figure 36. TG-51 calibration electron data

4.2 Solid Water-based Output & Energy Check Baseline

The ion chamber, electrometer and phantom are shown in Figure 37.

(a) (b) (c)

Figure 37. Solid water-based method instruments. (a) Exradin A19 ion chamber, (b) Max 4000 electron meter, and (c) multiple thickness solid water slabs.

The solid-water phantom setup for the photon beam output and energy constancy check is shown in Figure 38. The temperature and pressure were recorded (21.5˚C and 87.58 kPa) and measurements were taken with a bias voltage of, +300 V.

For the 6x photons, the following parameters were used: SSD of 100 cm, field size of 10x10 cm^2, dose of 100 MU, measurement depth of 10 cm and dose rate of 500 MU/minute. For the FFF beam, the dose rate was set to 1200 MU/minute.

Figure 38. Solid water-based output & energy check setup for photon. SSD 100 cm, 100 MU, depth of 10 cm for 6x, 6xFFF, 10x, 10xFFF, 15x measurements.

The solid water-based output and energy constancy check baseline ion chamber readings are shown below in Figure 39.

Photon energy	Reading 1	Reading 2
6x	-11.73	-11.73
10x	-13.12	-13.10
15x	-13.74	-13.71
6FFF	-11.07	-11.06
10FFF	-12.43	-12.43

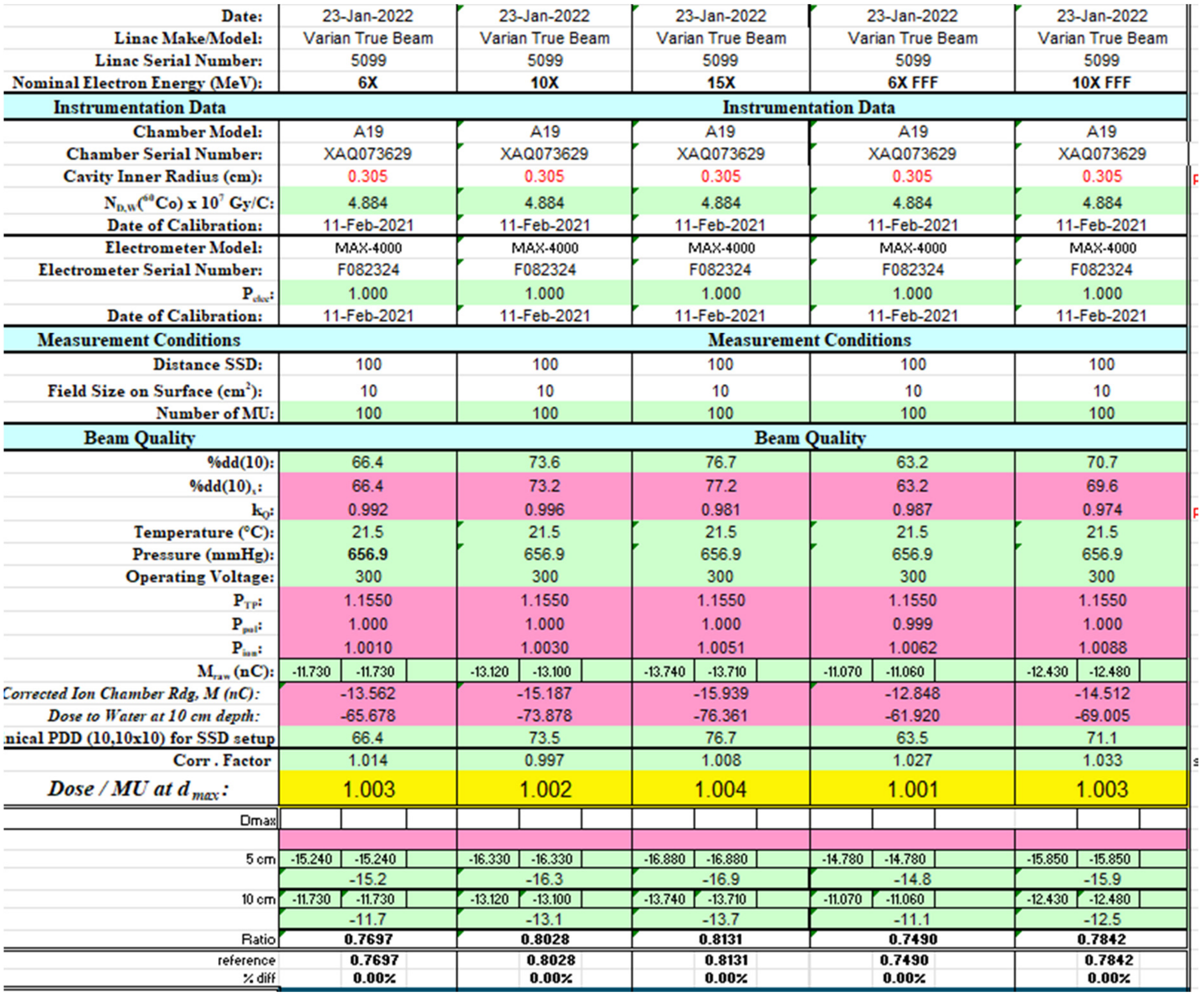
Figure 39. Solid water-based photon output baseline data

For the energy check (6x, 10x, 15x), the measurement depth was set at 5 cm and the following parameters were used: SSD = 100 cm, field size = 10x10 cm^2, 100 MU, bias = +300V, dose rate = 500 MU/minute. A dose rate of; 1200 MU/minute was used for 6FFF and 10FFF. To ensure the ion chamber readings were reproducible, two or three readings were taken, and the average was recorded as shown below in Figure 40.

Photon energy check	6x	10x	15x	6FFF	10FFF
Reading (average)	-15.24	-16.33	-16.88	-14.78	-15.85

Figure 40. Solid water-based electron output baseline data

A summary of the output and energy check baseline results is shown below in Figure 41.



Date:	23-Jan-2022	23-Jan-2022	23-Jan-2022	23-Jan-2022	23-Jan-2022
Linac Make/Model:	Varian True Beam	Varian True Beam	Varian True Beam	Varian True Beam	Varian True Beam
Linac Serial Number:	5099	5099	5099	5099	5099
Nominal Electron Energy (MeV):	**6X**	**10X**	**15X**	**6X FFF**	**10X FFF**
Instrumentation Data			**Instrumentation Data**		
Chamber Model:	A19	A19	A19	A19	A19
Chamber Serial Number:	XAQ073629	XAQ073629	XAQ073629	XAQ073629	XAQ073629
Cavity Inner Radius (cm):	0.305	0.305	0.305	0.305	0.305
$N_{D,W}(^{60}Co) \times 10^7$ Gy/C:	4.884	4.884	4.884	4.884	4.884
Date of Calibration:	11-Feb-2021	11-Feb-2021	11-Feb-2021	11-Feb-2021	11-Feb-2021
Electrometer Model:	MAX-4000	MAX-4000	MAX-4000	MAX-4000	MAX-4000
Electrometer Serial Number:	F082324	F082324	F082324	F082324	F082324
P_{elec}:	1.000	1.000	1.000	1.000	1.000
Date of Calibration:	11-Feb-2021	11-Feb-2021	11-Feb-2021	11-Feb-2021	11-Feb-2021
Measurement Conditions			**Measurement Conditions**		
Distance SSD:	100	100	100	100	100
Field Size on Surface (cm^2):	10	10	10	10	10
Number of MU:	100	100	100	100	100
Beam Quality			**Beam Quality**		
%dd(10):	66.4	73.6	76.7	63.2	70.7
$\%dd(10)_x$:	66.4	73.2	77.2	63.2	69.6
k_Q:	0.992	0.996	0.981	0.987	0.974
Temperature (°C):	21.5	21.5	21.5	21.5	21.5
Pressure (mmHg):	**656.9**	656.9	656.9	656.9	656.9
Operating Voltage:	300	300	300	300	300
P_{TP}:	1.1550	1.1550	1.1550	1.1550	1.1550
P_{pol}:	1.000	1.000	1.000	0.999	1.000
P_{ion}:	1.0010	1.0030	1.0051	1.0062	1.0088
M_{raw} (nC):	-11.730 -11.730	-13.120 -13.100	-13.740 -13.710	-11.070 -11.060	-12.430 -12.480
Corrected Ion Chamber Rdg, M (nC):	-13.562	-15.187	-15.939	-12.848	-14.512
Dose to Water at 10 cm depth:	-65.678	-73.878	-76.361	-61.920	-69.005
nical PDD (10,10x10) for SSD setup	66.4	73.5	76.7	63.5	71.1
Corr . Factor	1.014	0.997	1.008	1.027	1.033
Dose / MU at d_{max}:	1.003	1.002	1.004	1.001	1.003
Dmax					
5 cm	-15.240 -15.240	-16.330 -16.330	-16.880 -16.880	-14.780 -14.780	-15.850 -15.850
	-15.2	-16.3	-16.9	-14.8	-15.9
10 cm	-11.730 -11.730	-13.120 -13.100	-13.740 -13.710	-11.070 -11.060	-12.430 -12.480
	-11.7	-13.1	-13.7	-11.1	-12.5
Ratio	**0.7697**	**0.8028**	**0.8131**	**0.7490**	**0.7842**
reference	**0.7697**	**0.8028**	**0.8131**	**0.7490**	**0.7842**
% diff	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**

Figure 41. Solid water-based photon output & energy check baseline values

The solid-water phantom setup for the electron beam output and energy constancy check is shown in Figure 42. For the electron beam output and energy constancy check the following parameters were used: SSD=100, 10x10 cm^2 electron cone, dose rate = 500 MU/minute, 100 MU. For 6 MeV electrons: depth1=1.3 cm for output check, 2.3 cm for energy check; for 9 MeV electrons, depth1 = 2.3 cm for output check, depth2 = 3.3 cm for energy check; for 12 MeV electrons, depth1 = 3.3 cm for output check, depth2 = 5 cm for energy check.

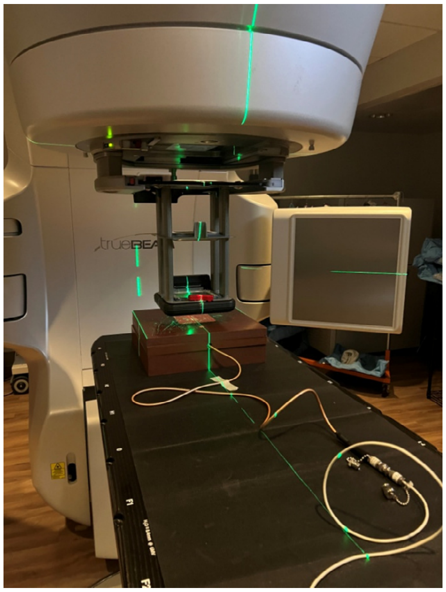


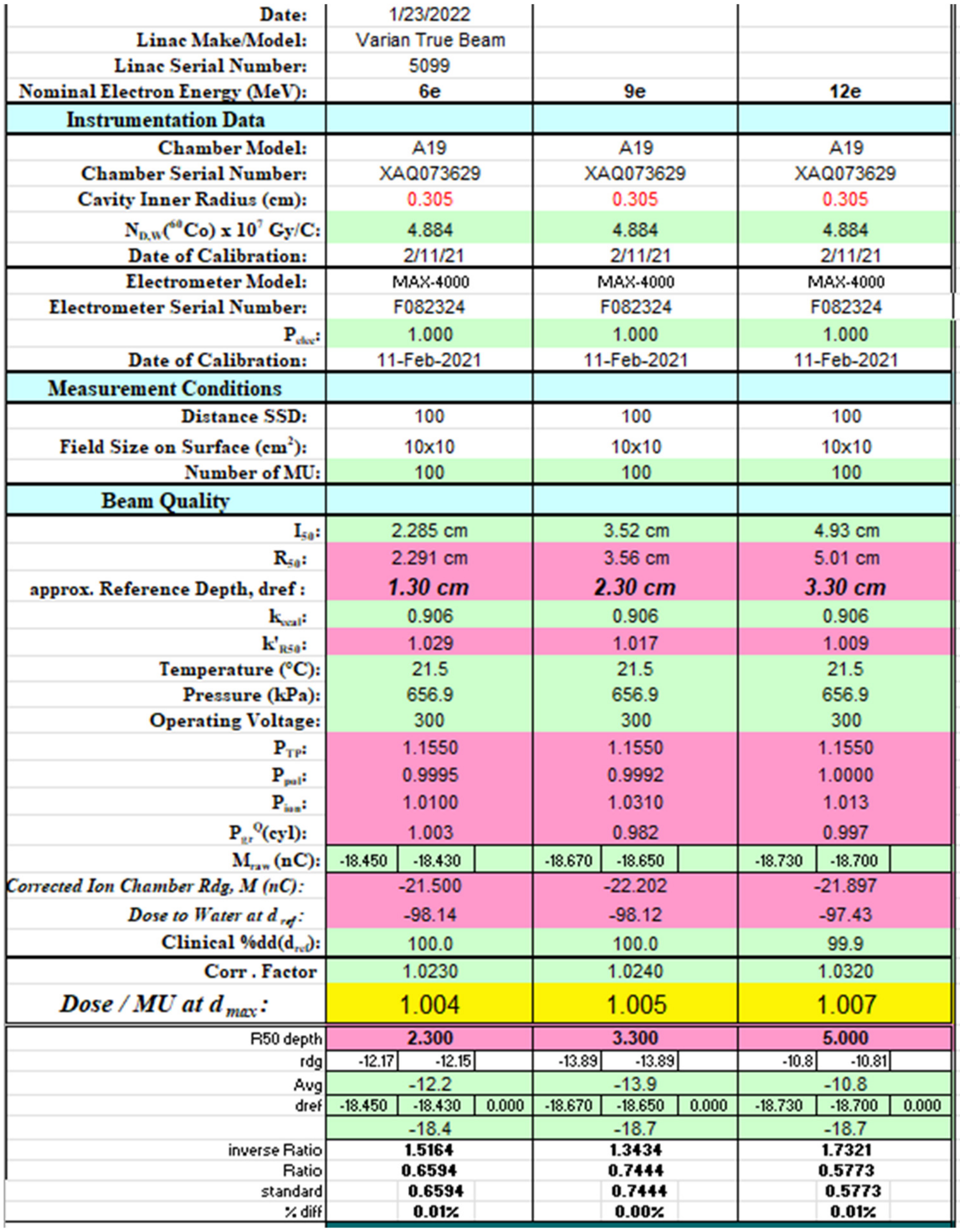
Figure 42. Solid water-based output & energy check setup for electron. For 9 and 12 MeV with 10x10 cm^2 electron cone, SSD 100 cm, 100 MU, and depth of 3.3 cm.

The output and energy check baseline ion chamber reading data is summarized in Figure 43.

Energy & Depth	6e 1.3cm	6e 2.3 cm	9e 2.3cm	9e 3.3 cm	12e 3.3 cm	12e 5cm
Reading 1	-18.46	-12.21	-18.69	-13.89	-18.73	-10.80
Reading 2	-18.43	-12.15	-18.65	-13.89	-18.70	-10.81

Figure 43. Solid water-based electron output & energy check baseline data

A summary of the output & energy check baseline results for electron beams is shown below in Figure 44.

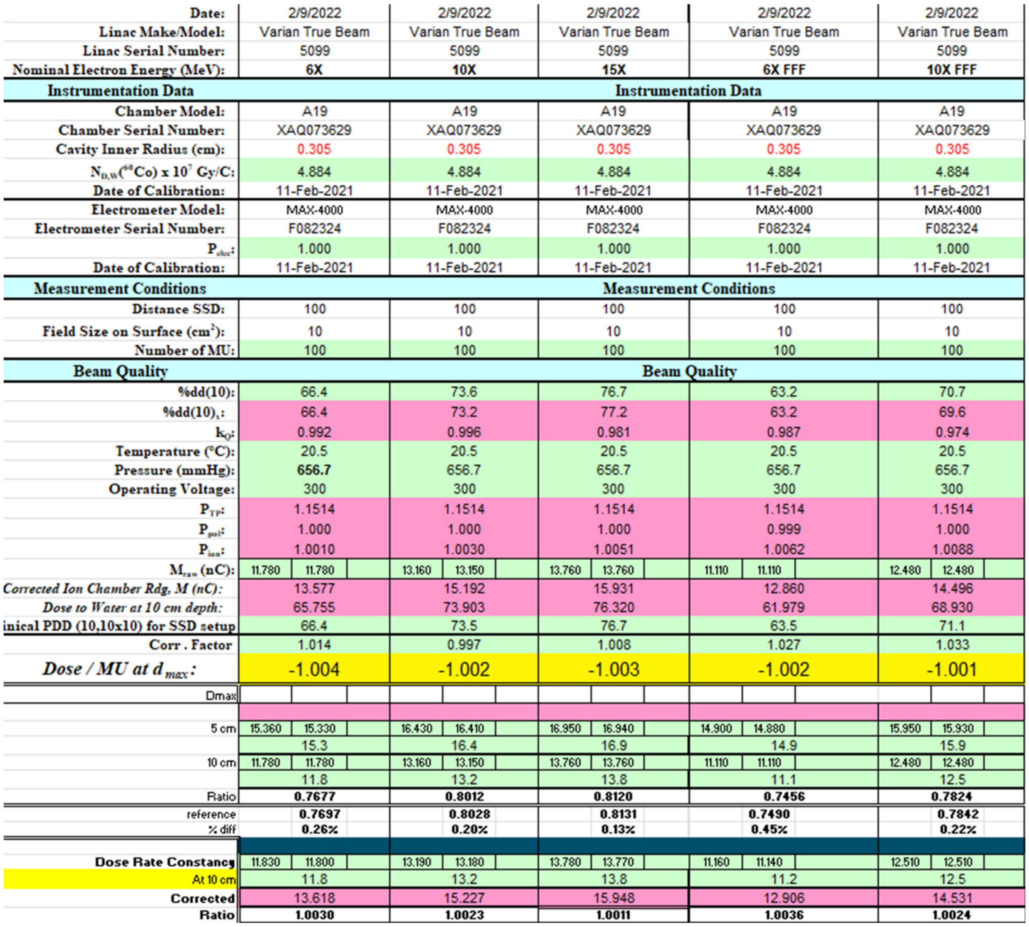


Date:	1/23/2022		
Linac Make/Model:	Varian True Beam		
Linac Serial Number:	5099		
Nominal Electron Energy (MeV):	**6e**	**9e**	**12e**
Instrumentation Data			
Chamber Model:	A19	A19	A19
Chamber Serial Number:	XAQ073629	XAQ073629	XAQ073629
Cavity Inner Radius (cm):	0.305	0.305	0.305
$N_{D,W}(^{60}Co) \times 10^7$ Gy/C:	4.884	4.884	4.884
Date of Calibration:	2/11/21	2/11/21	2/11/21
Electrometer Model:	MAX-4000	MAX-4000	MAX-4000
Electrometer Serial Number:	F082324	F082324	F082324
P_{elec}:	1.000	1.000	1.000
Date of Calibration:	11-Feb-2021	11-Feb-2021	11-Feb-2021
Measurement Conditions			
Distance SSD:	100	100	100
Field Size on Surface (cm^2):	10x10	10x10	10x10
Number of MU:	100	100	100
Beam Quality			
I_{50}:	2.285 cm	3.52 cm	4.93 cm
R_{50}:	2.291 cm	3.56 cm	5.01 cm
approx. Reference Depth, dref :	***1.30 cm***	***2.30 cm***	***3.30 cm***
k_{ecal}:	0.906	0.906	0.906
k'_{R50}:	1.029	1.017	1.009
Temperature (°C):	21.5	21.5	21.5
Pressure (kPa):	656.9	656.9	656.9
Operating Voltage:	300	300	300
P_{TP}:	1.1550	1.1550	1.1550
P_{pol}:	0.9995	0.9992	1.0000
P_{ion}:	1.0100	1.0310	1.013
P_{gr}^{Q}(cyl):	1.003	0.982	0.997
M_{raw} (nC):	-18.450 -18.430	-18.670 -18.650	-18.730 -18.700
Corrected Ion Chamber Rdg, M (nC):	-21.500	-22.202	-21.897
Dose to Water at d_{ref}:	-98.14	-98.12	-97.43
Clinical %dd(d_{ref}):	100.0	100.0	99.9
Corr . Factor	1.0230	1.0240	1.0320
Dose / MU at d_{max}:	1.004	1.005	1.007
R50 depth	**2.300**	**3.300**	**5.000**
rdg	-12.17 -12.15	-13.89 -13.89	-10.8 -10.81
Avg	-12.2	-13.9	-10.8
dref	-18.450 -18.430 0.000	-18.670 -18.650 0.000	-18.730 -18.700 0.000
	-18.4	-18.7	-18.7
inverse Ratio	**1.5164**	**1.3434**	**1.7321**
Ratio	**0.6594**	**0.7444**	**0.5773**
standard	**0.6594**	**0.7444**	**0.5773**
% diff	**0.01%**	**0.00%**	**0.01%**

Figure 44. Solid water-based electron output & energy check baseline values

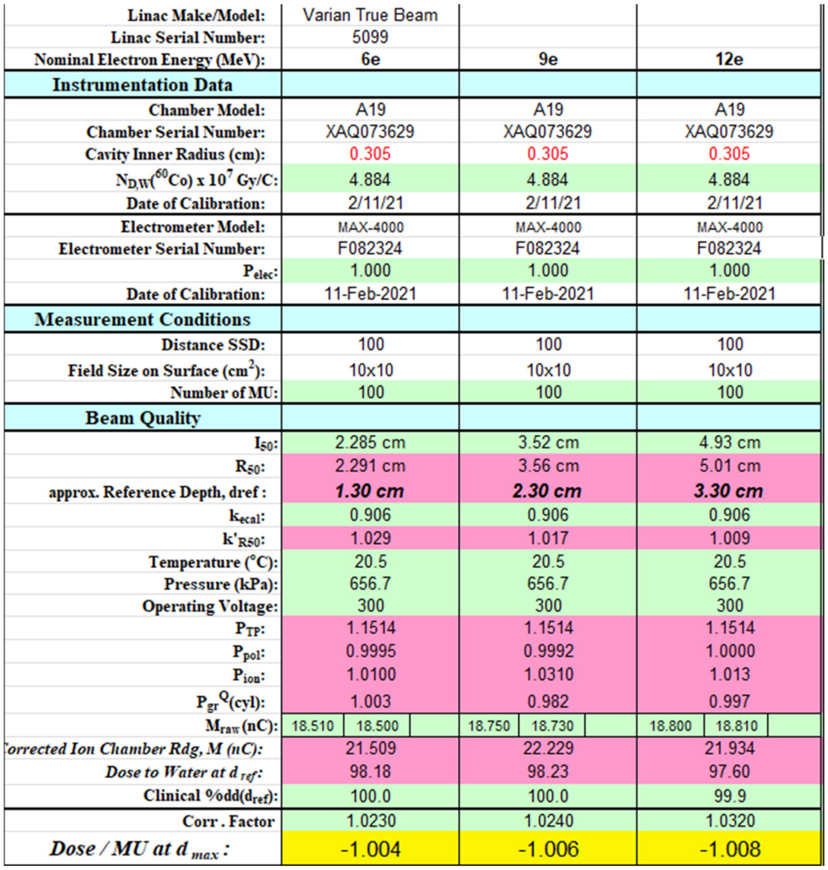
4.3 Solid Water-based Output & Energy measurements

After setting up the solid water phantom for the monthly output and energy check baseline measurements, the following routine monthly QA was performed and compared to the baseline. Figures 45 and 46 show the routine beam output and energy check results for photon and electron beams.



Date:	2/9/2022	2/9/2022	2/9/2022	2/9/2022	2/9/2022
Linac Make/Model:	Varian True Beam	Varian True Beam	Varian True Beam	Varian True Beam	Varian True Beam
Linac Serial Number:	5099	5099	5099	5099	5099
Nominal Electron Energy (MeV):	**6X**	**10X**	**15X**	**6X FFF**	**10X FFF**
Instrumentation Data			**Instrumentation Data**		
Chamber Model:	A19	A19	A19	A19	A19
Chamber Serial Number:	XAQ073629	XAQ073629	XAQ073629	XAQ073629	XAQ073629
Cavity Inner Radius (cm):	0.305	0.305	0.305	0.305	0.305
$N_{D,W}(^{60}Co) \times 10^7$ Gy/C:	4.884	4.884	4.884	4.884	4.884
Date of Calibration:	11-Feb-2021	11-Feb-2021	11-Feb-2021	11-Feb-2021	11-Feb-2021
Electrometer Model:	MAX-4000	MAX-4000	MAX-4000	MAX-4000	MAX-4000
Electrometer Serial Number:	F082324	F082324	F082324	F082324	F082324
P_{elec}:	1.000	1.000	1.000	1.000	1.000
Date of Calibration:	11-Feb-2021	11-Feb-2021	11-Feb-2021	11-Feb-2021	11-Feb-2021
Measurement Conditions			**Measurement Conditions**		
Distance SSD:	100	100	100	100	100
Field Size on Surface (cm^2):	10	10	10	10	10
Number of MU:	100	100	100	100	100
Beam Quality			**Beam Quality**		
%dd(10):	66.4	73.6	76.7	63.2	70.7
$\%dd(10)_x$:	66.4	73.2	77.2	63.2	69.6
k_Q:	0.992	0.996	0.981	0.987	0.974
Temperature (°C):	20.5	20.5	20.5	20.5	20.5
Pressure (mmHg):	**656.7**	656.7	656.7	656.7	656.7
Operating Voltage:	300	300	300	300	300
P_{TP}:	1.1514	1.1514	1.1514	1.1514	1.1514
P_{pol}:	1.000	1.000	1.000	0.999	1.000
P_{ion}:	1.0010	1.0030	1.0051	1.0062	1.0088
M_{raw} (nC):	11.780 11.780	13.160 13.150	13.760 13.760	11.110 11.110	12.480 12.480
Corrected Ion Chamber Rdg, M (nC):	13.577	15.192	15.931	12.860	14.496
Dose to Water at 10 cm depth:	65.755	73.903	76.320	61.979	68.930
inical PDD (10,10x10) for SSD setup	66.4	73.5	76.7	63.5	71.1
Corr . Factor	1.014	0.997	1.008	1.027	1.033
Dose / MU at d_{max}:	-1.004	-1.002	-1.003	-1.002	-1.001
Dmax					
5 cm	15.360 15.330	16.430 16.410	16.950 16.940	14.900 14.880	15.950 15.930
	15.3	16.4	16.9	14.9	15.9
10 cm	11.780 11.780	13.160 13.150	13.760 13.760	11.110 11.110	12.480 12.480
	11.8	13.2	13.8	11.1	12.5
Ratio	**0.7677**	**0.8012**	**0.8120**	**0.7456**	**0.7824**
reference	**0.7697**	**0.8028**	**0.8131**	**0.7490**	**0.7842**
% diff	**0.26%**	**0.20%**	**0.13%**	**0.45%**	**0.22%**
Dose Rate Constancy	11.830 11.800	13.190 13.180	13.780 13.770	11.160 11.140	12.510 12.510
At 10 cm	11.8	13.2	13.8	11.2	12.5
Corrected	13.618	15.227	15.948	12.906	14.531
Ratio	**1.0030**	**1.0023**	**1.0011**	**1.0036**	**1.0024**

Figure 45. Routine monthly output and energy check for photon beams

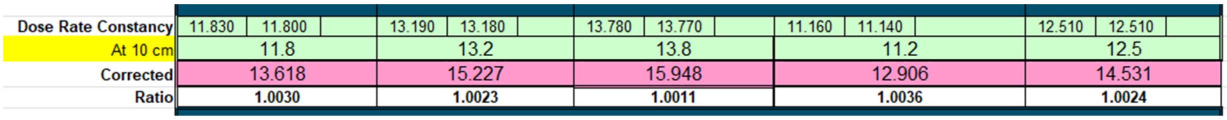


Linac Make/Model:	Varian True Beam		
Linac Serial Number:	5099		
Nominal Electron Energy (MeV):	**6e**	**9e**	**12e**
Instrumentation Data			
Chamber Model:	A19	A19	A19
Chamber Serial Number:	XAQ073629	XAQ073629	XAQ073629
Cavity Inner Radius (cm):	0.305	0.305	0.305
$N_{D,W}(^{60}Co) \times 10^7$ Gy/C:	4.884	4.884	4.884
Date of Calibration:	2/11/21	2/11/21	2/11/21
Electrometer Model:	MAX-4000	MAX-4000	MAX-4000
Electrometer Serial Number:	F082324	F082324	F082324
P_{elec}:	1.000	1.000	1.000
Date of Calibration:	11-Feb-2021	11-Feb-2021	11-Feb-2021
Measurement Conditions			
Distance SSD:	100	100	100
Field Size on Surface (cm^2):	10x10	10x10	10x10
Number of MU:	100	100	100
Beam Quality			
I_{50}:	2.285 cm	3.52 cm	4.93 cm
R_{50}:	2.291 cm	3.56 cm	5.01 cm
approx. Reference Depth, dref :	***1.30 cm***	***2.30 cm***	***3.30 cm***
k_{ecal}:	0.906	0.906	0.906
k'_{R50}:	1.029	1.017	1.009
Temperature (°C):	20.5	20.5	20.5
Pressure (kPa):	656.7	656.7	656.7
Operating Voltage:	300	300	300
P_{TP}:	1.1514	1.1514	1.1514
P_{pol}:	0.9995	0.9992	1.0000
P_{ion}:	1.0100	1.0310	1.013
P_{gr}^{Q}(cyl):	1.003	0.982	0.997
M_{raw} (nC):	18.510 18.500	18.750 18.730	18.800 18.810
orrected Ion Chamber Rdg, M (nC):	21.509	22.229	21.934
Dose to Water at d_{ref}:	98.18	98.23	97.60
Clinical %dd(d_{ref}):	100.0	100.0	99.9
Corr . Factor	1.0230	1.0240	1.0320
Dose / MU at d_{max} :	-1.004	-1.006	-1.008

Figure 46. Routine monthly output & energy check for electron beams

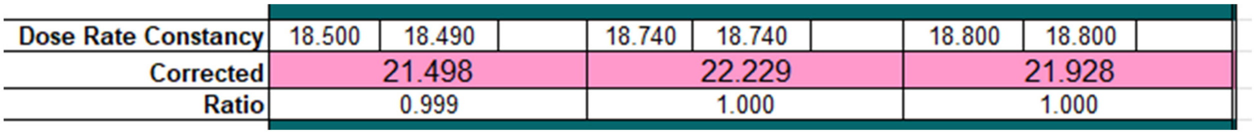
Dose rate constancy checks measure the impact of the dose rate on the output of the LINAC and were determined by comparing the ion-chamber data using the standard dose rate (600 MU/ minute for 6x, 10x, 15x; and 1200 MU/minute for 6xFFF, 10FFF) to the ion-chamber reading for the test 100 MU/minute dose rate for each photon energy. The dose rate results are summarized in Figure 47 for both photons and electrons. For the electron dose rate measurements, the regular dose rate was 400 MU/minute for all electron energies (6, 9 and 12 MeV). The test dose rate was set to 100 MU/minute for all the measurements.

6x 10x 15x 6xFFF 10xFFF



Dose Rate Constancy	11.830	11.800		13.190	13.180		13.780	13.770		11.160	11.140		12.510	12.510	
At 10 cm	11.8			13.2			13.8			11.2			12.5		
Corrected	13.618			15.227			15.948			12.906			14.531		
Ratio	**1.0030**			**1.0023**			**1.0011**			**1.0036**			**1.0024**		

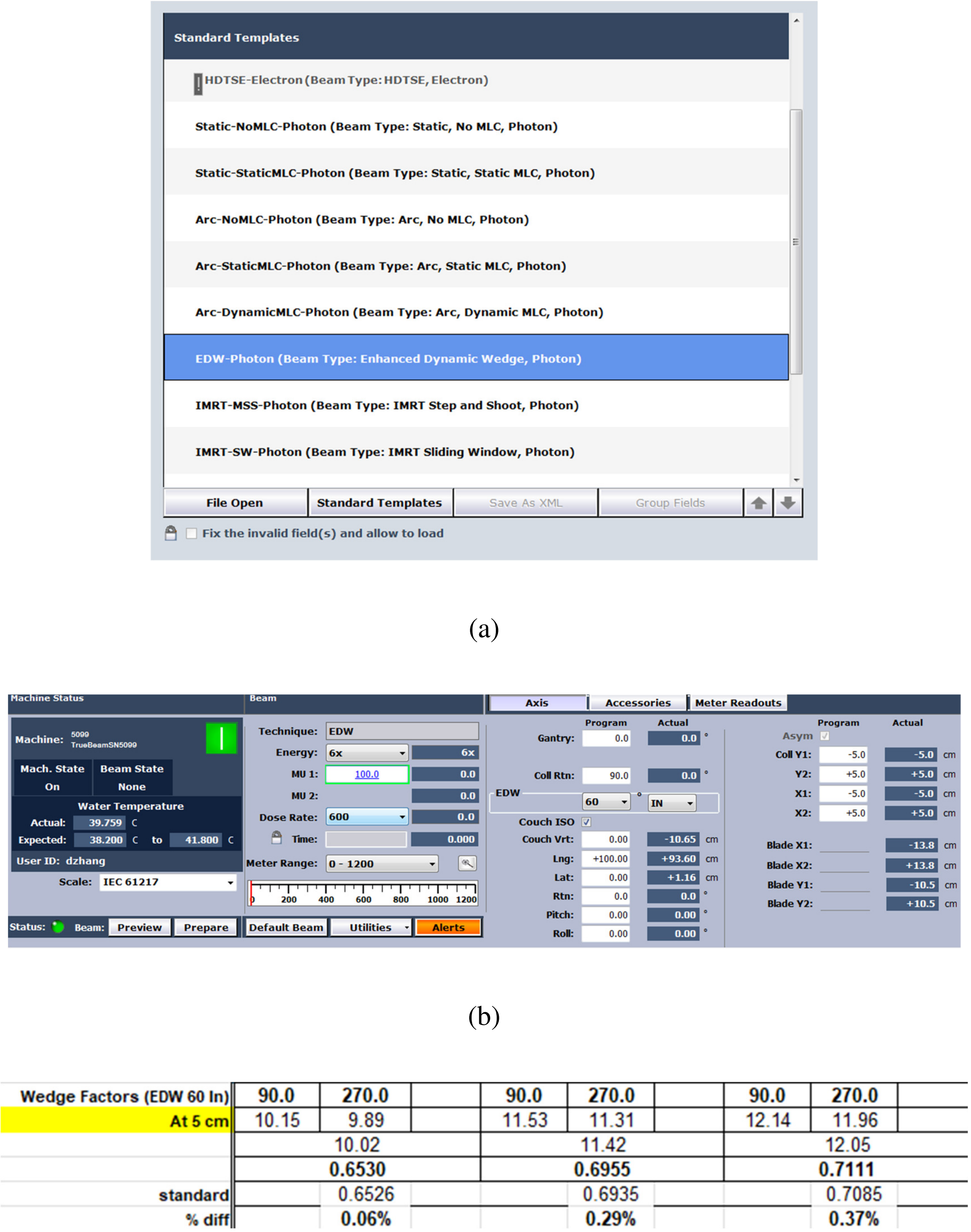
6e 9e 12e



Dose Rate Constancy	18.500	18.490		18.740	18.740		18.800	18.800	
Corrected	21.498			22.229			21.928		
Ratio	0.999			1.000			1.000		

Figure 47. Dose rate constancy results for photon and electron beams

To perform wedge factor constancy measurements for 6x, 10x and 15x photon beams, the solid water phantom setup was: 100 cm SSD, 10x10 cm^2 field size, and depth of 5cm. AAPM TG-142 recommends that energy check measurements should be performed in a water tank at a depth of 20 cm. Since a solid water phantom was used, a depth of 5 cm was chosen instead. The wedge factor measurements are summarized in Figure 48 (c).



Standard Templates

- HDTSE-Electron (Beam Type: HDTSE, Electron)
- Static-NoMLC-Photon (Beam Type: Static, No MLC, Photon)
- Static-StaticMLC-Photon (Beam Type: Static, Static MLC, Photon)
- Arc-NoMLC-Photon (Beam Type: Arc, No MLC, Photon)
- Arc-StaticMLC-Photon (Beam Type: Arc, Static MLC, Photon)
- Arc-DynamicMLC-Photon (Beam Type: Arc, Dynamic MLC, Photon)
- EDW-Photon (Beam Type: Enhanced Dynamic Wedge, Photon)
- IMRT-MSS-Photon (Beam Type: IMRT Step and Shoot, Photon)
- IMRT-SW-Photon (Beam Type: IMRT Sliding Window, Photon)

☐ Fix the invalid field(s) and allow to load

(a)

Machine Status

Machine: 5099 TrueBeamSN5099

Mach. State	Beam State
On	None

Water Temperature
Actual: 39.759 C
Expected: 38.200 C to 41.800 C

User ID: dzhang

Scale: IEC 61217

Beam

Technique: EDW
Energy: 6x | 6x
MU 1: 100.0 | 0.0
MU 2: 0.0
Dose Rate: 600 | 0.0
Time: 0.000
Meter Range: 0 - 1200

	Program	Actual	
Gantry:	0.0	0.0	°
Coll Rtn:	90.0	0.0	°
EDW	60 °	IN	
Couch ISO	☑		
Couch Vrt:	0.00	-10.65	cm
Lng:	+100.00	+93.60	cm
Lat:	0.00	+1.16	cm
Rtn:	0.0	0.0	°
Pitch:	0.00	0.00	°
Roll:	0.00	0.00	°

	Program	Actual	
Asym	☑		
Coll Y1:	-5.0	-5.0	cm
Y2:	+5.0	+5.0	cm
X1:	-5.0	-5.0	cm
X2:	+5.0	+5.0	cm
Blade X1:		-13.8	cm
Blade X2:		+13.8	cm
Blade Y1:		-10.5	cm
Blade Y2:		+10.5	cm

(b)

Wedge Factors (EDW 60 In)	90.0	270.0		90.0	270.0		90.0	270.0	
At 5 cm	10.15	9.89		11.53	11.31		12.14	11.96	
	10.02			11.42			12.05		
	0.6530			0.6955			0.7111		
standard		0.6526			0.6935			0.7085	
% diff		0.06%			0.29%			0.37%	

(c)

Figure 48. Linac Service mode standard template. (a) standard template. (b) LINAC console beam parameters. (c) Enhanced dynamic wedge (EDW) 60 IN wedge factor results.

4.4 Discussion of Absolute and Relative Dose Methodologies

The Standard-Imaging 1D/3D water tank setup for the measurement of the machine output and verification of the beam energy is relatively complicated and time consuming. It requires the physicist to setup the water tank, carefully position the ion-chamber, and align the ion chamber with the central axis of the beam. Any error during the setup process may introduce error in the ion-chamber positioning, hence causing errors in radiation dosimetry.

Compared to the 1D/3D water tank, the solid water phantom setup is much easier and less time consuming. In the solid water setup, one may only need a few phantom slabs to create the desired depth of measurement. The solid water phantom dosimetry is beneficial for a quick dosimetry check, such as verification of the output of the machine after a repair or upgrade of a component. Since the solid water slabs may have been made at different times with slight differences in their chemical composition and possibly densities, care must be taken to ensure that all solid water slabs originate from the same batch. Normally, one of the slabs is machined to accommodate the ion-chamber with the center of its sensitive volume at the center of the phantom. It should be noted that, if the ion-chamber is not waterproof, the chamber must be inserted into a rubber sleeve prior to submersion in the water tank. This is obviously not a requirement when using the solid water phantom.

For absolute photon dosimetry, P_{ion} and P_{pol} measurements require biases of -300V +300V, and -150V. Typically, three readings are taken at each bias setting, and the mean calculated. For absolute electron dosimetry, the ion-chamber is driven to a depth of $d_{ref} + 0.5r_{cav}$ and the mean of 3 readings are used to determine the P^{Q}_{Grad} correction factor. For solid water-based measurements, only one bias setting (+ 300V) is required. For electron output and energy checks, since the solid water-based method does not correct for P^{Q}_{Grad}, there is no need to measure $d_{ref} +$

$0.5r_{cav}$ and, as such, this makes the measurement process relatively easy to implement and a single correction factor is used to account for P_{ion}, P_{pol}. and P^{Q}_{Grad}.

While the 1D/3D water tank measurements are cumbersome, they are vital in situations where solid water measurements result in outputs that are in excess of the TG-142 tolerance, i.e., ± 2%.

Chapter 5. Conclusions

Oncology Nevada updated its LINAC from a Varian Clinac iX to a Varian TrueBeam. As a medical physics resident, I have been involved throughout the new LINAC acceptance tests and commissioning. After completion of the acceptance tests and commissioning, creating a quality assurance program is a requirement to fulfill the AAPM TG-142 recommendations, and to ensure accurate patient care. As part of my duties as a medical physicist, I evaluate clinical devices for usability, complexity of implementation and cost. In this center, we utilize the vendor-provided (Varian) MPC and IsoCal phantom. The MPC procedure is implemented to determine baselines for daily/weekly quality assurance tests for the following LINAC parameters: isocenter, imager isocenter offset, collimation, MLC offset, jaw offset, gantry positioning, 6 DoF couch positioning accuracy for lateral, longitudinal, vertical, rotation, and pitch and roll. MPC can also be used to evaluate photon and electron beam output constancy, uniformity change and beam center shifts. If the kV/MV imager offset is out of tolerance, the medical physicist can perform the isocenter calibration to correct that. If the kV/MV imager offset is significant, one isocenter verification is typically performed after the isocenter calibration. Generally, the IsoCal phantom is a very powerful tool which allows the physicist/therapist to perform the daily/weekly LINAC quality assurance and to re-calibrate the kV/MV imager offset from the LINAC isocenter and to verify the correction.

The MPC uses vendor-provided equipment and procedures to check the LINAC working status. To ensure that the LINAC is in optimal condition, other third-party modalities are also available to perform quality assurance tests, for example, Oncology Nevada also uses the Sun Nuclear Daily QA3. In collaboration with the IT group, the physicists install the software, sets up the hardware, perform temperature and pressure calibrations, absolute dose calibrations, and baseline measurements after the TG-51 beam output calibration. The physicist also sets up the baseline for the Daily QA3 and validates the baseline by performing confirmation of the baseline QA measurements. All these procedures establish the foundation for future routine LINAC daily QA measurements required to fulfill the AAPM TG-142 recommendations. If any photon or electron beam output is out of TG-142 tolerance, the physicist resets the baseline value for the Sun Nuclear Daily QA3 device after TG-51 beam output calibration to make sure the baseline is accurate for routine daily QA measurements.

The Sun Nuclear IC profiler is a device used to perform beam profile quality assurance. Physicists typically install the software, set up the hardware and perform temperature and pressure calibrations, absolute dose calibrations and baseline measurements. Physicists also perform resets of the IC profiler baseline value if the monthly profile measurement result is out of TG-142 tolerance. When this occurs, the beam profile is adjusted. These procedures ensure that the LINAC beam profile quality assurance fulfills the TG-142 recommendations.

Considering the patient workload and physicist workforce limitations, Oncology Nevada follows the AAPM MPPG 8.0a recommendation and, as such, the facility uses a solid water phantom instead of a 1-D water tank to conduct the monthly beam output and constancy checks as well as dose rate and wedge factor constancy checks.

Physicists at Oncology Nevada utilizes a wide variety of devices (MPC, Sun Nuclear Daily QA3, IC Profiler and solid water) for the Varian TrueBeam Linac quality assurance program. This program ensures that the Varian TrueBeam Linac performs optimally which is vital for high quality patient care.

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Curriculum Vitae

Yongquan Jiang

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Education and Training

08/2019 – present	**Doctor of Medical Physics (DMP)** University of Las Vegas, Doctor of Medical Physics Program (**CAMPEP-accredited**), Las Vegas, Nevada
08/2000 - 07/2006	**PhD Solid State Physics** West Virginia University, Morgantown, West Virginia Dissertation: EPR and ENDOR Studies of Point Defects in the Nonlinear Optical Crystals $RbTiOPO_4$ and $KTiOAsO_4$
09/1988 - 07/1992	**Bachelor of Engineering** Tianjin University, Tianjin China

Board Certification & License

The American Board of Radiology (**ABR**) Medical Physics **Part 1 Passed**

NRC licensed Authorized Medical Physicist in Nevada, Puerto Rico

Positions and professional Experience

5/2020-present **Medical Physics Resident,** Oncology Nevada, Reno, Nevada

-- Linac TrueBeam, Clinac iX, performing daily, monthly & annual QA

-- Treatment planning: Eclipse
EBRT: 3D-CRT, IMRT, VMAT, SBRT/ SRS.

-- Winston-Lutz test for SBRT SRS

-- Initial Chart check & weekly chart check, review and approve treatment plans, prepare special physics report, etc.

-- HDR BrachyVision (treatment planning on savi, OB/Gyn cylinder, customized skin applicator and Leipzig applicator), Ir-192 source exchange calibration & daily QA, Varian Gammamed afterloader.

--LDR: Volume study, ordering, receiving, shipping and handling Pd-103 seeds, assist Physician with seed implant in OR

-- Nuclear Medicine: Xofigo receiving, handling Ra 223 dose package, assist physician with dose injection.

--CT monthly QA, MV, KV, CBCT monthly QA (TG 142).

1/2019-7/2019 **Junior Medical Physicist,** Comprehensive Cancer Center, University of Puerto Rico, San Juan, Puerto Rico

-- Linac monthly QA (Truebeam), IMRT patient Specific QA

-- Treatment planning (Eclipse), 3D, IMRT, VMAT, SBRT

-- Initial Chart check & weekly Chart Check

-- Aria (R&V)

-- HDR

Varian GammaMed Afterloader Daily QA, Treatment Planning (Cylinder, Tandem & Ovoid), Radcalc check. Pre-treatment check, Post-treatment documentation, patient post-treatment survey.

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