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Implementing Radformation at Personalized Radiation Oncology: Enhancing Efficiency and Precision

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IMPLEMENTING RADFORMATION AT PERSONALIZED RADIATION ONCOLOGY: ENHANCING EFFICIENCY AND PRECISION

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Abstract

RadMachine is a data quality management application implemented at Personalized Radiation Oncology (PRO) to streamline quality assurance (QA) tests. It offers various functions assisting medical physicists in a radiation oncology clinic, including inputting, analyzing, managing, exporting, and monitoring QA data. Physicists create test lists following the recommendations provided by the American Association of Medical Physics (AAPM). These lists track results for units such as the Varian Edge, Varian BRAVOS, and Siemens SOMATOM go.Open Pro CT scanner. Ancillary equipment used for testing also has assigned test lists to store calibration factors and receive calibration expiration reminders. The primary goal of utilizing RadMachine is to standardize data management and tests performed, ensuring consistency even when different physicists are covering duties.

QA is conducted daily and monthly for the Varian Edge and Siemens SOMATOM go.Open Pro computer tomography (CT) scanner to verify proper unit performance. Therapists complete daily QA tasks in RadMachine, which physicists subsequently review. Monthly QA is undertaken by the physicists themselves. The Varian Edge's monthly QA comprises six test list types: dosimetry for photons and electrons, imaging, multileaf collimator (MLC), beam profile, and mechanical aspects. Monthly QA for the CT scanner evaluates its image quality characteristics and spatial accuracy.

The Nuclear Regulatory Commission (NRC) oversees radioactive sources. The Varian BRAVOS, a high dose rate afterloader with a high dose rate Iridium-192 (^{192}Ir) source used for treatment, undergoes tests created in RadMachine to verify source activity, dwell position, timer accuracy, and safety interlocks. PRO also employs the radioactive source Lutetium-177 (^{177}Lu) for its radiopharmaceutical program, requiring accurate measurements before and after infusion.

Quality control tests on ancillary equipment ensure accurate readings. RadMachine facilitates data accessibility for regulatory review in a clear and organized manner.

A debugging phase ensured all test lists were functioning properly. Previous QA data, recorded using spreadsheets, were used to validate the test lists' return values. Once all test lists were debugged, all previous QA performed before using RadMachine was inputted into the system. However, not all data were recorded in RadMachine. Some images did not meet RadMachine's requirements, such as the phantom not being fully imaged or insufficient separation between the phantom and the stand.

The next steps for RadMachine involve setting up a dedicated server to host RadMachine and its local agent. This will allow PRO to fully utilize RadMachine's automation features. Full automation includes automatically downloading images and scans into RadMachine. Additionally, test lists will need to be built to record results for the annual QA.

Acknowledgements

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I am deeply indebted to my clinical advisors, David Zhang and Hilary Loupee. Their mentorship and the opportunity to shadow them in their clinics have undoubtedly provided me with the confidence and invaluable experience as I transition into the workforce. I will always remember their trust in me and my capabilities. I also express my appreciation to Oncology Nevada and Personalized Radiation Oncology for welcoming me as a student in their facilities.

Lastly, I am grateful to all the professors and staff at UNLV who have equipped me with the knowledge necessary to make a meaningful impact in helping others.

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List of Abbreviations

Accredited Dosimetry Calibration Laboratory (ADCL)

American Association of Physicists in Medicine (AAPM)

American College of Radiology (ACR)

Ball Bearings (BBs)

Barium-133 (^{133}Ba)

Beam Eye View (BEV)

Cesium-137 (^{137}Cs)

Cobalt-57 (^{57}Co)

Code of Federal Regulations (CFR)

Computed tomography (CT)

Cone beam computed tomography (CBCT)

Contrast-to-Noise Ratio (CNR)

Curie (Ci)

Detective Quantum Efficiency (DQE)

Digital Imaging and Communications in Medicine (DICOM)

Digitally Reconstructed Radiographs (DRRs)

Dose Rate and Gantry Speed (DRGS)

Dose Rate and MLC (DRMLC)

Electronic Portal Imaging Device (EPID)

Europium-152 (^{152}Eu)

Full Width Half Maximum (FWHM)

Geiger-Mueller (GM)

Gray (Gy)

High dose rate (HDR)

High Definition (HD)

Hounsfield Units (HU)

Image-Guided Radiation Therapy (IGRT)

Information Technology (IT)

Intensity-Modulated Radiation Therapy (IMRT)

Iridium-192 (^{192}Ir)

Kilovoltage (kV).

Linear Accelerator (LINAC)

Lutetium-177 (^{177}Lu)

Million Electron Volt (MeV)

Million voltage (MV)

Millimeter (mm)

Modulation Transfer Function (MTF)

Monitor Units (MU)

Multileaf Collimator (MLC)

National Council on Radiation Protection and Measurements (NCRP)

National Institute of Standards and Technology (NIST)

National Institute of Standards and Technology (NIST)

Nuclear Regulatory Commission (NRC)

Optical Distance Indicator (ODI)

Personalized Radiation Oncology (PRO)

Pixel Intensity Uniformity (PIU)

Planning Target Volume (PTV)

Qualified medical physicists (QMPs)

Quality Assurance (QA)

Quality Control (QC)

Radiation Treatment (RT)

Radiopharmaceuticals Therapy (RPT)

Record and Verify (R&V)

Regions of Interest (ROI)

Standard Imaging (SI)

Task groups (TG)

Treatment Delivery System (TDS)

Volumetric Modulated Arc Therapy (VMAT)

1 Introduction

The primary objective of a quality management program in a radiation oncology clinic is patient protection from potential failures, which may include equipment malfunctions, patient-specific errors (such as identification, setup, or documentation inaccuracies), and insufficient training or resources. These aspects should be thoroughly reviewed by a qualified medical physicist. The role of a medical physicist encompasses ensuring the safe and effective delivery of radiation to achieve physician-prescribed results in patient care, and developing protocols to uphold the highest quality of care[1]. Medical physicists act as enforcers of the quality management program, which comprises two components: quality control (ensuring process integrity) and quality assurance (providing confidence in process output)[2]. However, protocol development for quality control and quality assurance is not solely the responsibility of medical physicists, as they are members of the American Association of Physicists in Medicine (AAPM).

The AAPM was established to ensure safety, accuracy, and quality in radiation-based medical procedures. It offers in-person training sessions and an extensive database of online courses. Additionally, it forms task groups (TG) that produce reports outlining proper procedures for specific clinical processes[2]. These reports cover various aspects, including acceptance and commissioning of new equipment, quality assurance, implementation guidelines, and recommendations for clinical workflow. AAPM Task Groups 40 and 100 recommend that medical physicists take responsibility for several key tasks, such as acceptance testing and commissioning of software and hardware used in treatment planning and delivery[1,2]. They are also tasked with establishing quality management programs, developing procedures to meet regulatory requirements, conducting patient-specific tests, educating the public and the radiation therapy community, reviewing patient treatment plans, and calibrating technology. Technology

calibration quality assurance (QA) ensures the accuracy and consistency necessary to meet the International Commission on Radiation Units and Measurements recommendation that the delivered dose should be within 5% of the prescribed dose[3]. TG-142, TG-40, TG-56, and TG-66 reports serve as comprehensive guides outlining machine QA standards that must be maintained to ensure the highest quality of care[1,4–6].

Personalized Radiation Oncology (PRO) in Reno, Nevada currently operates a Varian Edge linear accelerator (LINAC), Bravos brachytherapy afterloader, Siemens go.Open Pro computed tomography (CT) simulator, well calibrator for their radiopharmaceutical program, and ancillary equipment for QA. The responsibility for maintaining all of this equipment falls on a solo qualified medical physicist. These professionals, including the one at PRO, often manage their QA results using spreadsheets, typically Microsoft Excel. While spreadsheets are effective for data tracking, transferring them between workstations can be cumbersome (e.g., via copy and paste using flash drives). To facilitate access from multiple workstations, medical physicists commonly utilize a network server (e.g., physics M:), which stores spreadsheets and other relevant documents. Therefore, a medical physicist's ability to perform tasks safely and efficiently relies on their access to such a network.

Network servers vary in size, from small local networks (e.g., small businesses) to large cloud-based infrastructures (e.g., corporations). A cloud-based system delivers hosted services over the internet[7]. PRO utilizes a fully cloud-based network managed by Varian's FullScale Infinity Cloud management service. This service offers centralized information technology (IT) support for Varian software applications, eliminating the need for third-party IT intermediaries. FullScale Infinity also enhances cybersecurity and facilitates improved software communication

between Varian hardware and software. Additionally, it enables all data to be stored on a cloud-based system.

Compatibility of software is crucial for optimal functionality in cloud-based systems. FullScale Infinity Cloud, a Varian product, ensures compatibility and offers seamless integration with other Varian products used in radiation oncology. As previously mentioned, PRO utilizes various Varian products for treatment delivery, including Aria, a Varian oncology information system. As a result, PRO benefits from a fully integrated Varian product suite, making FullScale Infinity the ideal IT service complement for Varian software.

A cloud-based physics network drive offers medical physicists convenient access to data from any workstation, including remote locations, as opposed to being limited to their personal workstation. However, accessing a physics network drive may not be as straightforward as accessing a network drive connected solely to the site's local computers. PRO has encountered difficulties whereby new hires or covering physicists struggle to access this vital physics drive. This limitation hampers their ability to use spreadsheets for recording equipment QA results.

Spreadsheets can be challenging to access and to interpret by other physicists, emphasizing the lack of standardization in QA spreadsheets. Each site or medical physicist may have their own unique spreadsheet developed or adapted. However, there is no established protocol for the appearance of these spreadsheets, nor is there a secondary verification of their accuracy. TG-142 aims to standardize the QA procedures performed by medical physicists[4]. Although TG-198 provides PDF printouts of original Microsoft Excel forms, a universal standard spreadsheet is absent, necessitating a thorough review of spreadsheet accuracy before storing results[8].

Documentation for medical physics tests is crucial, ensuring they are documented and available for inspection. Medical physicists have various options for data documentation, including paper forms, electronic spreadsheets, or dedicated management software. Several options are available for QA data management software, such as Sun Nuclear's SunCHECK, Total QA, PTW's Track-it, and Radformation's RadMachine. QATrack+ is a free open-source software, although its developer has joined RadMachine's team.

At PRO, RadMachine is being implemented as the site's QA management software with the aim of transitioning from Excel spreadsheets to data collection in RadMachine. This transition will enable input and storage of QA results for a Varian Edge LINAC and Siemens SOMATOM go.Open Pro CT simulator. Additionally, RadMachine will document Varian high dose rate (HDR) brachytherapy Bravos and their radiopharmaceutical program QA, with additional features for PRO's ancillary equipment.

The implementation process involves building test lists from converted spreadsheets or creating new tests for data collection and analysis. The next phase involves debugging the test lists to ensure proper functionality. Finally, all measurements previously recorded on spreadsheets are being inputted into RadMachine.

1.1 RadMachine

RadMachine, developed by Radformation, is a cloud-based quality control (QC) data application accessible through any web browser. It facilitates storage, analysis, management, export, and monitoring of data. RadMachine comprises seven views: perform QA, review QA, service, faults, charts, reports, and data administration (Figure 1), which effectively organize QC information.

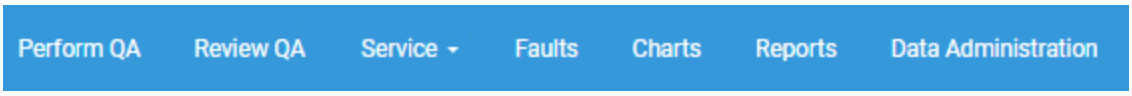


Figure 1. RadMachine Views. The workflow for RadMachine starts with performing QA, where data is inputted and recorded. Subsequently, the QA results are reviewed. As more results are inputted, the data can be charted to identify trends. The QA results or trends can be exported as reports. Equipment service and faults can be recorded to monitor machine downtime. However, before inputting data, users must create QA assignments and designate the users responsible for these tasks in the data administration section.

1.1.1 Data Administration

In Data Administration within RadMachine (Figure 2), users, equipment, and tests can be configured. Users, including qualified medical physicists, junior medical physicists, and radiation therapists, are assigned QA tasks (e.g., Daily QA) based on permissions and associated with a specific unit, such as PRO's EDGE LINAC, which consists of unit types (e.g., Varian EDGE) and classes (e.g., LINAC). The unit setup and assignment workflow are elaborated further in subsequent sections, namely Homepage and Perform QA. Initiating the RadMachine implementation from Data Administration enables us to specify who will conduct QA on which machines.

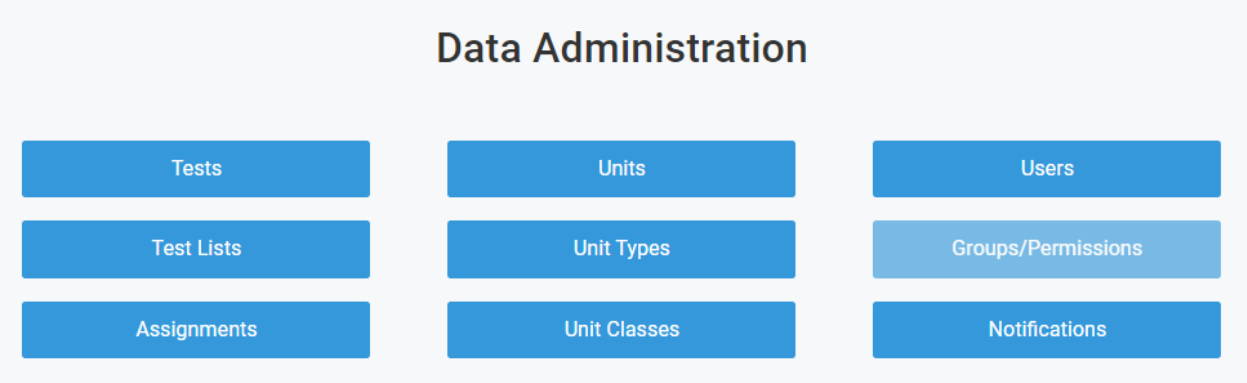


Figure 2. Data Administration Homepage. In data administration, users can add individuals and groups requiring access to the software, as well as the equipment and machines (units, unit types, unit classes) utilized on-site, along with the quality control assignments for test lists conducted by users on the equipment.

1.1.2 RadMachine Homepage

The RadMachine homepage displays the primary machines at the site (Figure 3), categorizing them under units. It's notable that RadMachine's licensing is contingent upon the number of primary units requiring QC. PRO operates three machines: a Varian Bravos, Varian Edge, and Siemens go.Open Pro, all utilized in patient care. The user-friendly interface lists machines subject to routine QA and categorizes QA tasks by frequency—daily, monthly, and annually, mirroring reports like TG-142 and TG-66. Furthermore, it highlights pending QA sessions for review and any logged events or faults associated with the machine[4,8]. This feature-rich page is tailored for radiation therapists and medical physicists to swiftly access and complete necessary QA assignments.

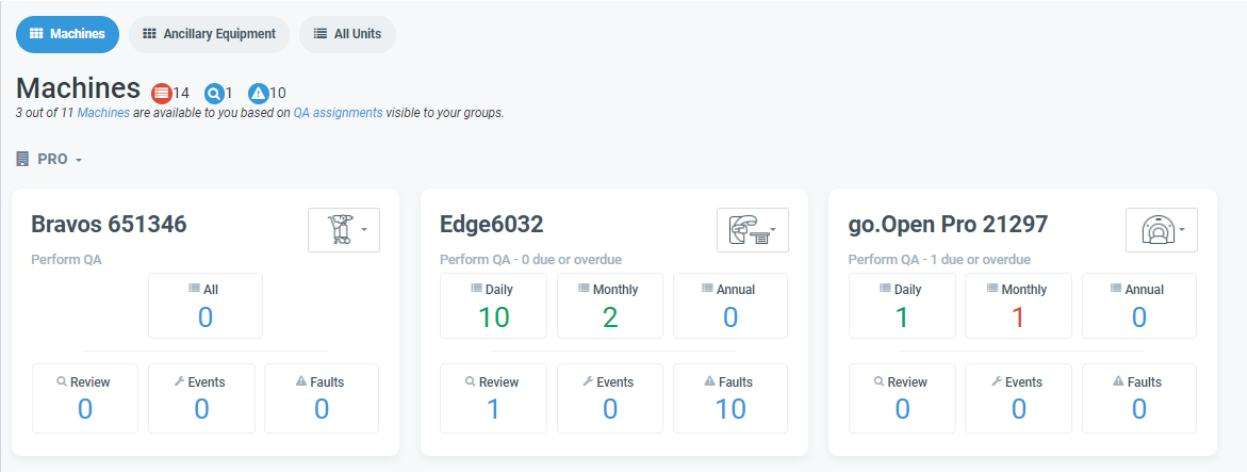


Figure 3. Personalized Radiation Oncology (PRO) Machines. PRO utilizes three machines: the Varian Bravos afterloader for HDR brachytherapy, the Varian Edge linear accelerator for radiation treatment, and the Siemens go.Open Pro CT simulator for treatment planning CT simulations.

Ancillary equipment, depicted in Figure 4, serves as an additional subcategory of units. It aids in conducting tests. PRO possesses various radiation detectors, electrometers, a well chamber, and a survey meter. Regulatory standards, specified in [10CFR35.61 & 10CFR20.15], mandate calibration and maintenance of radiation survey equipment, including PRO's Raysafe survey meter, well counter, and radioisotope dose calibrator. AAPM recommends that dosimetric measurements in US radiotherapy clinics adhere to standards set by the National Institute of Standards and Technology (NIST), with equipment calibration expiring biennially. PRO's electrometers (e.g., CDX2000B) and ion chambers (e.g., PTW TN30013 and Exradin A16) fall into this category. Following calibration, equipment is assigned a calibration factor and expiration date, both logged in RadMachine. RadMachine consolidates PRO's equipment along with its associated calibration factor, crucial for QA calculations like TG-51[9]. It also archives calibration reports, facilitating cloud-based documentation storage. Additionally, in data administration, notification reports are generated to alert us of impending equipment calibration expiration.

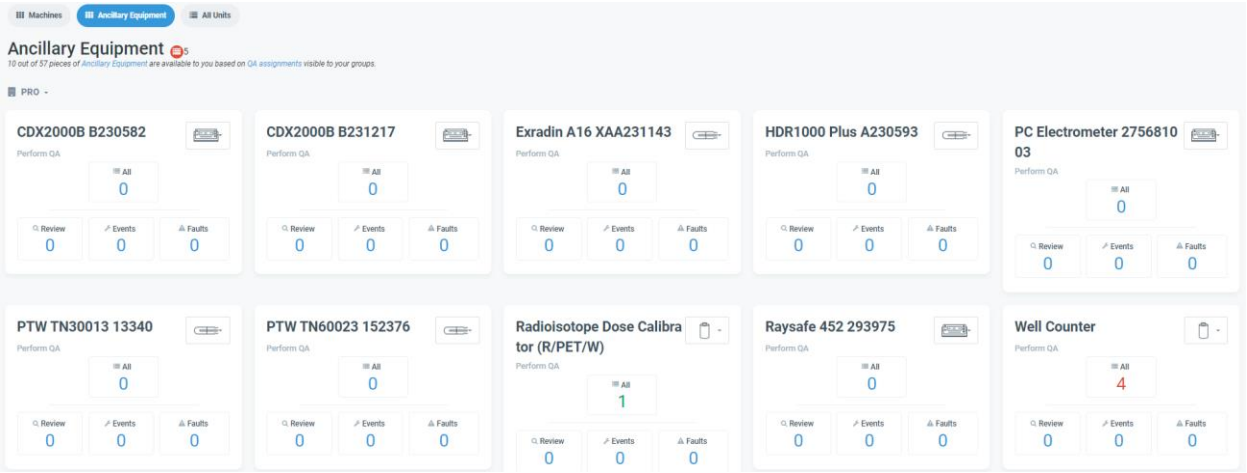


Figure 4. Personalized Radiation Oncology (PRO) Ancillary Equipment. PRO's dosimetry equipment includes: two CDX2000B electrometers, a PC electrometer™, two ion chambers (PTW TN30013 and Exradin A16), one diode (PTW TN60023), an HDR1000 Plus well chamber, a Capintec CRC-55t well counter and radioisotope dose calibrator, and a Raysafe Geiger-Muller survey meter with solid-state sensors.

1.1.3 Perform Quality Assurance (QA)

The primary interface for data entry is "Perform QA," where QA sessions are recorded and various QC tests, including numerical inputs, Boolean operations, equipment selection, Python snippets for calculations, and file uploads, can be customized to meet user needs. Additionally, digital imaging and communications in medicine (DICOM) images collected during QA can be uploaded into RadMachine for analysis. Figure 5 illustrates the workflow of "Perform QA." Users conducting QA record results within assignments, which host tests storing, calculating, or analyzing inputted data.

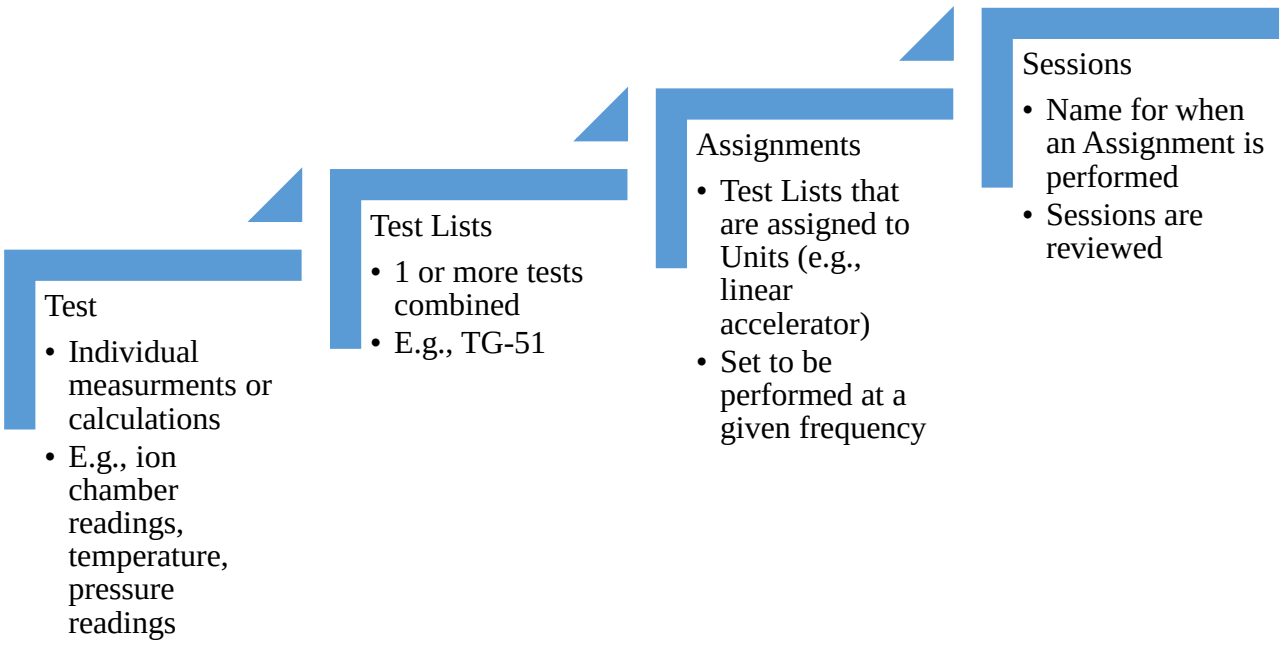


Figure 5. Perform QA Workflow. Perform QA is where sessions are completed. Each session is a completed assignment. An assignment is a composition of test lists and test designed to record data, give results or compute data analysis.

RadMachine's flexibility and strength stem from its tests, described as the heart and soul of the system on the RadMachine website. Tests are named and associated with a variable name, enabling other tests to reference them for calculations. Variable names must be Python-compatible, as RadMachine operates within a Python environment capable of executing full calculation scripts. Users can perform a wide range of tasks akin to Python's capabilities, primarily numerical input and output operations. For instance, they can input ion chamber readings and conversion factors to calculate correction factors and beam output. Tests using calculation inputs or outputs resemble Excel functionality, allowing data manipulation to derive results. Many medical physicists possess a basic understanding of programming languages like

C++ and Matlab, and currently use Excel sheets for data recording, calculations, and statistics. Hence, transitioning to RadMachine for mathematical calculations is straightforward.

RadMachine, leveraging the Python programming language, offers features beyond numerical calculations, including Boolean tests. These tests allow the creation of true or false questions, like "Does the door function?" Unlike Excel's text-based Boolean tests, RadMachine's Boolean test answers are compared against an expected value, flagging discrepancies and preventing users from advancing until discrepancies are resolved. This double-checking mechanism helps prevent patient treatment failures.

Several test features in RadMachine, not readily available in Excel, include wraparound, multiple choice, string, and file upload/image analysis tests. Wraparound tests, useful for mechanical axes (e.g., 360 degrees), permit tolerances like 0.5 degrees, with measurements ranging from 359.5 to 0.5 degrees, both 0.5 degrees from 0 or 360 degrees. Multiple-choice tests offer various options, facilitating selection from a list, such as choosing ancillary equipment, which automatically loads unit attributes like calibration factors upon selection. String calculations handle Unicode characters, returning words instead of numerical values. Particularly beneficial for medical physicists, file upload tests enable file uploads, accelerating workflow. RadMachine accepts text, CSV, or Excel files for data extraction and supports binary imports (e.g., images, DICOM) for image processing. Users can devise custom calculation tests or utilize RadMachine's built-in image analysis tools. The full advantages of RadMachine's image analysis capabilities will be explored later in this paper.

1.1.4 Review Quality Assurance (QA)

The review QA process involves examining inputted QA data. At PRO, physicists are designated to conduct these reviews. After assessment, the QA status may change, transitioning between "unreviewed" and "reviewed." Auto-review rules, configurable within permissions, automate status changes based on session pass/fail outcomes. Occasionally, multiple QA sessions, such as the DailyQA3 test for all energies, require review. A bulk review feature facilitates updating the status of selected sessions efficiently. At PRO, radiation therapists execute daily QA, subject to review by physicists. In other settings, chief physicists may utilize review QA to oversee QA results while delegating tasks to other physicists or physics assistants.

1.1.5 Charts

Charts in RadMachine depict QA data, offering insights into trends observed during QA processes. Medical physicists bear the responsibility of ensuring the consistency of a LINAC's output. They may need to adjust the beam periodically to maintain consistency with the commissioned specifications. For beam output, medical physicists adhere to TG-51 guidelines, employing ion chambers and electrometers for measurements. However, TG-51 can be cumbersome for daily output measurements. A simpler alternative involves utilizing a device equipped with diode chambers and ionization chambers for routine monitoring. The Daily QA 3 (Sun Nuclear Corporation, Melbourne, USA) has been validated for meeting the routine quality control requirements for linear accelerator output, flatness, symmetry, and energy[10]. RadMachine enables the creation of trends from imported data. Figure 6 illustrates a trend for 6 MV measured dose centiGray (cGy) using a Daily QA 3. Physicists can promptly assess the dose trend and

gauge deviations from the set reference. Trends are particularly valuable during monthly QA sessions for verifying the necessity of beam tuning. A notable feature of RadMachine is its capability to save and share plots effortlessly. Saving a chart is as simple as clicking “save chart,” or users can copy the URL link to share with colleagues. Trends offer medical physicists a visual tool to monitor measurements over time, facilitating rapid identification of changes.

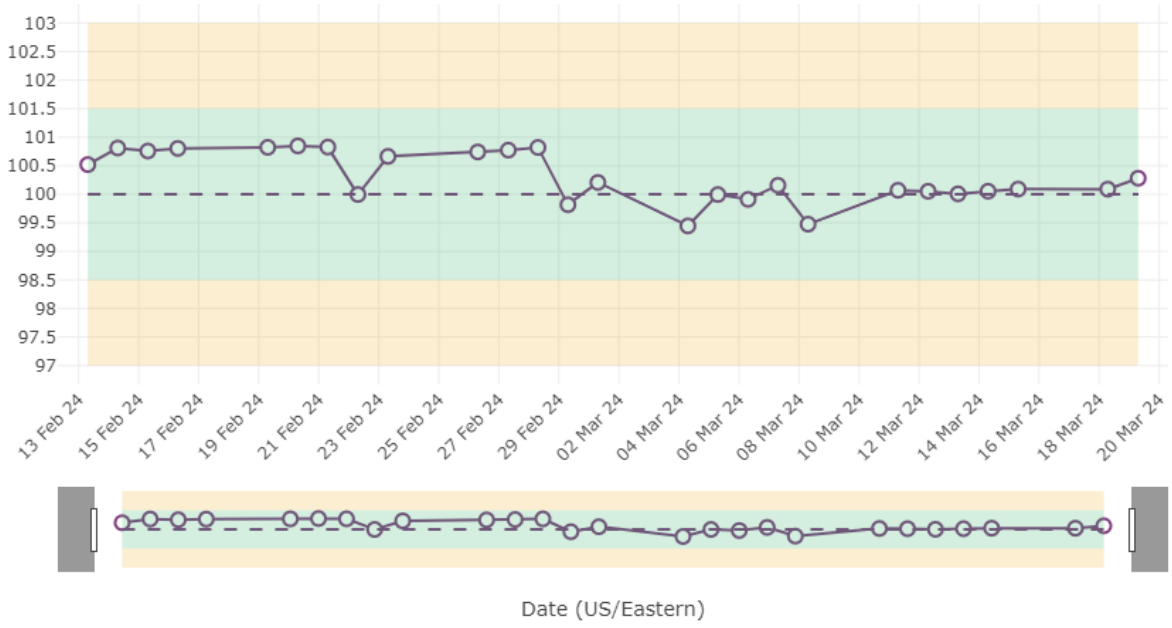
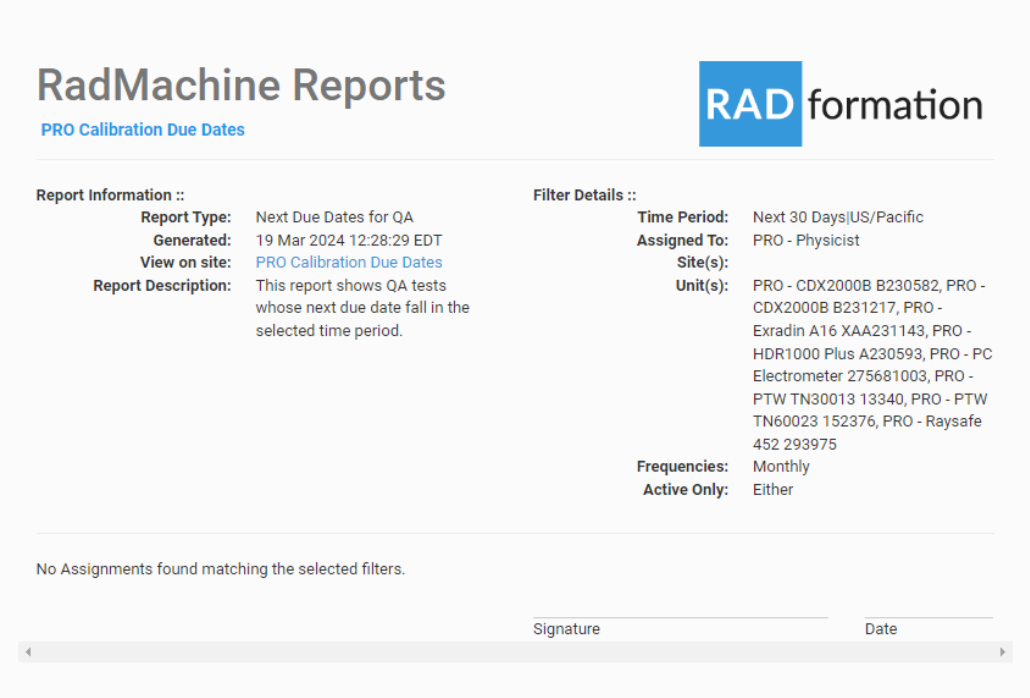


Figure 6. RadMachine DailyQA3 Beam Check: 6 MV Measured Dose (cGy). The dash line is the reference value and the green area is the tolerance constraint.

1.1.6 Reports

Reports of QA data can be sent to specific individuals, such as the manager or chief physicist, or retained as hard backup copies. RadMachine streamlines the reporting process by enabling the generation, scheduling, and dispatch of reports. To generate a report, a test list is required to input data. Figure 7 depicts a report tailored to remind the medical physicist of

upcoming calibration due dates. We utilize our test list "PRO Calibration Due Dates" to record ancillary equipment calibration data, set at specific test frequencies (e.g., every two years for electrometers). Leveraging the report features, we've crafted a report to email the chief physicist a month prior to calibration expiration.



RadMachine Reports

PRO Calibration Due Dates

RAD formation

Report Information ::

Report Type:	Next Due Dates for QA
Generated:	19 Mar 2024 12:28:29 EDT
View on site:	PRO Calibration Due Dates
Report Description:	This report shows QA tests whose next due date fall in the selected time period.

Filter Details ::

Time Period:	Next 30 Days|US/Pacific
Assigned To:	PRO - Physicist
Site(s):	
Unit(s):	PRO - CDX2000B B230582, PRO - CDX2000B B231217, PRO - Exradin A16 XAA231143, PRO - HDR1000 Plus A230593, PRO - PC Electrometer 275681003, PRO - PTW TN30013 13340, PRO - PTW TN60023 152376, PRO - Raysafe 452 293975
Frequencies:	Monthly
Active Only:	Either

No Assignments found matching the selected filters.

Signature Date

Figure 7. RadMachine Calibration Due Dates Report.

Several benefits arise from utilizing the report feature. Firstly, two years can elapse swiftly, and dates may easily slip from memory. By employing the report, the physicist receives automated reminders, affording ample time to prepare for equipment calibration. Secondly, reports offer the advantage of scheduling. The chief physicist or manager can receive summaries of performed QA activities. Summary reports serve to verify and review machine QA, allowing a manager overseeing multiple sites to ensure comprehensive QA adherence. Moreover, sites with

a solitary physicist can submit reports for review, such as annual QA evaluations. Reports can also encapsulate service events, aiding medical physicists by summarizing machine downtime and tracking faults. This functionality facilitates service engineers and management in identifying trends in part failure and machine downtime.

1.1.7 Faults and Service

Faults can occur on units, such as LINACs. The fault component in RadMachine records and tracks these faults. Tracking error codes can be beneficial for service engineers and physicists, enabling them to identify patterns or prevent larger faults from occurring. Evaluating a unit's performance through fault tracking is essential. Moreover, the fault tracking feature, when utilized at a corporate scale, empowers physicists to find solutions for faults. For instance, if one site records and resolves a fault, this information can save another clinic time in resolving a similar issue. Fault recording and tracking not only evaluate a unit’s performance but also provide a solution list for others.

Units require service, either planned (routine maintenance) or to repair a fault. The service component in RadMachine allows clinics to log service events, schedule them, and manage service-related inventory. This feature provides status updates on service events and keeps track of service performers and overseeing physicists. Post-service, physicists often need to perform QA to ensure the unit functions as expected. Using the service features, service QA can be assigned to events before the unit returns to the clinic. This ensures necessary QA procedures are conducted and can be reviewed by the chief physicist or others.

Service event logs can include recorded downtime and repair information. Downtime tracking is crucial for units that frequently require service. Downtime directly impacts treatment

availability for patients, disrupting treatment schedules and potentially affecting treatment efficacy. Maintaining downtime and repair records provides valuable insights for both the company and vendors regarding unit performance, potentially indicating the need for larger repairs to minimize downtime.

RadMachine's service module also facilitates inventory management. Spare parts are often kept on-site, eliminating the need to order and wait for parts to be shipped. This expedites repairs, as service engineers can quickly determine if required parts are available locally, reducing downtime. Cloud-based inventory tracking enables engineers to monitor part usage trends, potentially identifying components requiring closer attention. This efficient inventory management saves time and aids in evaluating component performance.

2 Varian Edge

2.1 Daily Quality Assurance (QA)

Daily dosimetry testing, as outlined in TG-142, is essential[4]. At Personalized Radiation Oncology (PRO), radiation therapists conduct quality assurance (QA) in the morning before seeing the first patient. Daily QA 3 assesses output, beam quality, symmetry, and flatness across all energies (6 MeV, 9 MeV, 12 MeV, 16 MeV, 6 MV, 6-FFF MV, 10 MV, 10-FFF MV, 15 MV). A dedicated test list for Daily QA3 data input and analysis was created for each energy. This test list records QA performers, temperature, pressure, measured dose (cGy), symmetry, flatness, and field size (refer to Figure 8). RadMachine automates data querying and uploading. A local data tool is used to retrieve data from the RadMachine agent, which operates as a local server accessible through a browser. The agent monitors the Sun Nuclear Daily QA3 database for changes and uploads data accordingly. At PRO, the "DailyQA3 Beam Check" test list for each energy receives automatic data input. Once inputted, results are analyzed and made available for physicist review via the internet.

Categories to perform	Name	Value	Skip	Status	Comment	Reference
DailyQA3 Beam Check :: 10 FFF						
DQA3	DailyQA3 Beam Check Upload	Upload	☐	Not Done		No Ref
DQA3	Machine SN			Not Done		No Tol
DQA3	Calibration File			Not Done		No Tol
DQA3	Device SN			Not Done		No Tol
DQA3	Comments			Not Done		No Tol
DQA3	Performer			Not Done		No Tol
DQA3	Temperature (C)			Not Done		No Ref
DQA3	Pressure (kPa)			Not Done		No Ref
DQA3	Measured Dose (cGy)			Not Done		100
DQA3	Axial Symmetry (%)			Not Done		0.0834767
DQA3	Transverse Symmetry (%)			Not Done		0.132351
DQA3	QA Flatness (%)			Not Done		0
DQA3	Energy (%)			Not Done		0
DQA3	X field size (cm)			Not Done		19.9854
DQA3	X field shift (cm)			Not Done		0.00807292
DQA3	Y field size (cm)			Not Done		19.91
DQA3	Y field shift (cm)			Not Done		-0.00644602
DQA3	Wedge Type			Not Done		No Tol
DQA3	Wedge Orientation			Not Done		No Tol
DQA3	Wedge Angle			Not Done		No Tol

Figure 8. DailyQA3 Beam Check: 10FFF Test List. This test list evaluates measured dose, symmetry, flatness, energy, and field size. Reference values are inputted to compare the results against.

Radiation therapists at PRO conduct daily mechanical and safety checks. Previously, these checks were documented using paper forms. With RadMachine, mechanical and safety checklists are completed online (Figure 9). Transitioning to RadMachine eliminates the need for paper forms and ensures QA documentation is backed up and accessible online to authorized personnel.

Categories to perform	Name	Value	
Daily :: Morning QA Checklist			
Mechanical	Lasers with 1.5 mm of center?	No	Yes
Mechanical	ODI within 100cm +/- 2mm?	No	Yes
Safety	Door start and stop functional?	No	Yes
Safety	"Beam On" indicator illuminates when beam on?	No	Yes
Safety	Audio/Video systems operational?	No	Yes
Safety	Safety interlocks functional?	No	Yes
Safety	Collision interlocks functional?	No	Yes
Safety	Shift QA test passes	No	Yes

Figure 9. Daily: Morning QA Checklist. The radiation therapists are required to perform mechanical and safety checks each morning before treatment begins. The morning checklist test lasers, optical distance indicator (ODI), door function, video systems, and interlocks.

2.2 Monthly Quality Assurance (QA)

The monthly QA at PRO comprises six test lists: dosimetry for photons and electrons, imaging, MLC, mechanical, and beam profile. These test lists adhere to TG-142 guidelines[4]. While many tests are conducted in service mode, some require a designated test patient or plan. Qualified medical physicists (QMPs) and physics trainees perform the monthly QA tests. Each test list is signed off by the QMP upon completion.

2.2.1 Dosimetry

Verifying the correct operation of the unit is crucial, particularly as a linear accelerator's (LINAC) output may vary over time from baseline conditions (1.00 cGy/MU at dmax). Output consistency is assessed using a calibrated ionization chamber and electrometer, following

standard testing parameters (10 x 10 cm^2 field size, 100 cm SSD, 100 MU). Any deviations detected require prompt adjustments to restore output within a tolerance limit (+/- 1%). Most modern units incorporate two monitor chambers to ensure redundancy in monitoring radiation output, flatness, and symmetry. Should one chamber fail, both chamber readings should recalibrated. LINACs, especially those used in intensity-modulated radiation therapy (IMRT), offer various dose rates across a treatment field. Ensuring dose rate consistency involves measuring the dose per MU for all available rates. Additionally, beam energy consistency is confirmed by measuring ionization at two depths. Monthly evaluation of central axis dose delivery by enhanced dynamic wedge is conducted for photon energies (6 MV, 10 MV, and 15 MV). Performing these monthly tests is essential to maintaining functionality compared to original baselines.

In RadMachine, a "Monthly Dosimetry" test list has been established for both photons and electrons to evaluate output, dose rate output consistency, energy consistency, and wedge factors for photon energies (6 MV, 10 MV, 15 MV) (Figures 10-12). RadMachine streamlines the recording and analysis of monthly dosimetry QA measurements at PRO (Figures 10-12). The "Monthly Dosimetry" test list encompasses various tests and test lists for storing inputted data (e.g., measured readings) and performing calculations. For instance, the "TG-51 Factors Lookup" test list retrieves previously inputted data for calculations. These combined tests and test lists evaluate measured readings for output and dose rate consistency, energy consistency for both photon and electron energies, and wedge factors for photon energies. At PRO, photon energies include 6 MV, 10 MV, 15 MV, 6-FFF MV, and 10-FFF MV, while electron energies comprise 6 MeV, 9 MeV, 12 MeV, and 16 MeV.

Perform Edge6032 : PRO :: Monthly :: Dosimetry

Categories to perform	Name	Value	Skip	Status	Comment	Reference
PRO :: Monthly Dosimetry :: Equipment						
Dosimetry	Monthly Chamber Select		☐	Not Done		No Tol
Dosimetry	Chamber calibration current?			Not Done		Choice
Dosimetry	Monthly Electrometer Select		☐	Not Done		No Tol
Dosimetry	Electrometer calibration current?			Not Done		Choice
Dosimetry	TG-51 Factors Lookup	Results: 'PRO :: TG-51 Factors'	☐	PRO :: TG-51 Factors: 14 Mar 2024 19:43:00		No Ref
Dosimetry	Monthly Phantom Material		☐	Not Done		No Tol
Dosimetry	Temperature (°C)		☐	Not Done		22
Dosimetry	Pressure (mmHg)		☐	Not Done		760
Dosimetry	Temperature/Pressure Correction (Ptp)			Not Done		No Ref

Figure 10. Monthly Dosimetry (Photons) Equipment Test List. A test list can encompass multiple components. The "Monthly Dosimetry Equipment" test list, for instance, records and verifies equipment utilized in monthly QA procedures, incorporates values obtained from other test lists (e.g., values determined during annual/commissioning using the TG-51 protocol), logs temperature and pressure readings, and specifies the phantom material (solid water for monthly QA).

Perform Edge6032 : PRO :: Monthly :: Dosimetry

Categories to perform	Name	Value	Skip	Status	Comment	Reference
PRO :: Monthly Dosimetry :: Equipment						
PRO :: Output Constancy :: Photon :: 6X						
Dosimetry	Ppol :: 6X	0.999		NO TOL		No Ref
Dosimetry	Pion :: 6X	1.002		NO TOL		No Ref
Dosimetry	kQ :: 6X	0.992		NO TOL		No Ref
Dosimetry	Corr. Factor :: 6X			Not Done		No Ref
Dosimetry	Clinical %dd :: 6X	66.170		NO TOL		No Ref
Dosimetry	MU :: 6X		☐	Not Done		100
Dosimetry	MU2 :: 6X		☐	Not Done		100
Dosimetry	Ion chamber readings (nC) :: 6X	Mean = *No Values*	☐	Not Done		No Ref
Dosimetry	Corrected Ion Chamber Rdg, M (nC) :: 6X			Not Done		No Ref
Dosimetry	Dose to Water at 10cm depth :: 6X			Not Done		No Ref
Dosimetry	Dose / MU at dmax :: 6X			Not Done		1

Figure 11. Monthly Dosimetry (Photons) Output Constancy Test List. The Output Constancy: Photon (6 MV) test list incorporates previously inputted data and records additional inputted data, such as monitor unit (MU) chamber readings and ion chamber readings. These data are then utilized in various tests within the list, including corrected ion chamber reading, dose to water at 10 cm depth, and dose per monitor unit (MU) at d_{max}, to derive calculated values.

Categories to perform	Name	Value	Skip	Status	Comment
PRO :: Monthly Dosimetry :: Equipment					
PRO :: Output Constancy :: Photon :: 6X					
PRO :: Output Constancy :: Photon :: 6X - Post Adjustment					
PRO :: Energy Constancy :: Photon :: 6X					
Dosimetry	Ion chamber readings (nC) :: Energy constancy :: 6X	Mean = *No Values*	☐	Not Done	
Dosimetry	Energy Constancy :: 6X			Not Done	
PRO :: Dose Rate Constancy :: Photon :: 6X					
Dosimetry	Ion chamber readings (nC) :: Dose Rate constancy :: 6X	Mean = *No Values*	☐	Not Done	
Dosimetry	Corrected Ion Chamber Rdg, M (nC) :: 6X			Not Done	
Dosimetry	Dose Rate Constancy :: 6X			Not Done	
PRO :: Wedge Factors :: 6X					
Dosimetry	Ion chamber reading (nC) :: 90 :: 6X		☐	Not Done	
Dosimetry	Ion chamber reading (nC) :: 270 :: 6X		☐	Not Done	
Dosimetry	Wedged Field Average :: 6X			Not Done	
Dosimetry	Wedge Factor :: 6X			Not Done	

Figure 12. Monthly Dosimetry (Photon) Energy Constancy, Dose Rate Constancy, and Wedge Factors Constancy. This test incorporates previously inputted data, such as ion chamber readings (nc) for 6x and corrected ion chamber readings (nc) for 6x, and records additional inputted data, including ion chamber readings (nc) for energy constancy 6x, ion chamber readings (nc) for dose rate constancy 6x, and ion chamber readings (nc) for wedge angles 90° and 270°. Subsequently, calculations are performed to determine the values of energy constancy, dose rate constancy, and wedge factors based on the data within the test list.

2.2.2 Imaging

Imaging, or image-guided radiation therapy (IGRT), plays a crucial role in verifying patient alignment. It enables precise localization and tracking of both the tumor and adjacent critical structures before each treatment session, ensuring accurate targeting of the tumor by radiation beams. Tumor margins are established to accommodate uncertainties in patient setup and anatomical changes, and IGRT allows for tighter margins, facilitating precise localization and minimizing toxicity to surrounding healthy tissues. Acquired images are compared to reference images or digitally reconstructed radiographs (DRRs), enhancing the effectiveness of radiation therapy treatments.

The LINAC's integrated imaging technology undergoes monthly evaluation at PRO. To streamline this process, PRO employs a test patient within the record and verify (R&V) system. This test patient comprises multiple fields used to capture images for each available modality: cone beam computed tomography (CBCT), megavoltage (MV), and kilovoltage (kV). A different phantom is utilized for monthly QA with each imaging modality. The R&V system stores these images, which are then exported into RadMachine. Within RadMachine, a dedicated test list analyzes the images in accordance with TG-142 standards (Figure 13)[4]. Parameters evaluated include spatial resolution, contrast resolution, uniformity, noise, and geometric accuracy. Multiple QA tests are conducted to ensure the imaging system produces high-quality images suitable for precise treatment delivery.

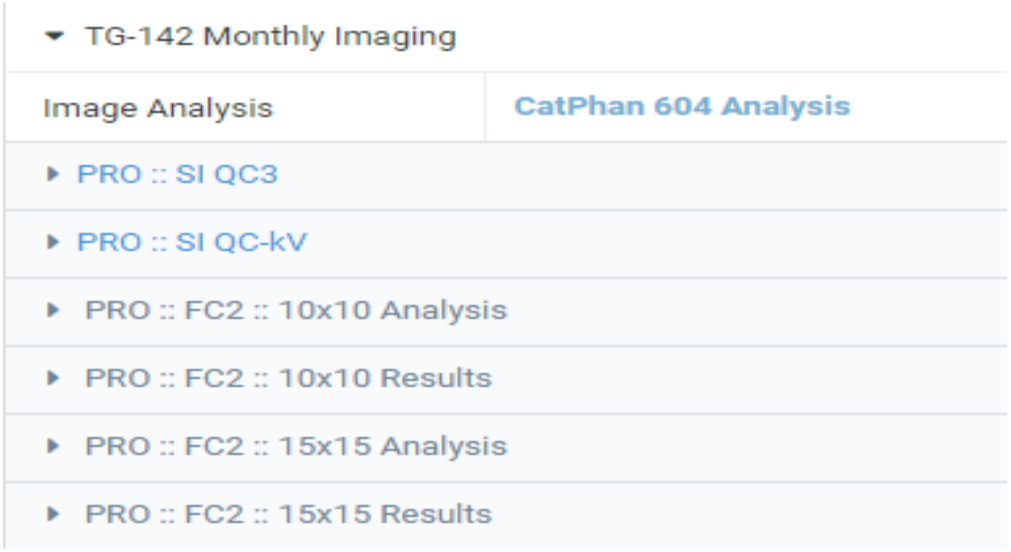


Figure 13. Task Group (TG)-142 Monthly Imaging Test List. This figure presents the test lists utilized to comply with TG-142 imaging quality assurance on a monthly basis. The CatPhan 604 phantom assesses cone beam computed tomography (CBCT) imaging, while the Standard Imaging (SI) QC3 and QC-kV phantoms evaluate planar megavoltage (MV) electronic portal imager device (EPID) and planar kilovoltage (kV) imaging, respectively. Radiation field coincidence, both symmetric and asymmetric, is assessed for field sizes of 10 x 10 cm^2 and 15 x 15 cm^2.

The modulation transfer function (MTF) quantifies the system's ability to accurately reproduce object details in an image (Figures 15 and 17). Image performance is characterized by two components: resolution and contrast. Resolution, expressed in line-pairs per millimeter (mm) or frequency, refers to the system's ability to distinguish object detail, represented by a sequence of one black line followed by one white line. In assessing optical systems, the parameter of contrast, as measured by RadMachine employing the Michelson contrast definition (Equation 1), serves as a pivotal metric. It delineates the fidelity with which the boundaries of intensity, both minimal and maximal, traverse from the plane of the object to that of the resultant image. Concurrently, the Modulation Transfer Function (MTF) stands as a cornerstone in interpreting the relationship between the contrast of the object and the ensuing contrast evident in the image, across a spectrum of spatial frequencies[11]. This analytical framework not only provides insights into the efficacy of imaging systems, but also serves as a fundamental tool in discerning their performance characteristics.

$$\text{Equation (1): Michelson contrast (\%)} = \frac{I_{max}\text{-}I_{min}}{I_{max}+I_{min}}$$

The LINAC's imaging technologies undergo monthly evaluation, as per TG-142 guidelines, regarding uniformity and noise. Uniformity assesses the consistency of pixel intensities across an image, determined by RadMachine according to the American College of Radiology (ACR) definition (Equation 2)[12].

$$\text{Equation (2): Pixel Integral Uniformity (PIU)} = 100*\left(1-\frac{\text{high-low}}{\text{high+low}}\right)$$

The analysis calculates the pixel intensity uniformity (PIU) over all low-contrast regions of interest (ROIs), returning the lowest PIU value. High and low ROIs are determined using the 1st and 99th percentile of pixel values within the central ROI. Noise, which manifests as graininess, speckles, or distortions, is quantified by the standard deviation of detective quantum efficiency (DQE), providing a measure of image quality[12,13]. RadMachine utilizes DQE to compute the contrast-to-noise ratio (CNR) (Equation 3), an indicator of image quality.

$$\text{Equation (3): CNR(I)} = \frac{\text{Contrast (I)}}{\text{Noise (I)}} = \frac{\text{Contrast (I)}}{\text{Standard Deviation (I)}}$$

Monthly evaluation of uniformity and noise is crucial as they directly influence image accuracy. Low uniformity and noise values may lead to image artifacts or hinder the ability to distinguish anatomy, hence ensuring optimal image performance.

A monthly test unique to planar imaging is scaling, which assesses the image modality's ability to maintain spatial accuracy or the size of an object[14]. Ideally, during treatment setup, the object's size should match the image size precisely. If the object size (e.g., phantom) is unknown, scaling serves as a consistency check. In RadMachine, the phantom's area is determined, and scaling is regularly monitored to ensure planar images accurately replicate objects.

2.2.2.1 Cone Beam Computed Tomography (CBCT)

Geometric distortion, a parameter specific to monthly CBCT QA, refers to how well the CBCT system detects the actual distance between two objects[15]. The catphan phantom, utilized for CBCT evaluation, features several "nodes" spaced accurately (50 mm apart). In RadMachine, the area surrounding the four nodes is sampled, and a high-pass filter is applied to identify the node within the ROI sample. The node's center of mass is then determined, and the distance between nodes is calculated[16]. Geometric distortion can cause the image dimensions to appear longer or shorter than actuality or lead to slice position errors, impacting precise imaging required for accurate patient alignment[16].

The Hounsfield Units (HU) QA test is crucial for CBCT as it ensures the reliability of acquired imaging data. HU is a standardized scale used in CT imaging to quantify the radiodensity of tissues, enabling differentiation based on X-ray attenuation properties. Consistency in HU measurement ensures that tissues with similar densities are represented consistently across different CBCT scans, reducing image artifacts that may obscure important details. Consistent HU values lead to clearer images, vital for aligning and verifying patient positioning before each treatment session. Clear CBCT images must match those used in planning CT images for plan development. HU constancy ensures the prescribed dose is delivered accurately to the target volume while minimizing exposure to surrounding healthy tissues.

A test list titled "CBCT Analysis" is utilized to assess the LINAC's CBCT imaging capabilities on a monthly basis (Figure 14). This evaluation employs a CatPhan® 604 phantom to gauge spatial resolution, contrast, Hounsfield units (HU) constancy, geometric distortion, and

uniformity, in line with TG-142 guidelines[4]. The obtained image quality results are then compared against baselines established during commissioning testing. Geometric distortion and HU are compared to predefined distance or HU values, respectively, with the aim of ensuring that the LINAC's imaging systems maintain their capabilities over time. Poor-quality images may pose challenges in interpretation and/or lead to artifacts, potentially resulting in the loss of critical details necessary for patient setup. Subsequently, a CBCT scan is acquired and fed into RadMachine for further analysis (Figure 15).

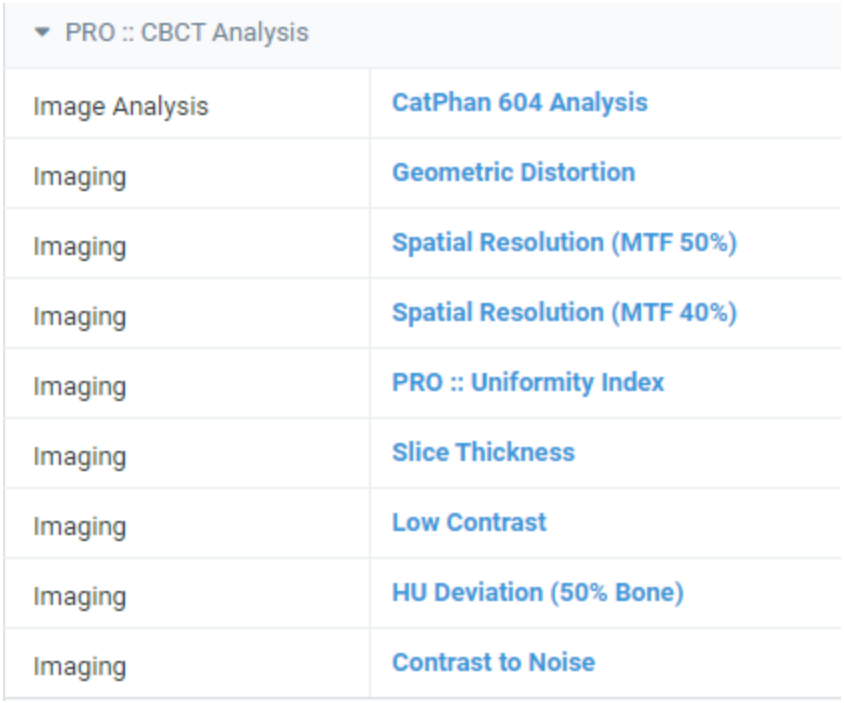


Figure 14. Cone Beam Computed Tomography (CBCT) Analysis Test List. RadMachine analyzes CBCT images using the CatPhan 604 Analysis test. The analysis comprises several quantitative tests to evaluate image quality, geometric accuracy, and Hounsfield unit constancy.

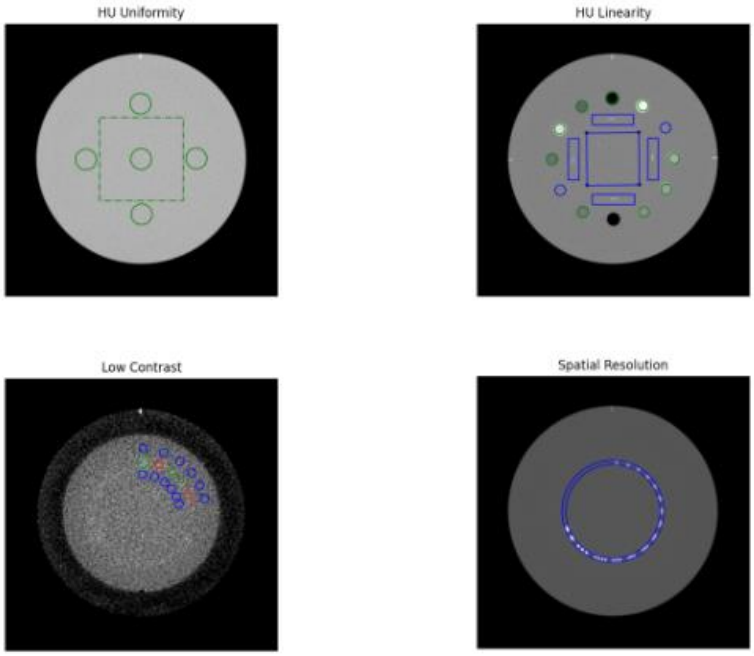


Figure 15. CatPhan 604 Analysis. Cone beam computed tomography (CBCT) imaging undergoes monthly evaluation for spatial resolution, contrast, Hounsfield unit (HU) constancy, uniformity, and noise. These tests utilize an image quality phantom, specifically the CatPhan® 604 phantom. HU uniformity involves selecting regions of interest for analysis, while HU linearity assesses slide width, HU constancy, and slide width. Targets with varying diameters and contrasts are employed to evaluate low contrast, whereas bar patterns aid in quantitative modulation transfer function analysis for spatial resolution measurements.

2.2.2.2 Planar Imaging

Planar kV imaging parameters undergo monthly evaluation utilizing the test list “SI QC-kV” (Figure 16). This list assesses spatial resolution, contrast, uniformity, and noise against baselines established during commissioning. Scaling is also assessed and compared to the known area of the QC-kV phantom (Standard Imaging). The SI QC-kV phantom is preferred over the vendor-supplied Leeds phantom due to its simpler setup. While the SI QC-kV phantom only requires placement on a stand on the treatment couch and alignment using in-room lasers, the Leeds phantom necessitates taping the copper filter on the kV panel cover, which is more time-consuming and requires greater care to prevent damage to the phantom and the kV panel.

Subsequently, a planar kV image is acquired and inputted into RadMachine for analysis (Figures 17 and 18).

PRO :: SI QC-kV	
QC-kV-1	PRO :: SI QC-kV Analysis
QC-kV-1	Number of Contrast Regions Seen
QC-kV-1	Median Contrast
QC-kV-1	Median CNR
QC-kV-1	MTF 80% (lp/mm)
QC-kV-1	MTF 50% (lp/mm)
QC-kV-1	MTF 30% (lp/mm)
QC-kV-1	Integral Uniformity
QC-kV-1	Scaling Discrepancy

Figure 16. Monthly Planar Kilovolt (kV) Quality Assurance Test List “SI QC-kV”. Monthly evaluations are conducted on planar kV imaging parameters, including spatial resolution, contrast, scaling, uniformity, and noise, using the designated test list. The assessment of spatial resolution involves calculating the relative modulation transfer function (MTF) to evaluate the high-contrast line pair regions.

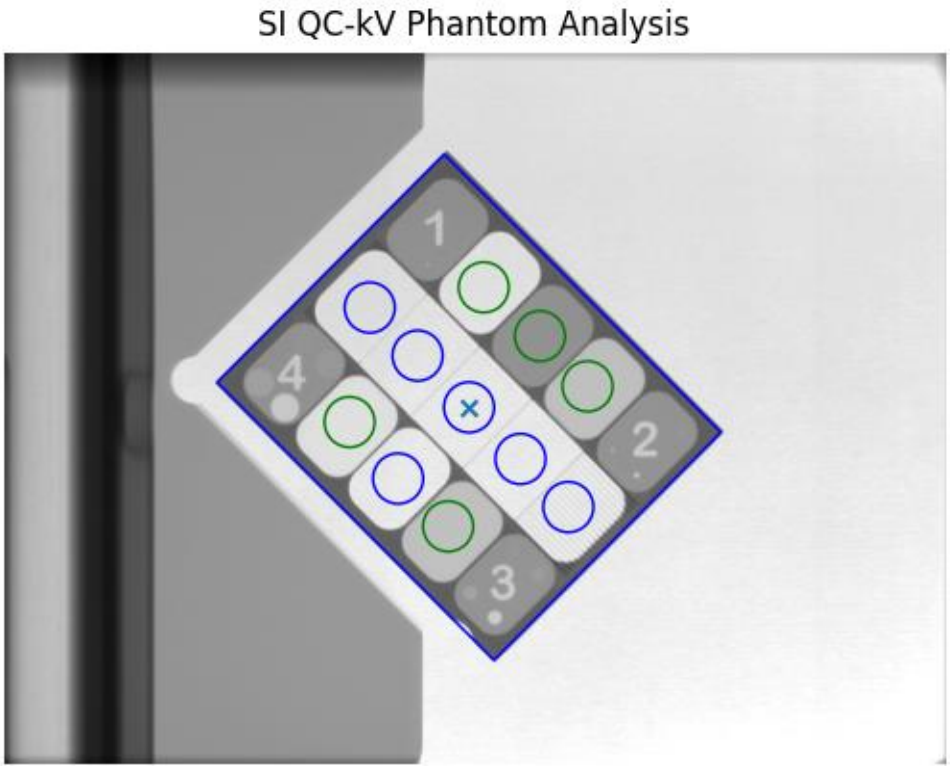


Figure 17. Standard Imaging QC-kV Phantom Analysis. The phantom is positioned with number 4 facing the top of the couch. Subsequently, the image is uploaded into the test, and the edge of the phantom is identified by establishing the longest axis (indicated by the blue box), with the center of the box designated as the phantom's center. The orientation of the edge determines the angle of the phantom. Contrast is calculated from the phantom center and angle, while spatial resolution is assessed by applying offsets to sample the line pair regions.

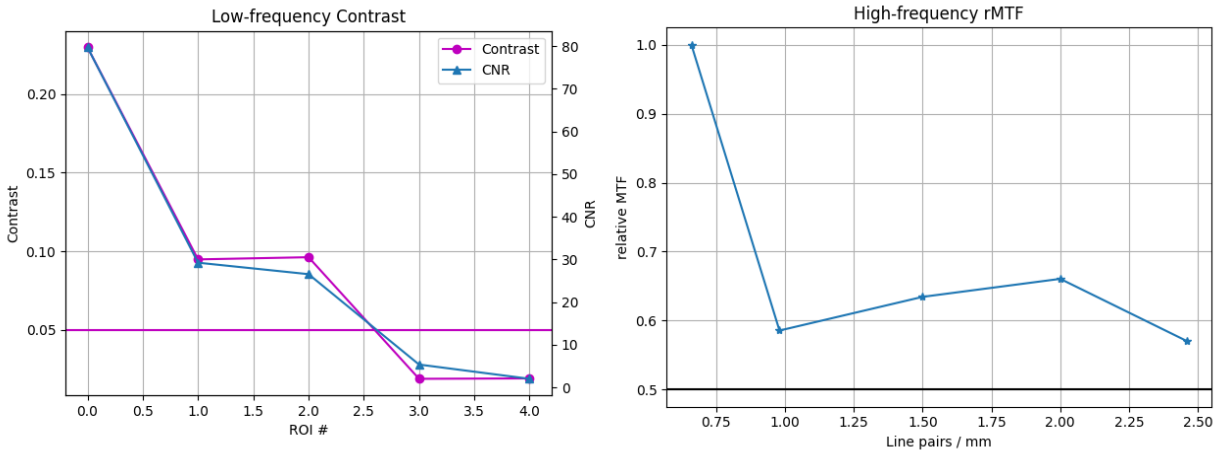
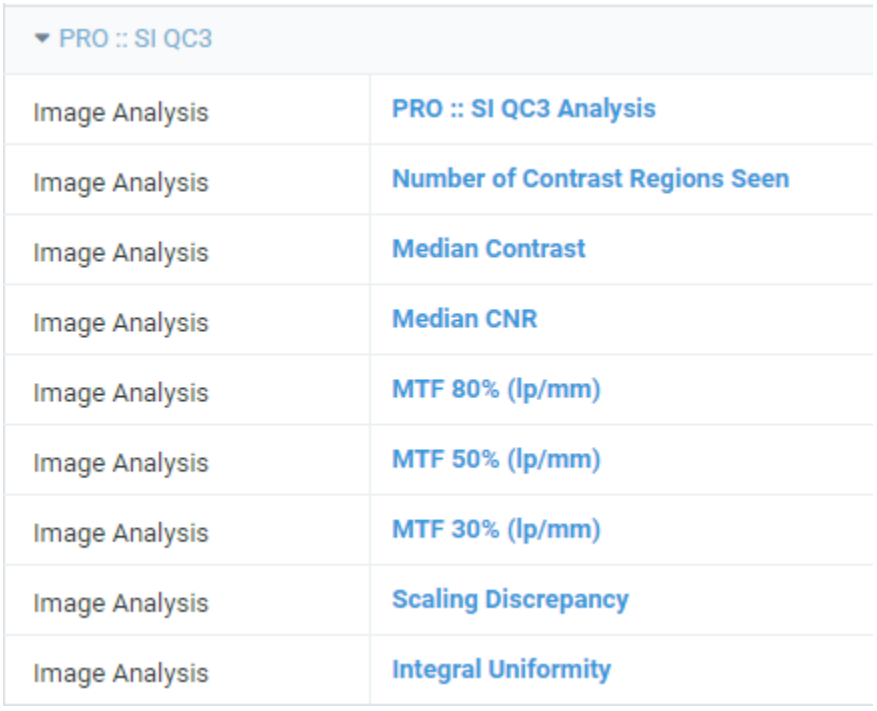


Figure 18. Kilovolt (kV) Image Analysis Plots. Post-analysis calculates values for both low and high contrast regions against the threshold, and a plot is generated to indicate the pass/fail status.

MV imaging, employing high-energy X-rays in the MV range, is utilized for alignment and verification purposes and undergoes monthly evaluation. The analysis is facilitated by the "SI QC3" test list, dedicated to planar MV imaging assessment (Figure 19-21). Utilizing an electronic portal imaging device (EPID), MV images are captured. A planar MV image is acquired using a test patient and the SI QC3 phantom (Figure 20), which are then processed through the "SI QC3" test list (Figure 19). Similar parameters to those in the "QC-kV" test list are evaluated. Monthly evaluations of planar MV imaging are conducted to ensure proper functionality and the production of high-quality images.



PRO :: SI QC3	
Image Analysis	PRO :: SI QC3 Analysis
Image Analysis	Number of Contrast Regions Seen
Image Analysis	Median Contrast
Image Analysis	Median CNR
Image Analysis	MTF 80% (lp/mm)
Image Analysis	MTF 50% (lp/mm)
Image Analysis	MTF 30% (lp/mm)
Image Analysis	Scaling Discrepancy
Image Analysis	Integral Uniformity

Figure 19. Monthly Planar Megavoltage (MV) Imaging Test List “SI QC3”. Planar MV imaging undergoes monthly evaluation, assessing spatial resolution, contrast, scaling, uniformity, and noise using a dedicated test list. The evaluation involves calculating the relative modulation transfer function (MTF) to assess the spatial resolution of high-contrast line pair regions.

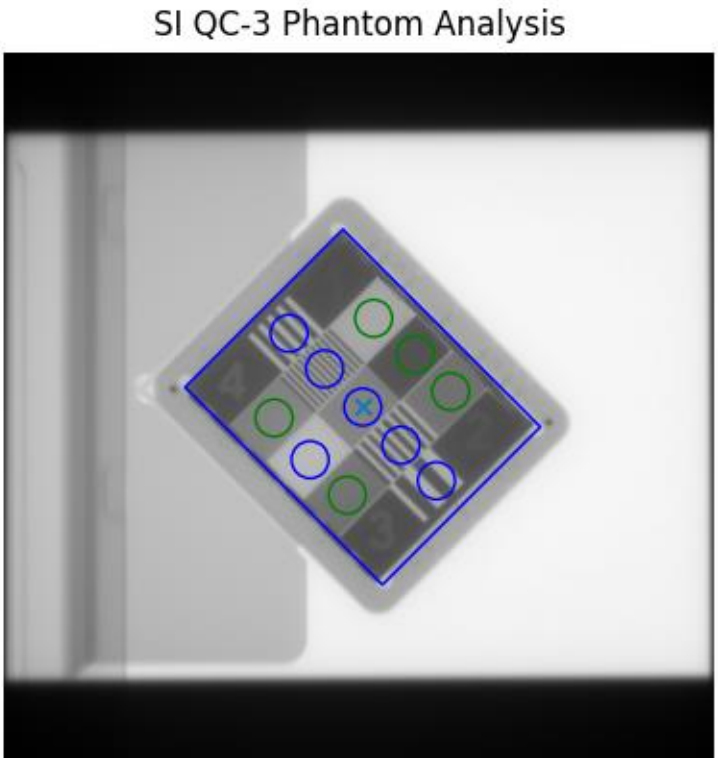


Figure 20. Standard Imaging QC-3 Phantom Analysis. The phantom is positioned with number 4 facing towards the top of the couch. The image is then loaded into the test software, and the edge of the phantom is identified by determining the longest axis (represented by a blue box), with the center of the box designated as the phantom center. The orientation of this edge determines the angle of the phantom. Contrast is assessed from the phantom center and angle, while spatial resolution is determined by applying offsets to sample the line pair regions. Green circles indicate a passing grade for the low contrast area, while red circles denote a failure (not shown). Blue circles are used to identify the high contrast regions.

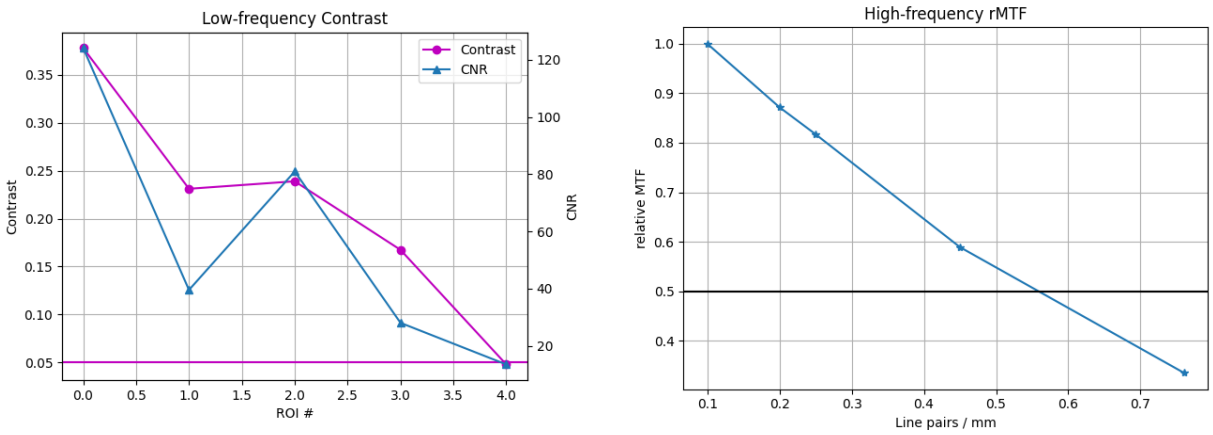


Figure 21. Megavoltage (MV) Image Analysis Plots. Post-analysis calculates values for both low and high contrast regions against the threshold, and a plot is generated to indicate the pass/fail status.

Post-image analysis for planar kV and MV imaging is identical, but the setup required for RadMachine differs between the two modalities. For each modality, an image of a phantom designed for that energy is captured. Standard Imaging (SI) provides an acrylic mount to hold the phantom during imaging. The phantom is positioned orthogonally to the imager. While RadMachine can detect the kV phantom (QC-kV) without difficulty, it struggles to detect the MV phantom (QC3) using the mount due to the similar densities of the mount and phantom's edge. To evaluate MV images using the SI phantom, the phantom and holder must be separated. This is achieved by placing a stack of notecards between the phantom and the holder. The contrast resolution of the kV images is sufficient to differentiate between the phantom and holder, allowing RadMachine to detect the phantom without any modifications to the setup. However, RadMachine's image analysis capabilities are limited, complicating the use of SI phantoms.

2.2.2.3 Light/Radiation Field Coincidence

A light field is an integral part of the process for aligning patients during treatment. It serves as a visual representation of the delivered radiation field. Monthly evaluations ensure proper alignment and accurate treatment delivery by assessing the coincidence between the light and radiation fields. This assessment includes two field sizes: 10 x 10 cm^2 and 15 x 15 cm^2 (Figure 22). Using the SI FC-2 phantom, the light field is aligned with its corresponding area, and radiation is delivered while the electronic portal imaging device (EPID) captures the images. The FC-2 phantom features two sets of ball bearings (BBs), one for each field size. RadMachine determines the field size using these BBs, utilizing the larger set if the field size exceeds 14 cm. Measurements are taken along the center of the image in both the in-plane and cross-plane directions. By comparing the irradiated field centroid to the image center and BB centroid, the field size is determined (Figure 23). Accurate field size and radiation field coincidence are essential for precise patient alignment.

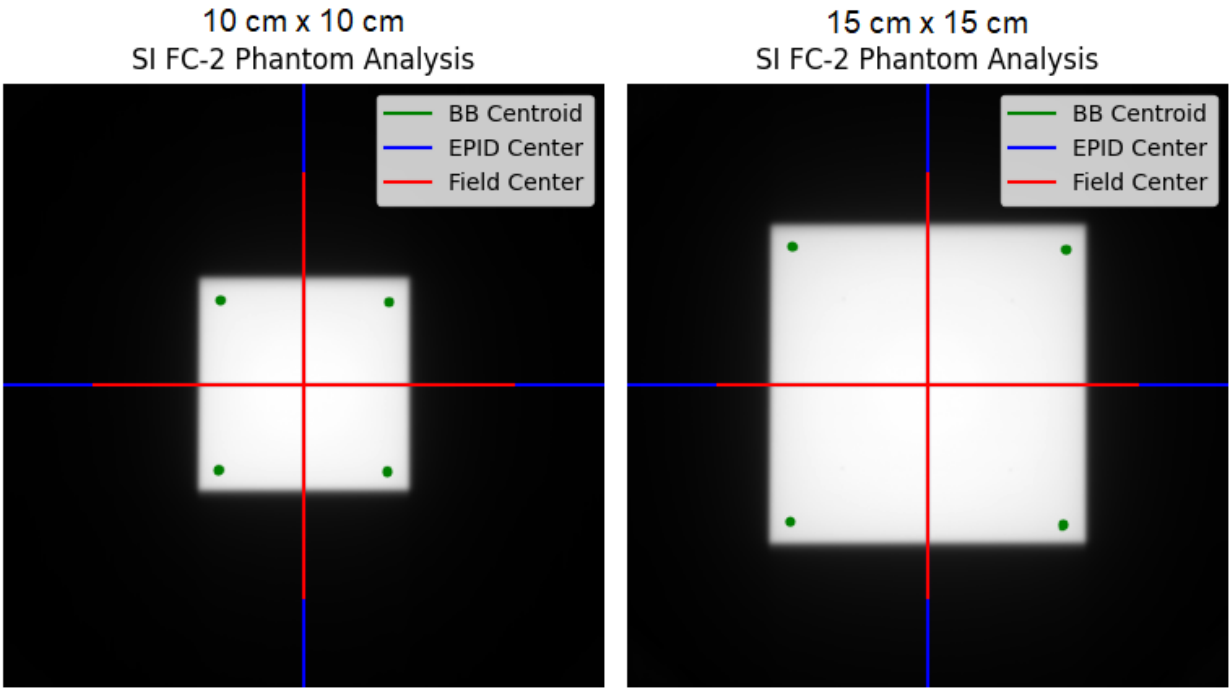


Figure 22. Test Analysis for Light/Radiation Field Coincidence.

Field Size X (mm)	
Field Size Y (mm)	
Field to BB X Offset (mm)	
Field to BB Y Offset (mm)	
Field to EPID X Offset (mm)	
Field to EPID Y Offset (mm)	

Figure 23. "FC2 Results" Test Lists. The alignment between the light and radiation fields is assessed for both 10 x 10 cm^2 and 15 x 15 cm^2 areas. Field size in both the x and y dimensions is compared by comparing the light field readout to the radiation field images.

2.2.3 Multileaf Collimator (MLC)

The primary function of a multileaf collimator (MLC) is to enhance treatment delivery efficacy. Initially, treatment units shaped x-ray fields using dense material jaws (i.e., collimators) within the machine to obstruct some of the radiation beam, resulting in square or rectangular fields. Modern machines utilize MLCs, employing movable leaves to shape fields by blocking radiation beams. MLC leaves enable fields to conform to specific shapes, such as tumors[17]. Additionally, computer software facilitates continuous adjustment of the field shape to match the beam's eye view (BEV) projection of a planning target volume (PTV) during arc rotation treatment, making beam-intensity modulation treatments more achievable by dynamically compensating filter creation during irradiation[18]. The ability of MLCs to enhance treatment outcomes by shielding sensitive tissues around the target is the primary reason for their standard use in clinics.

PRO employs a Varian Edge unit with a high-definition (HD) 120 MLC collimator (HD 120 MLC), featuring 2.5 mm width leaves for delivering treatments directly to the tumor while sparing surrounding normal tissues[19]. The maximum field size is 32 cm x 22 cm for an IMRT field. The maximum physical field size is projected at the isocenter plane.

The design of MLC leaves introduces uncertainties[17]. Firstly, the tongue-and-groove design minimizes leakage between leaves but creates a low dose region where one leaf overlaps the other, resulting in leakage between adjacent leaves when closed (i.e., interleaf transmission). Additionally, a small amount of radiation transmits through the leaves when closed (i.e., leaf end transmission), despite being designed to block transmitted radiation, leading to some dose transmission (i.e., leaf transmission or intra-leaf leakage). During commissioning, an evaluation

of these MLC characteristics is conducted, impacting the geometrical and dosimetry accuracy of the dose applied to the patient, which is routinely monitored.

MLCs are frequently tested to ensure proper functioning and accurate positioning[20]. Leaf position accuracy is verified by delivering radiation to the electronic portal imaging device (EPID) while the MLC creates 1 mm wide strips at 2 cm intervals (i.e., Picket fence test). The picket fence test is performed weekly as a qualitative test. Monthly, RadMachine is used to quantify leaf positions using the picket fence test. Any differences between expected and measured leaf positions may indicate potential issues with leaf positioning accuracy.

PRO utilizes Varian RapidArc for both treatment planning and the delivery of volumetric modulated arc therapy (VMAT). The positioning of multileaf collimators (MLC) and monitor units (MU) is optimized based on dose-volume constraints for the target and surrounding normal tissues. Additionally, constraints are imposed on MLC motion, dose-rate, and gantry speed to maximize the benefits of RapidArc, enhancing dose conformality, delivery efficiency, accuracy, and reliability[21].

Three crucial features require commissioning and routine QA testing when employing RapidArc. These include assessing the accuracy of dynamic MLC positioning, precise dose-rate control during gantry rotation, and accurate control of gantry speed, all of which are executed by the LINAC according to the treatment plan. Regular assessment of these features is essential to evaluate the machine's performance[21].

The speed of MLC leaf movement greatly affects treatment accuracy, necessitating that leaf modulation align with the treatment plan's design. Any deviations could lead to inaccuracies in treatment delivery, possibly caused by dirt accumulation between leaves, component deterioration such as motor malfunctions, or sudden component failures. Monthly QA

procedures are conducted to ensure that MLC leaf speed operates as intended, thereby maintaining treatment accuracy.

QA tests are performed to evaluate the smooth movement and precise positioning of MLC leaves, focusing on their speed and travel distance. A RapidArc QA plan is utilized to deliver radiation while the gantry rotates and the MLC sweeps across the field in a strip pattern (i.e., dose rate and MLC speed)[21]. EPID dose profiles are then analyzed to assess leaf speed and travel distance, aiming to identify any alignment issues that could result in uneven dose delivery or the formation of cold/hot spots in the radiation field. The alignment of MLC leaves relative to each other and the radiation isocenter is evaluated monthly.

PRO employs RadMachine for the analysis of monthly MLC QA (Figure 24). Varian-supplied digital imaging and communications in medicine (DICOM) radiation treatment (RT) files are used to deliver radiation to the EPID, facilitating the evaluation of MLC speed and travel alignment, as well as the LINAC's dose output across various regions while adjusting dose rate and gantry speed[21]. The plans are accessed from the treatment console (i.e., treatment delivery system (TDS) drive) using Machine QA mode, and after delivery, the images are saved in the same folder as the plans. Subsequently, the images are exported to a local drive for importation into RadMachine's "TG-142 Monthly MLC" test lists for analysis.

▾ VMAT Dose Rate & Gantry Speed (DRGS)		
Image Analysis	VMAT DRGS Analysis	
Image Analysis	Absolute Mean Deviation %	
Image Analysis	Max Deviation %	
▾ VMAT Dose Rate & MLC Speed (DRMLC)		
Image Analysis	VMAT DRMLC Analysis	
Image Analysis	Absolute Mean Deviation %	
Image Analysis	Max Deviation %	
▾ Picket Fence		
Image Analysis	Picket Fence: Upload	
Image Analysis	Number of Pickets Found	
Image Analysis	Percent Leaves Passing (%)	
Image Analysis	Maximum Error (mm)	
Image Analysis	Absolute Median error (mm)	
Image Analysis	Mean Picket Spacing (mm)	

Figure 24. "TG-142 Monthly MLC" Test List. The test list is utilized to assess both the performance of the multileaf collimator (MLC) and the constancy of the linear accelerator (LINAC) output. Dose rate and MLC speed, along with the picket fence test, are employed to gauge MLC position accuracy. Furthermore, dose rate and gantry speed are employed to assess the LINAC's dose output across various regions under varying dose rates and gantry speeds.

RadMachine features a built-in image analysis module specifically designed for VMAT. This analysis module is founded on the Varian RapidArc QA test and procedures[22]. Three key tests are conducted: dose rate and gantry speed (DRGS), dose rate and MLC speed (DRMLC), and the picket fence test during gantry rotation. The DRGS assessment evaluates the LINAC's capability to modulate dose rate and gantry speed to achieve the planned value. It involves irradiating seven static MLC fields (20 cm x 1.8 cm) with a 2 cm center spacing, utilizing variable dose rates during gantry rotation. DRMLC scrutinizes the MLC control or leaf speed during RapidArc. Here, the EPID is exposed to the same dose using the MLC sliding window technique, combined with gantry rotation, variable leaf speeds, and dose rates to replicate the

planned dose pattern[22]. Correspondingly, an open field is also measured. RadMachine's VMAT analysis module analyzes two image files for each test (Figure 24).

The RadMachine VMAT analysis of DRMLC and DRGS images can be customized. The module's algorithm defaults to identifying 10 cm x 0.5 cm exposure sections (Figure 25a, b and 26a, b). Each section's measurement is then corrected (i.e., M_{corr}), and the deviation (i.e., $M_{deviation}$) is calculated (Equation 4 and 5). Subsequently, the radiation profile is plotted, normalized, and superimposed on the profile of the open field (Figure 25c, 26c). The results are detailed in the test list (Figure 24).

$$\text{Equation (4): } M_{corr}(x) = \frac{M_{DRGS}(x)}{M_{open}(x)} * 100$$

$$\text{Equation (5): } M_{deviation}(x) = \frac{M_{corr}(x)}{\overline{M}_{corr}(x)} * 100 - 100$$

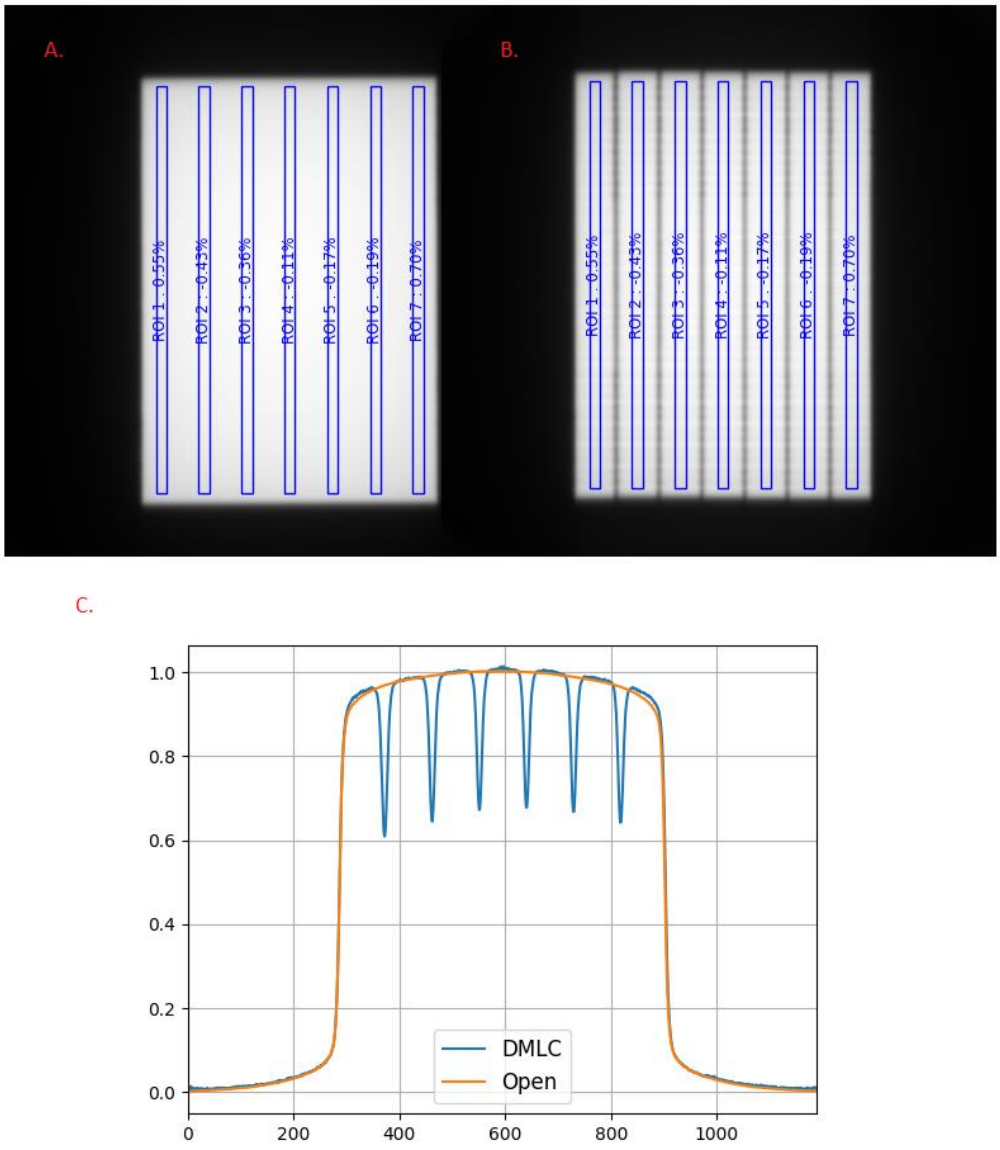


Figure 25. Dose Rate and Gantry Speed (DRGS) Analysis. DRGS results for March 2024 include: (a) Open field, (b) Radiation segments, and (c) Median profiles for dose rate versus gantry speed. The region of interest (ROI) constraint measures 5 mm x 190 mm. The absolute mean deviation percentage is 0.358, with a maximum deviation percentage of 0.697.

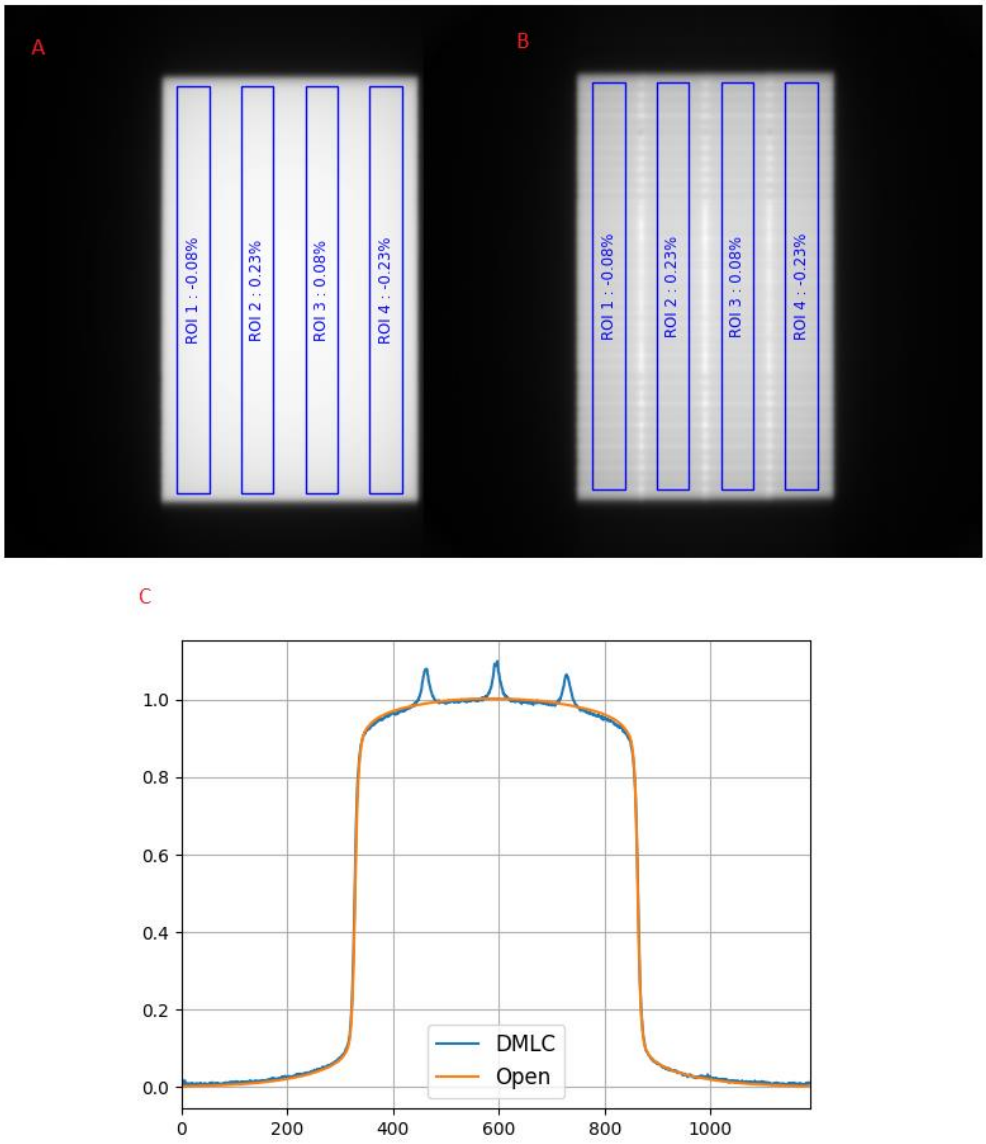


Figure 26. Dose Rate and Multileaf Collimator (DRMLC) Analysis. DRMLC results for March 2024 consist of: (a) Open field, (b) Radiation segments, and (c) Median profiles for MLC and gantry speed. The region of interest (ROI) constraint measures 5 mm x 190 mm. The absolute mean deviation percentage is 0.158, with a maximum deviation percentage of 0.235.

MLC positioning is assessed to ensure accuracy and proper alignment during treatment. The picket fence test, a visual inspection, is conducted weekly, with deviations quantified monthly. RadMachine features a picket fence module designed to analyze picket fence images by identifying MLC peaks and their error relative to each picket (Figure 17). In RadMachine, the

"MLC position" refers to the center of the full width half maximum (FWHM) of the peak formed by one MLC pair at one picket. The picket fence analysis yields the number of pickets detected, and by comparing each peak of a picket with the ideal picket, the error is determined (Figure 20). Performing the picket fence test while the gantry rotates is crucial for detecting any sagging of the leaves caused by gravity. RadMachine's picket fence analysis provides numerical results for MLC alignment.

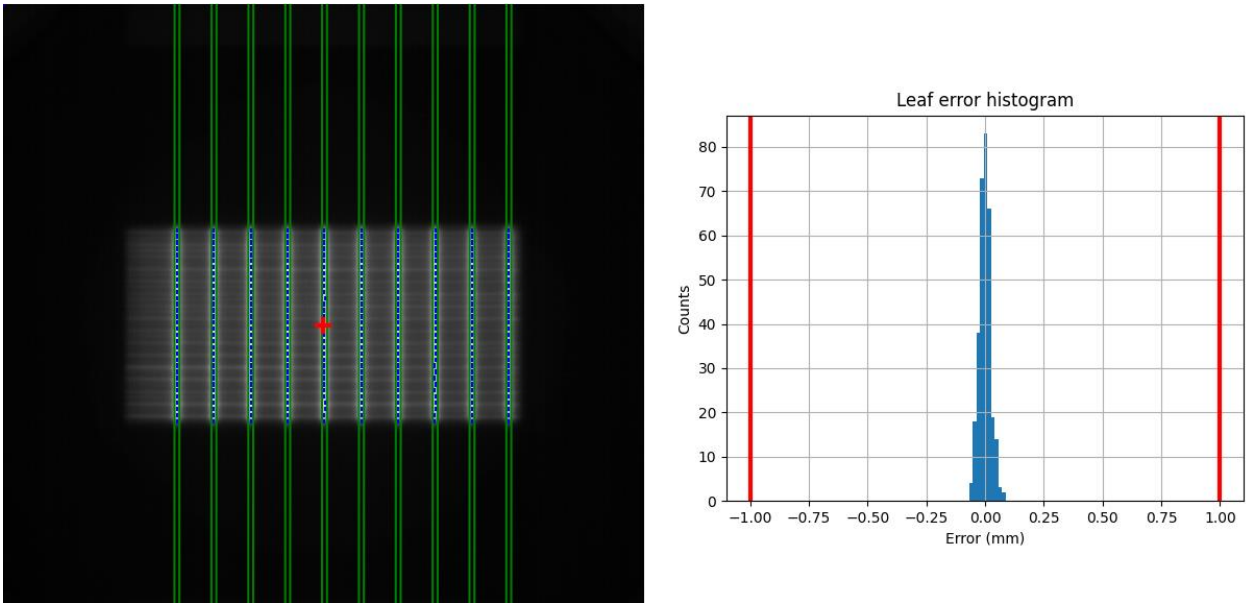


Figure 27. Picket Fence Analysis. RadMachine displays the results on the console and generates images showing the picket fence or MLC peaks with a color overlay (left), along with a plot of picket leaf error. MLC error is defined as the variance between the center of a measured picket and an ideal one

2.2.4 Beam Profile

A radiation beam profile is a crucial parameter for precise and consistent dose delivery. It represents the distribution of radiation intensity within the cross-section of a radiation beam[23].

Given that radiation beams are typically not perfectly uniform, their profiles can vary. Beam flatness refers to the maximum percentage variation from the average dose across the central 80% of the FWHM of the profile in the transverse plane of the beam[24]. Cross-beam profiles obtained for flatness are also utilized for symmetry assessment. Ideally, the dose should not differ by more than 2% at any pair of points symmetrically situated to the central ray. QA procedures are conducted to assess the beam profile, ensuring precise treatment delivery.

PRO employs the "Monthly Profile (Flatness/Symmetry)" test list to evaluate the unit's beam profile on a monthly basis. The SI IC-Profiler™ device is utilized to measure the beam and perform constancy checks of flatness and symmetry. Leveraging the IC-Profiler™ helps reduce workload time and ensures accurate reproduction of water tank profiles[25]. To measure beam profiles, we access service mode to deliver 100 monitor units (MU) using a 20 x 20 cm field size with 5 cm buildup for all photon energies. For electrons, a 25 x 25 cm cone applicator is employed, with no buildup for 6 MeV and 9 MeV, and a 1.5 cm buildup for 12 MeV and 16 MeV. The SI IC-Profiler™ software is used to measure and save the profiles as parameter files (.prm). Subsequently, these files are imported into a test list in RadMachine. RadMachine features a built-in profile analysis module for analyzing the profiles, including cross-plane, in-plane, and diagonal directions, providing flatness and symmetry results for each.

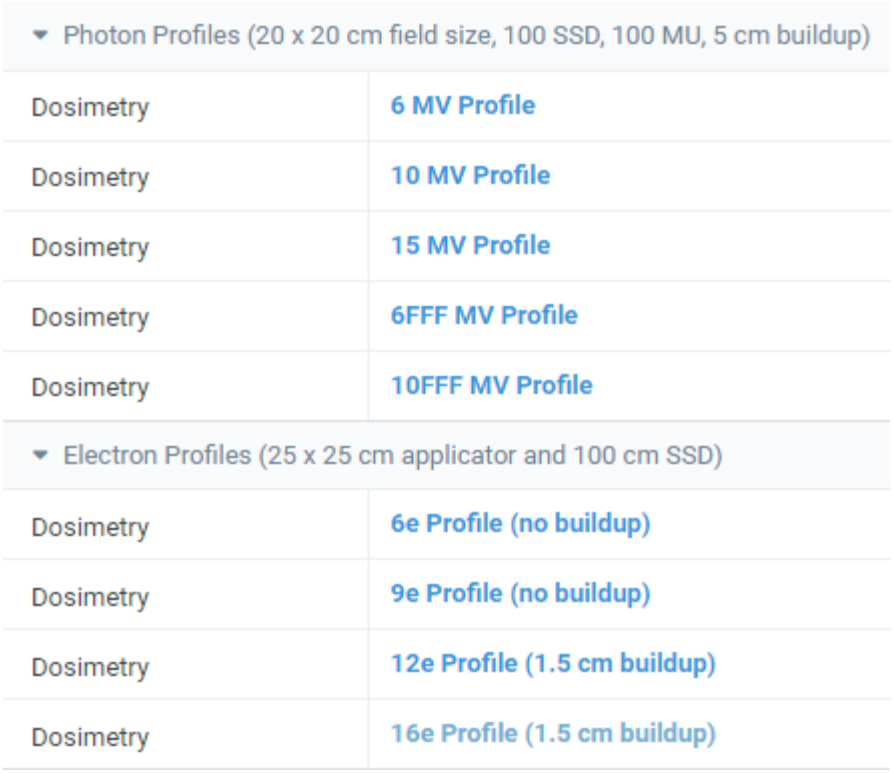


Figure 28. Monthly Profile (Flatness/Symmetry) Test List.

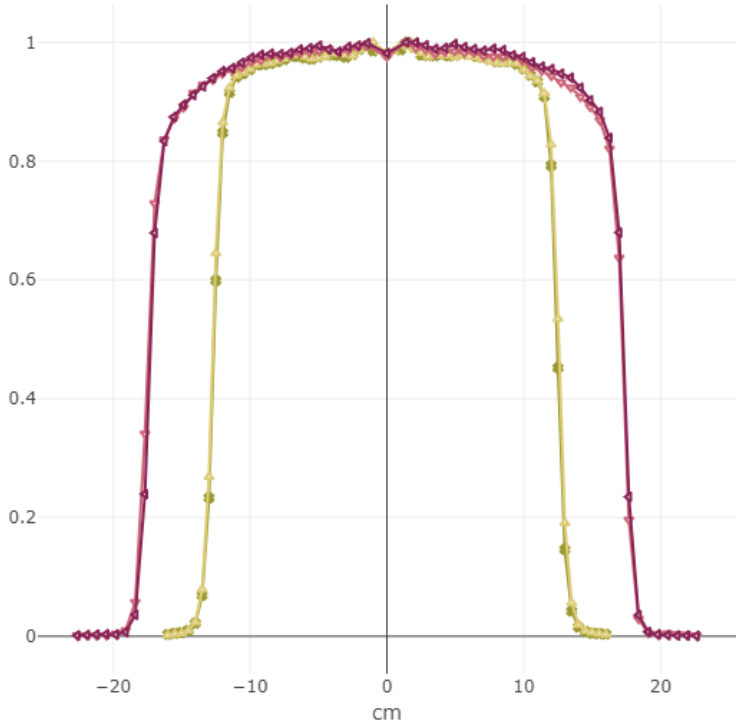


Figure 29. 6 MeV Beam Profile. Four planes are present: diagonal fields consist of triangles pointing downward in the northeast (NE) direction and triangles pointing leftward in the northwest (NW) direction, representing the outside profiles. Additionally, there are in-plane fields with triangles pointing upward and cross-plane fields with double triangles, symbolizing the inside profiles.

2.2.5 Mechanical

Mechanical inspections on the LINAC are conducted monthly to ensure operational integrity. The lasers and the optical distance indicator (ODI) are critical for accurate patient positioning, thus their precision is vital for optimal setup and treatment. Digital readouts for the gantry, collimator, and jaws undergo testing against mechanical readouts to confirm accuracy. Additionally, safety interlocks are examined, which include door interlocks designed to deactivate the beam when a door is opened, prevent the beam from activating when a door is open, and halt door closure if someone is obstructing the path. An audiovisual monitor maintains constant communication between the treatment vault and the treatment console, facilitating

immediate response in emergencies. The beam-on indicator function is also assessed to alert personnel to the use of X-rays. RadMachine's "Monthly Mechanical" test list documents these readings for review.

2.3 Implementation and Customization for Varian Edge Test List

RadMachine provides technical support to assist with product implementation. The RadMachine team converted the chief physicist's spreadsheets into the RadMachine format. For example, at PRO, the chief physicist previously used spreadsheets to record machine output (e.g., dosimetry). These spreadsheets were transformed into RadMachine tests. Initially, RadMachine provided a test list for one energy, specifically 6 MV. However, I had to create test lists for other energies. RadMachine's bulk test editing and duplication features streamlined this process.

Often, converting a spreadsheet into a test initially resulted in errors. Each test list was debugged until the calculated values were correct. The results in RadMachine were validated against the original spreadsheet results and the daily QA3 output.

I created test lists for monthly "Imaging," "MLC," and "Profile (Flatness/Symmetry)" tests by using pre-built tests that analyze supplied images or beam profile data. I duplicated and edited one profile analysis for each energy. RadMachine support successfully converted the monthly mechanical spreadsheet with minimal debugging required. References and tolerance values were also inputted for each test, allowing results to be flagged for physics review when out of tolerance.

Once the test lists were complete, I recorded all previous QA results into RadMachine. RadMachine now stores results dating back to August 2023, when PRO opened and began commissioning. However, not all data could be recorded, such as the MV monthly imaging

results, due to RadMachine's inability to differentiate between the phantom and the stand. Since completing the RadMachine test list, MV imaging has been recorded with a stack of notecards separating the phantom and the stand.

3 Varian BRAVOS

Brachytherapy is a treatment technique that employs a sealed radioactive source to deliver radiation at short distances through interstitial, intracavitary, or surface application[23]. At Personalized Radiation Oncology (PRO), brachytherapy is conducted using a high dose rate (HDR) source, defined as 20 cGy/min or higher[26]. This approach enables the delivery of high radiation doses locally with rapid dose fall-off, reducing the dose to surrounding healthy tissue.

The most commonly used HDR source is Iridium-192 (^{192}Ir), which is welded to a flexible drive cable known as the source wire. Radioactive sources ^{192}Ir has a half-life of 73.83 days, indicating the time required for either the activity (source strength) or the number of radioactive atoms to decay to half the initial value (e.g., 15 Ci)[23]. Regarding radiation therapy, these sources have a treatment lifetime, representing the duration during which the source is feasible for use in treatment. As the source strength diminishes over time, longer treatment times are required. To ensure efficient treatment, PRO replaces the ^{192}Ir source quarterly.

In HDR treatment, an afterloader is utilized to store and shield the source wire when not in use and to remotely administer treatment to the patient. This minimizes staff exposure and enables precise dose delivery. Afterloaders feature multiple channels connected to transfer tubes, which serve as guides between the afterloader and an applicator affixed to the patient. Dummy cables are employed to verify the clearance of the path from kinks or debris and to assess the overall length of the transfer tube and applicator assembly. This safety measure ensures that treatment is only administered when the path is clear. The advent of afterloaders has facilitated the use of HDR sources in treatment.

Personalized Radiation Oncology employs a Varian BRAVOS remote afterloader unit for HDR brachytherapy. An outstanding feature of the BRAVOS system is its capability to adjust

the lengths of the cables, including the source wire and dummy cable. Using the BRAVOS CamScale Device, the positions of the cable tips are verified at three predetermined positions: 90 cm, 120 cm, and 150 cm. This verification process, conducted with three cameras, entails recording and displaying images of the cable tips. It is performed after source exchanges and on the day of treatments.

3.1 Source Exchanges

Several quality assurance (QA) tests for an HDR afterloader require periodic measurements, typically conducted after a source exchange. The Nuclear Regulatory Commission (NRC) mandates that source positioning accuracy be within 1 mm, which is challenging to achieve across all radiation treatment applications[27]. For clinical purposes, afterloaders should achieve a positional accuracy of 2 mm source positioning, the dwell time of a source must be validated[5]. Dwell time refers to the duration the source remains stationary at a treatment position. Dwell time accuracy, or timer accuracy, is confirmed by using a stopwatch while delivering a fixed-time treatment. The variance between the recorded times should be less than the greater of 1 second or 1 percent of the planned time (Figure 30)

Additionally, the source strength of a new source should be measured following each source exchange[28]. The source manufacturer provides a reference date and time (point of creation) and air-kerma strength (μGy-m²/h), used to calculate the source strength in apparent activity (Ci). Medical physicists are tasked with verifying the source strength using a calibrated well-type ionization chamber and electrometer. Multiple readings are recorded at different dwell positions to determine the maximum current reading (nA). The measured air-kerma strength (S_k)

is calculated using the maximum reading, well chamber calibration factor (N_k), and correction factors for temperature, pressure (P_{TP}), and the electrometer (P_{Elec}) (Equation 6).

$$\text{Equation (6): } S_k = P_{TP} * P_{Elec} * N_k * \text{Reading (nA)}_{MAX}$$

At PRO, a RadMachine test list (PRO: HDR Source Exchanges) is utilized to record measurements and perform analysis after an HDR source exchange. This list includes the date of source manufacture, initial activity, and initial air-kerma strength factor for comparison with calculated values. Dwell positions where peak current (nA) occurs are determined during commissioning. Following a source exchange, 12 readings (nC) are taken to determine the maximum (Activity readings [nA]). This maximum reading is used to ascertain the air-kerma strength, with a tolerance of 3 percent compared to the manufacturer's specifications. Additionally, three treatment plans (5 seconds, 30 seconds, and 300 seconds treatment times) are measured using a stopwatch and recorded (Timer Test).

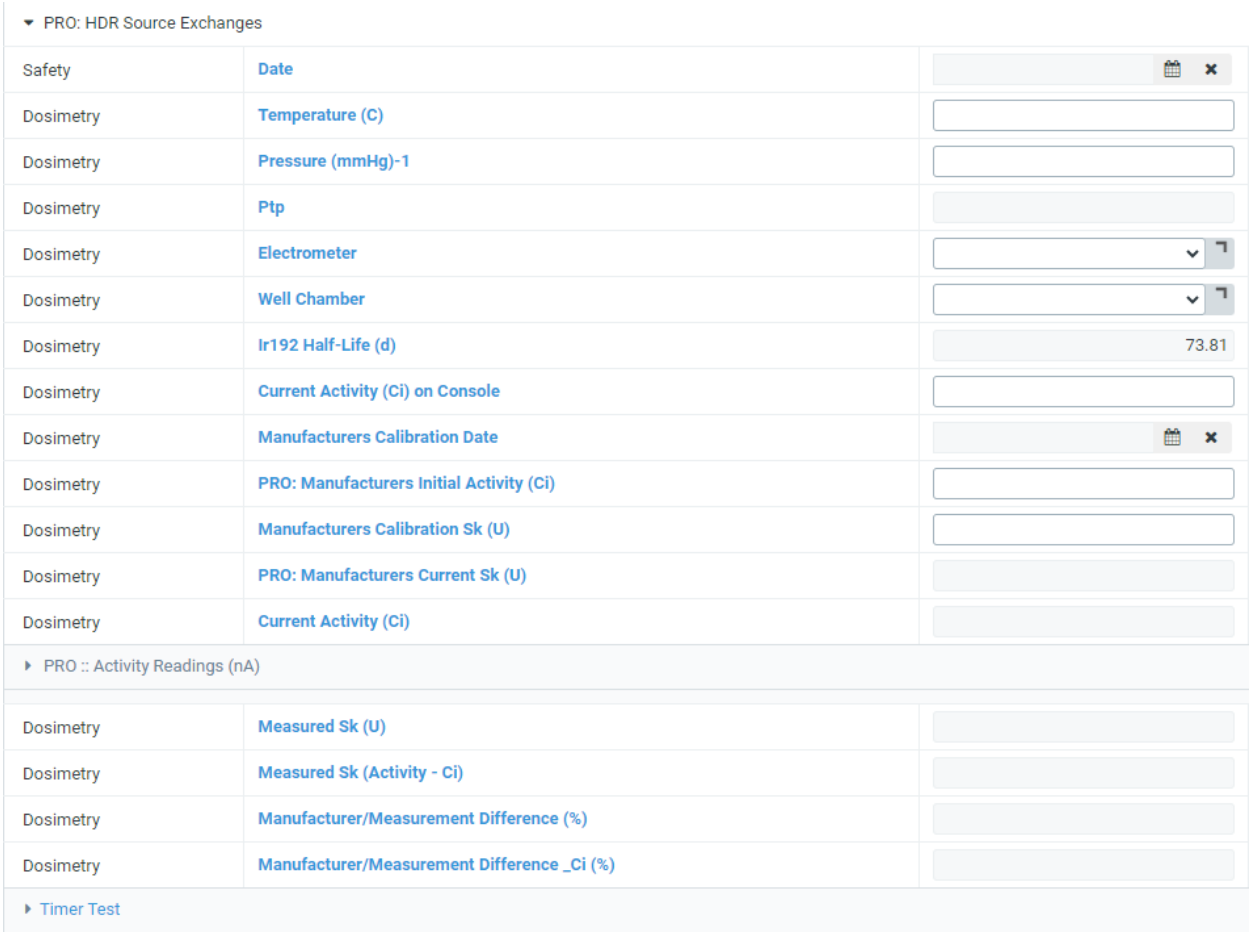


Figure 30. Source Exchange Test List. The information pertaining to the source's manufacture (such as the date of manufacture, air-kerma strength, and activity [Ci]) is documented and juxtaposed with the calculated air-kerma strength and activity. Twelve measurements at various dwell positions constitute the activity readings. Additionally, three timer tests are conducted and compared against the treatment plan durations (i.e., 5, 30, 300 seconds).

3.2 Daily or Day of Treatment Quality Assurance (QA)

Afterloader quality assurance (QA) is conducted regularly to ensure the ongoing functionality of both the afterloader and the treatment console[28]. First and foremost, this is crucial to uphold the safety of the patient, the public, and the facility, thereby preventing catastrophic events[5]. Guidelines provided by the Nuclear Regulatory Commission (NRC) in NRC Title 10, Parts 20 and 35 of the Code of Federal Regulations (10 CFR Part 20 and 10 CFR

Part 35) outline procedures for handling sealed sources, establishing exposure limits for the public and staff (Part 20), and managing inventory and radiation monitoring (e.g., exposure surveys).

QA procedures are executed on a daily basis following a source exchange or patient treatment to assess the functionality of the afterloader's safety features[29]. These features encompass door interlocks, emergency source retraction mechanisms, treatment interrupt buttons, and source out indicators (Figure 31). Additionally, the integrity of both the afterloader and the vault shielding is evaluated daily (Figure 32). Daily assessments are also made regarding source tip positioning and dwell time accuracy (Figure 33). Ensuring proper afterloader functionality is paramount for patient safety.

Safety	Door Interlock	○ No	○ Yes
Safety	Perform Door Stop Button Test	○ No	○ Yes
Safety	Perform Console Interrupt Test	○ No	○ Yes
Safety	Perform Afterloader Key Test	○ No	○ Yes
Safety	Perform Console Key Test	○ No	○ Yes
Safety	Perform Console Stop Test	○ No	○ Yes

Figure 31. Daily Afterloader Safety Interlock Checks.

Dosimetry	Afterloader Hot Spot Test (mR/h)	
Dosimetry	Survey @ door with source out (uR/h)	

Figure 32. Shielding Integrity Measurements.

Safety	Source timing (30 sec)	
Safety	Source positioning - 90 cm (cm)	
Safety	Source positioning - 120 cm (cm)	
Safety	Source positioning - 150 cm (cm)	

Figure 33. Dwell Time and Source Tip Positioning Accuracy Test.

The source strength or activity is pivotal for patient treatments. Ensuring the accuracy of the afterloader console display is crucial, as any miscalculations in treatment time can lead to mistreatment (Figure 34). RadMachine software is utilized to document and assess these measurements, facilitating the integration of previously inputted information. The radioactive source, ^{192}Ir, has a half-life used to calculate its activity on a given day relative to its manufacturing date. This calculated value is compared against the value reported on the console, with any discrepancy ideally being less than 3 percent.

PRO: TG-59 HDR Pre-Treatment QA

Safety	Date	
Dosimetry	Bravos Source Exchange Data	Results: 'PRO: HDR Source Exchanges'
Dosimetry	Console Reported Activity (Ci)	
Dosimetry	Time Difference (days)	
Dosimetry	PRO: Calculated Decay Activity (Ci)	
Dosimetry	PRO: Console activity vs decay calc (%)	

Figure 34. Daily Quality Assurance (QA) Activity Verification.

Applicators utilized for treatment must undergo testing to confirm their operational condition and structural integrity (Figure 35)[29]. Prior to each treatment, the appropriate applicator

is meticulously reviewed, ensuring availability and sterilization of both the applicator and its associated components. This step is crucial for minimizing patient wait time and discomfort before a procedure. Medical physicists also verify the lengths of transfer tubes and ensure they are free of kinks, as all components must function properly to ensure safe treatments.

While QA aims to minimize the likelihood of emergencies, it is essential to be prepared for any eventuality to safeguard both patients and staff (see Figure 35). Therefore, written emergency procedures should be readily accessible during treatments, along with emergency equipment. An emergency kit typically includes Kelly surgical clamps, long-handled forceps, and a container (e.g., lead-shielded pig) to safely contain the applicator if the source fails to retract. Inventory checks of emergency equipment are conducted daily during treatment. Furthermore, the afterloader is evaluated daily to confirm that the source retracts properly in the event of a power failure, with patient monitoring available for added safety measures.

Safety	Applicator components available and sterilized	○ No	○ Yes
Safety	Interstitial/Single-use applicator identity	○ No	○ Yes
Safety	Interstitial/Single-use applicator function	○ No	○ Yes
Safety	Interstitial/Single-use applicator completeness	○ No	○ Yes
Safety	Interstitial/Single-use applicator positional accuracy	○ No	○ Yes
Safety	Templates/custom devices function	○ No	○ Yes
Safety	Templates/custom devices identity	○ No	○ Yes
Safety	Operating room readiness	○ No	○ Yes
Safety	Afterloader backup battery functional	○ No	○ Yes
Safety	Source out indicator (console)	○ No	○ Yes
Safety	Independent radiation area monitor	○ No	○ Yes
Safety	A/V communication	○ No	○ Yes
Safety	Treatment Simulation	○ No	○ Yes
Safety	Emergency Kit present	○ No	○ Yes
Safety	Emergency Safe present (Pig)	○ No	○ Yes
Safety	Emergency instructions present	○ No	○ Yes
Safety	Survey Meter available	○ No	○ Yes

Figure 35. Applicator and Emergency Kit Check List. The specific treatment applicator undergoes evaluation on the day of treatment to ensure safety. The emergency kit and procedures are checked daily before treatment and remain readily available.

3.3 Implementation and Customization for Varian BRAVOS Test List

RadMachine support was initially utilized to create a test list for HDR QA recording. They provided a pre-built test list that reflected TG-59 recommended tests. However, several adjustments and additions were made by the physicist (i.e., myself).

The RadMachine-supplied test list calculated activity based on the date and time when data was inputted and submitted. This posed a problem when trying to backdate measurements, which was necessary because RadMachine was implemented after the first source installation. The solution was to create a test that required the date to be inputted. This allows the user to

input the day the QA was performed, enabling the determination of the decay-corrected activity at the time of the QA.

A debugging phase ensued to ensure the calculated decay-corrected activity was accurate. The activity was validated against the chief physicist's Excel worksheet. Additionally, RadMachine's pre-built test list did not provide the activity in units of Curies. Therefore, tests were created to display both decay-corrected activity and measured activity in Curies. Displaying activity in Curies is more appropriate because the BRAVOS treatment console shows the activity in Curies, providing a more consistent comparison.

RadMachine's supplied test list utilized a statistical method to find the maximum from several inputted measurements. However, to better replicate the source exchange Excel worksheet, several activity reading tests were created for inputting measurements. These results are used to create a chamber reading plot, which displays the maximum reading relative to the source location in centimeters.

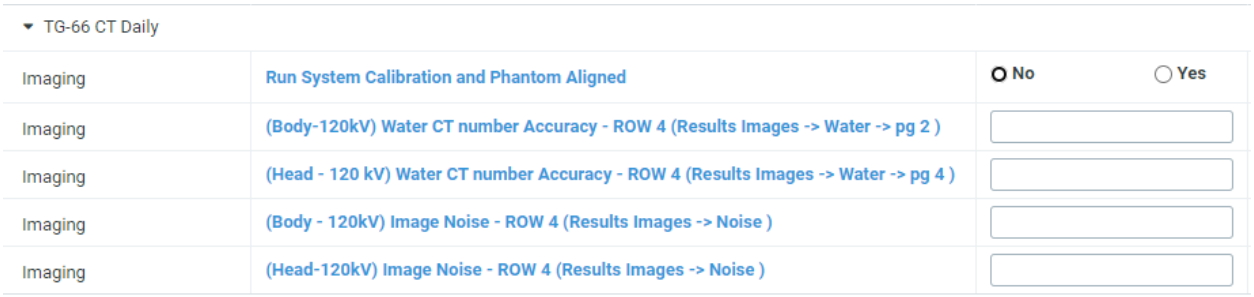
Additional tests were created to record the source timing for several different intervals, performed after a source exchange. To fully utilize the daily QA test list, a test was created to integrate the source exchange manufacturer data into the daily QA test list. This allowed the decay-corrected activity for that day to be calculated and compared to the console activity reading. Tests were also created to record the afterloader hot spot, the survey at the door with the source out, and source positioning measurements during daily QA. In addition, references and tolerance values had to be inputted for each test to flag physics to review the result. Previous information saved in the Excel sheets were inputted into RadMachine once the test list were finished.

4 Computed Tomography Simulation (CT sim)

Before treatment planning, patients undergo imaging using a computed tomography (CT) scanner to collect volumetric data. CT offers a significant advantage in obtaining electron density values (known as CT numbers) of tissues and generating digital reconstruction radiographs. CT simulation involves the integration of the CT scanner, patient positioning, marking system (such as lasers), and contouring (for structure outlining). A CT simulation generates a digital patient model for treatment planning and serves as the initial step in a patient's treatment plan. QA tests for CT simulation are crucial to ensuring the highest quality images and accurate geometric information. Personalized Radiation Oncology (PRO) utilizes a Siemens SOMATOM go.Open Pro CT scanner for CT simulations.

4.1 Daily Quality Assurance (QA)

Electromechanical components and image performance evaluation are conducted daily (Figure 36). The alignment of the gantry laser with the center of the imaging plane is assessed daily during the unit's warm-up before imaging the daily phantom. Additionally, the scanner's imaging functionality is assessed each day. The accuracy of the measured CT number of water is evaluated, as water should have a CT number of 0 Hounsfield Units (HU), with a daily measurement tolerance of within 5 HU. Imaging noise is also measured daily to assess the scanner's imaging performance. The software of the scanner's system automatically measures and analyzes both electromechanical and imaging performance. To maintain a record of the QA results, radiation therapists complete the RadMachine test list. The "TG-66 CT daily" test list is specifically assigned to PRO's CT scanner for image performance QA.



TG-66 CT Daily		
Imaging	Run System Calibration and Phantom Aligned	○ No ○ Yes
Imaging	(Body-120kV) Water CT number Accuracy - ROW 4 (Results Images -> Water -> pg 2)	
Imaging	(Head - 120 kV) Water CT number Accuracy - ROW 4 (Results Images -> Water -> pg 4)	
Imaging	(Body - 120kV) Image Noise - ROW 4 (Results Images -> Noise)	
Imaging	(Head-120kV) Image Noise - ROW 4 (Results Images -> Noise)	

Figure 36. Computed Tomography (CT) Simulation Daily Test. CT number and imaging noise values are recorded for the two main protocols: head and body at 120 kV.

4.2 Monthly Quality Assurance (QA)

Image artifacts can arise from equipment design, beam-hardening, or image reconstruction software, manifesting as variations in CT numbers (HU)[6]. To minimize these variations, it's crucial to quantify systematic changes. This quantification is achieved through the uniformity test. Monthly, the Catphan 604 phantom undergoes imaging to validate CT numbers for all materials within it and to assess field uniformity for the most common protocol (i.e., 120 kVp – body or head) (Figure 37). This straightforward test can uncover significant system errors.

The quality properties of CT sim images must be accurately assessed as treatment planning heavily relies on faithfully reproducing the patient[6]. Spatial integrity is verified monthly to detect potential dosimetry errors stemming from image distortions (Figure 38-39). HU values of density plugs are measured, and their uniformity across an image is plotted. Additionally, spatial resolution, or high contrast resolution, is measured monthly to evaluate the system's ability to distinguish between small objects in proximity (Figure 38-39). We calculate the 50% modulation transfer function (MTF) to quantify the spatial resolution capabilities of the imaging system. The ability to differentiate small anatomical details is crucial. Furthermore, the scanner should effectively differentiate large objects of similar density from the background. Contrast

resolution, or low contrast resolution, is assessed by measuring low-contrast objects of various sizes (Figure 38). A Catphan 604 phantom is employed to measure image quality characteristics for PRO's CT sim. The "TG-66 Monthly imaging evaluation" test list is assigned to PRO's Siemens SOMATOM go.Open Pro CT scanner. RadMachine analyzes the images and quantifies the imaging system's ability to accurately capture patient images for treatment.

▾ TG-66 Monthly Imaging Evaluation

Imaging	CatPhan 604 Analysis TG-66	
Imaging	CT Sim uniformity index	
Imaging	CT number uniformity, water (HU)	
Imaging	CT number Air (HU)	
Imaging	CT number PMP (HU)	
Imaging	CT number LDPE (HU)	
Imaging	CT number Poly (HU)	
Imaging	CT number Acrylic (HU)	
Imaging	CT number 20% Bone (HU)	
Imaging	CT number Delrin (HU)	
Imaging	CT number 50% Bone (HU)	
Imaging	CT number Teflon (HU)	
Imaging	Number of low-contrast ROIs detected	
Imaging	Low Contrast Visibility	
Imaging	Slice Thickness (mm)	
Imaging	CT In-plane spatial integrity (mm), Monthly	
Imaging	CT Spatial Resolution (lp/mm)	

Figure 37. Monthly Computed Tomography (CT) Simulator Quality Assurance (QA) Test List.

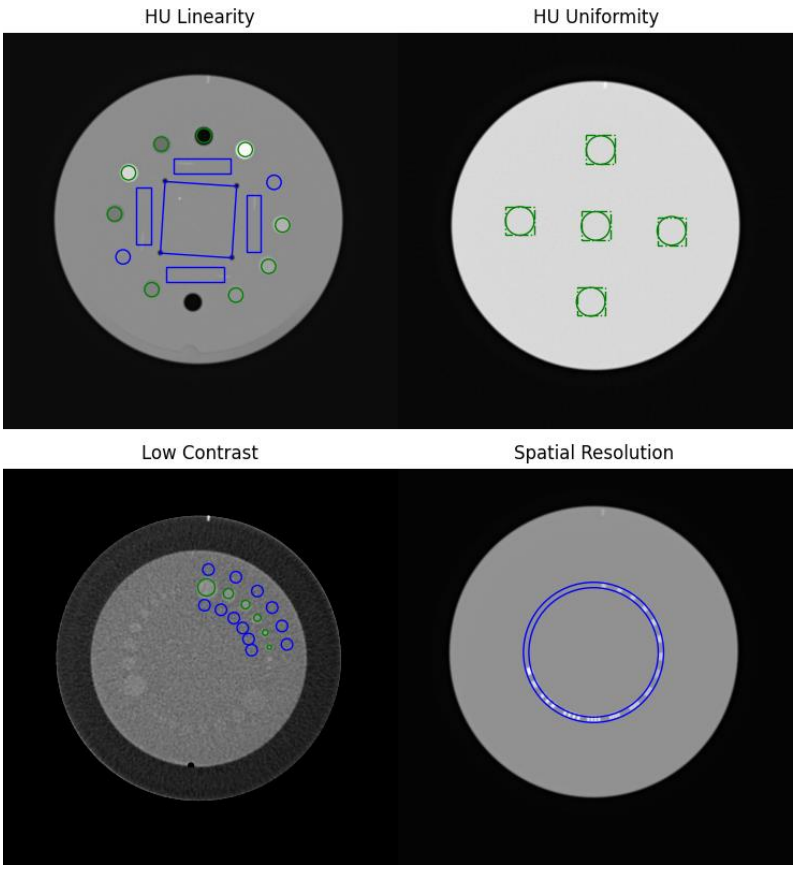


Figure 38. CatPhan 604 Analysis Task Group 66 Test List. Computed tomography (CT) imaging characteristics, including spatial resolution, contrast, Hounsfield unit (HU) constancy, and uniformity, are assessed on a monthly basis. These evaluations are conducted using an image quality phantom, specifically the CatPhan® 604 phantom. HU uniformity involves selecting regions of interest for analysis. HU linearity assesses slide width and constancy. Targets with varying diameters and contrasts are employed to evaluate low contrast, while bar patterns aid in quantitative modulation transfer function analysis for spatial resolution measurement.

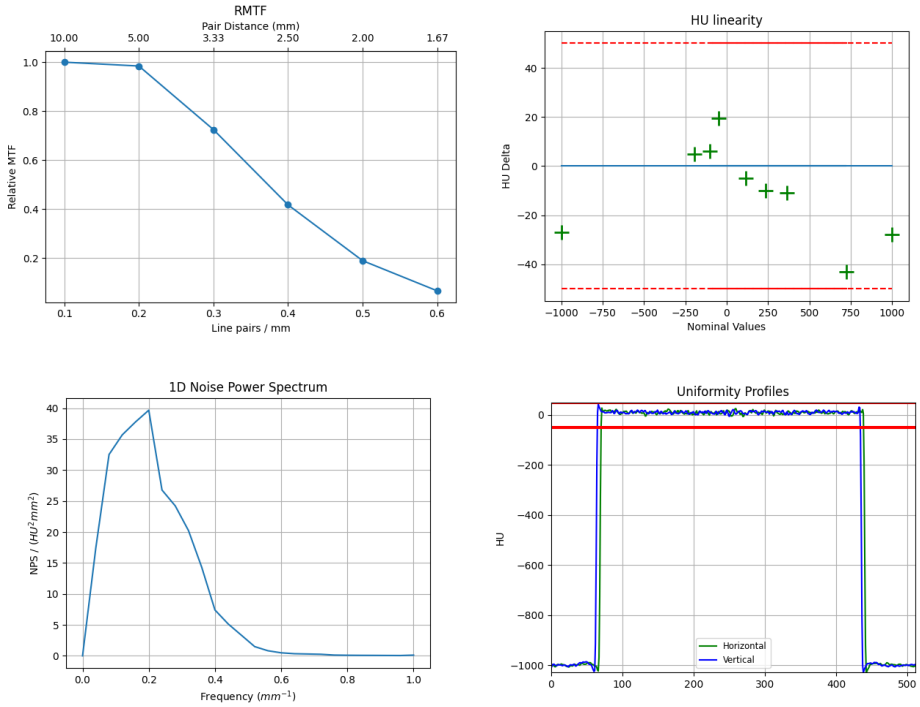


Figure 39. CT Sim Image Analysis Plots. The relative modulation transfer function (RMTF) assesses spatial resolution by analyzing various line pair sequences. Hounsfield units (HU) linearity is depicted through a plot showcasing the variance between the HU of the CatPhan 604 density plugs and the measured HU values. The noise power spectrum measures image noise across different pixel sizes. Uniformity profiles indicate the consistency of pixel intensities throughout the image.

4.3 Implementation and Customization for Siemens Scanner Test List

RadMachine does not currently offer imaging analysis for the supplied phantom used for daily QA. I created a test list to record results provided by the scanner after running the system warm-up and daily test. This setup allows physicists to track the consistency of water CT number accuracy and noise and document therapists completing daily QA.

RadMachine provides a pre-built test for the CatPhan 604 used in monthly QA. However, it does not directly provide CT numbers for different materials. To address this, I created additional tests, as shown in Figure 37, to track these results each month.

Once the test lists were debugged and finalized, the previously recorded images were inputted into RadMachine. However, only a few months' data could be analyzed by RadMachine because it requires the entire phantom to be scanned for the test analysis.

5 Ancillary Equipment/Hot Lab Quality Assurance (QA)

5.1 Ancillary Equipment

Ancillary equipment, or in RadMachine, an ancillary unit, is utilized for testing purposes. PRO's ancillary unit list comprises ion chambers, electrometers, a well counter, a dose calibrator, and a survey meter, each designated for specific test measurements. Similar to primary units, ancillary equipment also has assignments to monitor calibration dates (e.g., ion chambers and electrometers) or for hot lab QA.

Cylindrical ionization chambers (e.g., Farmer chambers) are recommended for radiation beam measurement. The charge generated within the chamber's cavity determines the dose delivered to a medium. An essential aspect of measuring dose with an ion chamber is determining the absorbed-dose to water calibration factor ($N_{D,w}$). This factor represents the absorbed dose measured at the chamber's point of measurement in the absence of the chamber[9]. In the US, the calibration factor is established at the National Institute of Standards and Technology (NIST) calibration laboratories under standard environmental conditions. Calibration, known as NIST traceable, requires ion chamber units to be calibrated every two years. PRO sends its equipment to an Accredited Dosimetry Calibration Laboratory (ADCL), a secondary laboratory with direct traceability to NIST, for calibration. Upon return, the calibration factor is provided, facilitating radiation beam measurements.

Well-type ionization chambers measure ^{192}Ir source strength utilized in HDR brachytherapy[3]. To determine the source strength, the air-kerma strength factor is essential[30]. This calibration factor, NIST traceable for the specific source used (e.g., ^{192}Ir), necessitates

calibration of the well-type ion chamber every two years. PRO employs micro ion and micro diode chambers, both NIST traceable, for small field dosimetry. These detectors improve spatial resolution and reduce volume averaging compared to large Farmer chambers[31]. Electrometers that measure small currents (e.g., 10^{-9} A or less), are used with detectors to measure the chamber's current or charge of a radiation beam or radioactive source. NIST traceable electrometers provide electrode correction factors upon return, converting readings to true coulombs[9]. Calibration of NIST traceable equipment expires every two years.

To manage calibration effectively, PRO utilizes a RadMachine test list titled "PRO Equipment Calibration" to track equipment calibration schedules (Figure 38). Assigned to each piece of equipment, this test list monitors shipments for calibration and stores calibration certificates and factors upon return. Due dates attached to the test list assignments serve as reminders for physicists when calibration is due.

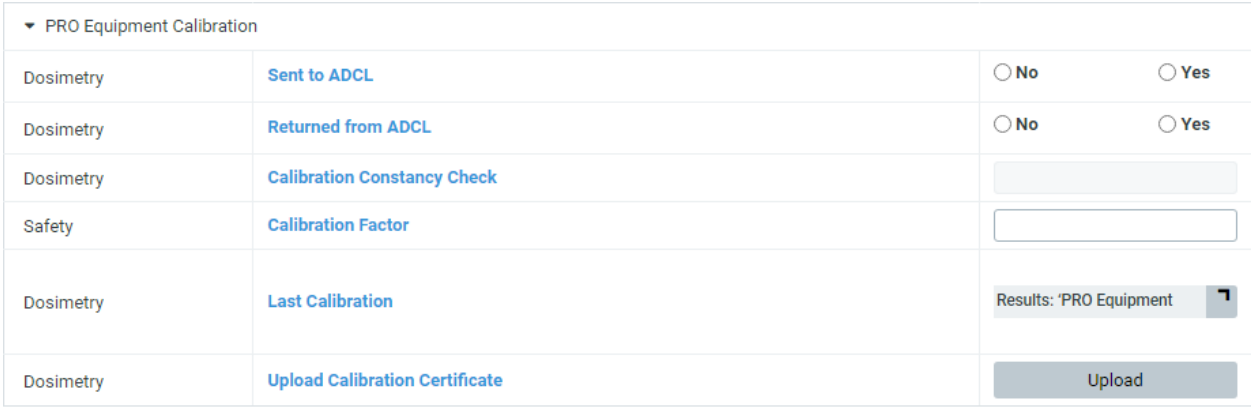


Figure 40. Equipment Calibration Test List. The test list is assigned to Personalized Radiation Oncology's (PRO's) ancillary units, reminding the physicist when equipment calibration expires, is sent, or returned from calibration. Additionally, it records the calibration factor for use in other tests and stores the calibration certificate as a backup. This test is designed to be due every two years, or biennially.

5.2 Hot Lab Quality Control (QC)

PRO administers treatment to patients using radiopharmaceuticals therapy (RPT), which deliver radioactive atoms to tumor-associated targets[32]. The radionuclide employed is Lutetium-177 (^{177}Lu). Prior to and following treatment, several measures must be undertaken to mitigate risks for patients, staff, and the public. One such measure involves surveys, conducted using a radiation survey meter to detect contamination during RPT procedures or to assess radiation exposure from sources. PRO utilizes a RaySafe 452 survey meter equipped with a Geiger-Mueller (GM) tube and solid-state diodes for this purpose. However, the sensitivity of the survey meter may not always suffice to detect radiation. Hence, wipe test-well counters are employed to detect low levels of radiation activity[33]. These counters measure radiation by analyzing wipes from surfaces or areas where RPT has been utilized. Additionally, it is crucial to measure the RPT both before and after treatment to accurately determine the administered activity. This is achieved using a radioisotope dose calibrator, which measures RPT activity (in mCi).

The RPT activity undergoes assay prior to clinical use, to ensure that patients receive the prescribed dose for achieving the desired therapeutic outcome[33]. While the Nuclear Regulatory Commission (NRC) allows dosage determination based on manufacturer-provided activity assay with decay correction, the National Council on Radiation Protection and Measurements (NCRP) recommends measuring all individual doses[34]. The recommended assayed dosage should fall within 5 percent of the prescribed dose, with NRC imposing a restriction that the activity remains within 20% of the prescribed dose[33,35]. PRO employs a radionuclide dose calibrator to measure RPT activity upon receipt of the shipment, with activity at treatment determined using the decay correction method. Post-infusion, residual activity in the vial and associated injection sets (i.e.,

tubing) is assayed. RPT measurement serves to assess the treatment quality, aiming for less residual activity or activity closer to the prescribed dose.

5.2.1 Radioisotope Dose Calibrator QA

Routine quality assurance (QA) tests are conducted on the dose calibrator to document any changes from the initial performance established during acceptance testing. PRO adheres to the recommendations outlined in TG-181 for dose calibrator QA[33]. Using RadMachine, a test list called "Radioisotope Dose Calibrator (R/PET/W) Daily Test" records the dose calibrator's performance (Figure 41). This test is conducted on the day when measurements are required (e.g., upon package receipt or treatment administration). It verifies the correctness of date and time readings, ensures the dose calibrator's operational status, tracks auto-zero, chamber voltage, and background levels. It also records the activity of a long half-life check source (Cesium-137 [^{137}Cs]), demonstrating the calibrator's consistency in response. Additionally, it determines the contamination of the liner by measuring the background with the isotope holder and comparing it to the background measurement without the holder.

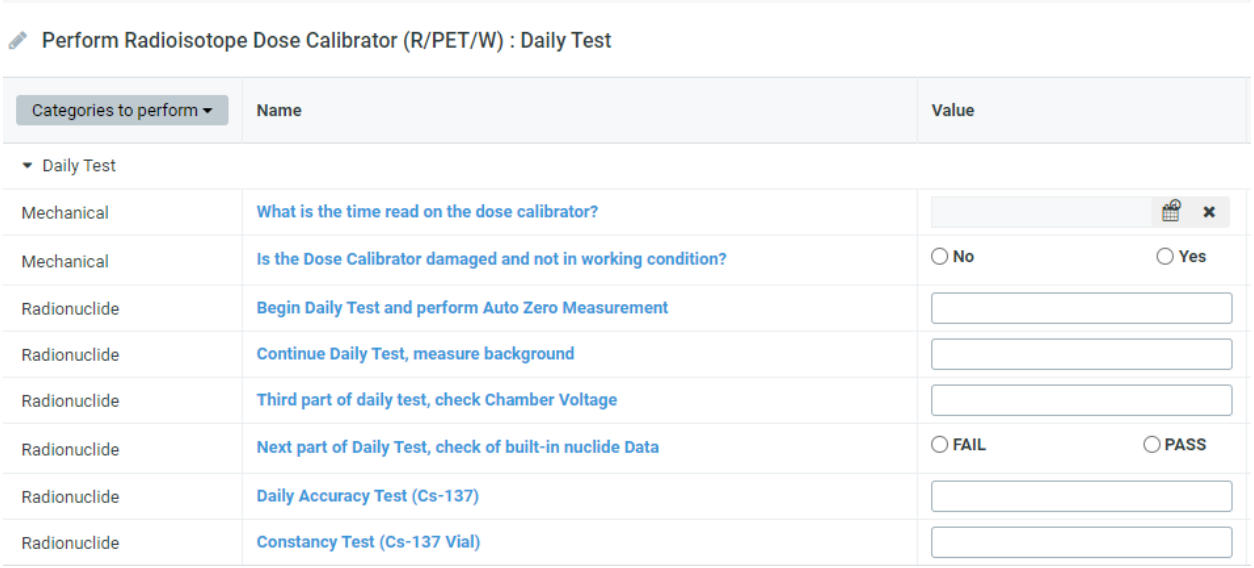


Figure 41. Dose Calibrator Daily Test List. The test list is utilized to monitor the stability of the system and aids a covering physicist who may not be familiar with dose calibrator routine quality assurance procedures.

The dose calibrator's performance is evaluated quarterly (Figure 42). A test list called "Dose Calibrator Performance Test" assesses its accuracy, reproducibility (i.e., precision), linearity, and system functionality (i.e., diagnostic test). Three test sources (Barium-133 [^{133}Ba], Cobalt-57 [^{57}Co], and ^{137}Cs) are utilized to determine the accuracy of measurements compared to the decay-corrected activity (Figure 43). Measurements should fall within 5% of the decay-corrected values. Ten measurements of ^{137}Cs are taken, and the mean is calculated. The dose calibrator is deemed precise if measurements are within 1% of the average activity. A diagnostic test scans the calibrator's internal memory to ensure proper software functionality.

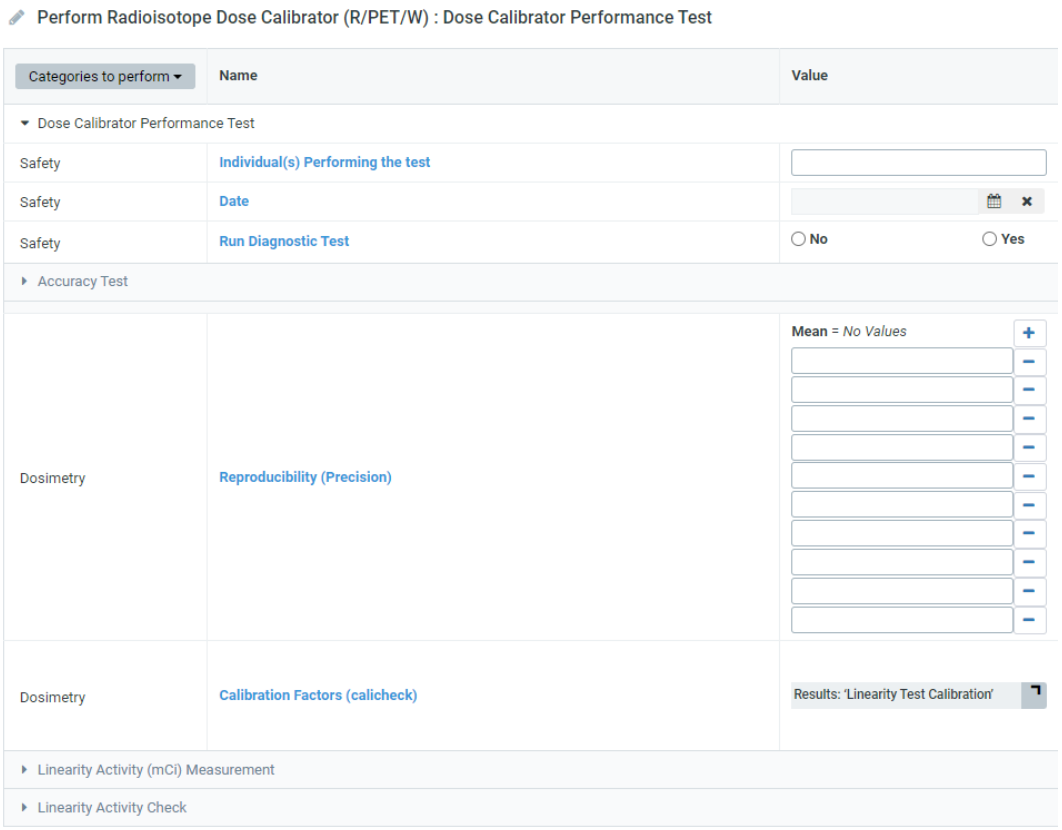
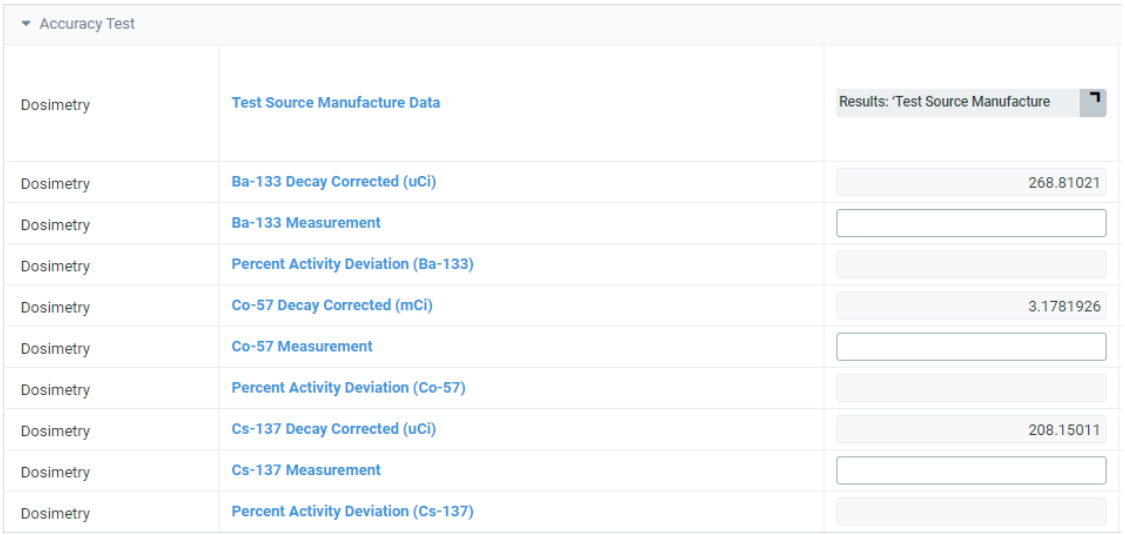


Figure 42. Dose Calibrator Performance Test. The test list is conducted quarterly. It commences with a system diagnostics scan to ensure proper functioning of the internal memory and functions. Subsequently, the accuracy of the measurements made by the dose calibrator is assessed. Precision is evaluated through ten measurements of a test source (Cesium-137), and the linearity of the dose calibrator is determined using the shielding method.



Accuracy Test

Dosimetry	Test Source Manufacture Data	Results: 'Test Source Manufacture
Dosimetry	Ba-133 Decay Corrected (uCi)	268.81021
Dosimetry	Ba-133 Measurement	
Dosimetry	Percent Activity Deviation (Ba-133)	
Dosimetry	Co-57 Decay Corrected (mCi)	3.1781926
Dosimetry	Co-57 Measurement	
Dosimetry	Percent Activity Deviation (Co-57)	
Dosimetry	Cs-137 Decay Corrected (uCi)	208.15011
Dosimetry	Cs-137 Measurement	
Dosimetry	Percent Activity Deviation (Cs-137)	

Figure 43. Accuracy Test for Three Test Sources (i.e., Barium-133, Cobalt-57, and Cesium-137). The test list "Test Source Manufacture Data" retrieves information about the test source from the vendor. This test includes the date of manufacture and initial activity, both of which are utilized in calculating the activity on a specific day using the decay corrected method. It employs the decay corrected method to ascertain the percentage deviation from the measured activity.

A calibrator is linear if the ratio of the measured response to predicted response is constant over a range of inputs. PRO evaluates a dose calibrator's linearity using the shield method (Figure 44). This involves placing color-coded tubes (Capintec CALICHECK) into the dose calibrator in a specific order and measuring the activity of ^{137}Cs for each tube sequentially while ensuring the previous tube(s) are shielded or removed from the chamber. The activity of each tube combination is recorded in RadMachine. Before use, the CALICHECK tubes are calibrated, and their calibration factors are stored in RadMachine as a test list named "Calibrator Factors (calicheck)," which are used in the "Dose Calibrator Performance Test" to evaluate the system's linearity. The product of shielded activities and calibration factors should all be within 5% of the same value[33].

Dosimetry	Calibration Factors (calicheck)	Results: 'Linearity Test Calibration'
▾ Linearity Activity (mCi) Measurement		
Dosimetry	Black Tube Activity (mCi)	
Dosimetry	Black & Red Tube Activity (mCi)	
Dosimetry	Black & Orange Tube Activity (mCi)	
Dosimetry	Black & Yellow Tube Activity (mCi)	
Dosimetry	Black & Green Tube Activity (mCi)	
Dosimetry	Black & Blue Tube Activity (mCi)	
Dosimetry	Black & Purple Tube Activity (mCi)	
Dosimetry	Black/Purple/Red Tube Activity (mCi)	
Dosimetry	Black/Purple/Orange Tube Activity (mCi)	
Dosimetry	Black/Purple/Yellow Tube Activity (mCi)	
Dosimetry	Black/Purple/Green Tube Activity (mCi)	
Dosimetry	Black/Purple/Blue Tube Activity (mCi)	
▸ Linearity Activity Check		

Figure 44. System Linearity Evaluation. The test list assesses the linearity of the dose calibrator by employing the shield method. Each color-coded tube combination is inserted into the dose calibrator's chamber, and the activity of Cesium-137 is recorded. The calibration factors of the tubes are imported into the test list and multiplied by the measured activity to determine the system's linearity.

5.2.2 Well Counter

The daily QA test for the well counter starts with an automated calibration using ^{137}Cs, and Europium-152 (^{152}Eu) rod sources for linearity correction. A checklist in RadMachine is utilized to document and track the completion of the test (Figure 45). Subsequently, the system measures the background radiation levels. A daily system test is conducted using the ^{137}Cs rod source. It calculates the deviation in activity between the measured and decay-corrected values. This deviation should not exceed 5%. These tests are conducted before any measurements related to the use of RPT.

Multiple measurements are taken on days when RPT treatments are administered (Figure 46-48). Area monitoring is mandated by federal regulations to ensure workplace safety[36]. Surveys involve evaluating radiological conditions and may include measurements using a survey instrument or wipe tests for contamination[37]. PRO measures ambient radiation in areas where RPT or patients undergoing RPT treatment are present. Areas surveyed with a RaySafe 452 survey meter include the infusion vault, bathroom, and hot lab area. These measurements are documented in RadMachine (Figure 46). Wipe tests for contamination are conducted in the infusion vault, bathroom, hot lab, and RPT transport cart (Figure 48). These tests aim to confirm that the previously used areas are free from contamination. Subsequently, the liner in the well counter is inspected for contamination after all measurements are recorded (Figure 47). Radiation monitoring is mandated by the NRC, and all records are available for regulatory review.

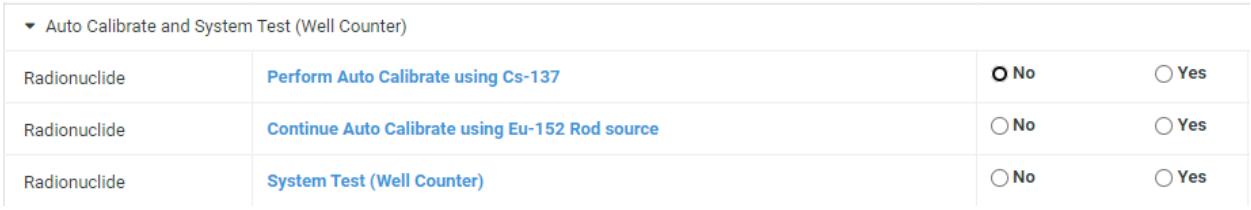


Figure 45. Daily Quality Assurance Check List for Well Counter. An auto-calibration and system test are performed on days when the well counter is used.

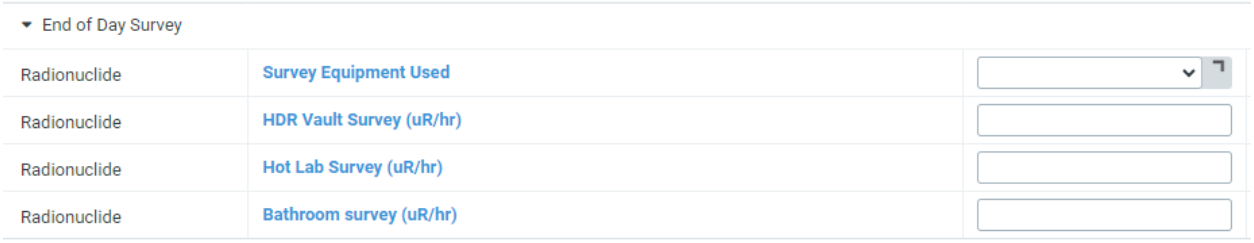


Figure 46. End of Day Ambient Radiation Survey. Radiation survey measurements are documented for the HDR vault (infusion vault), hot lab, and bathroom.

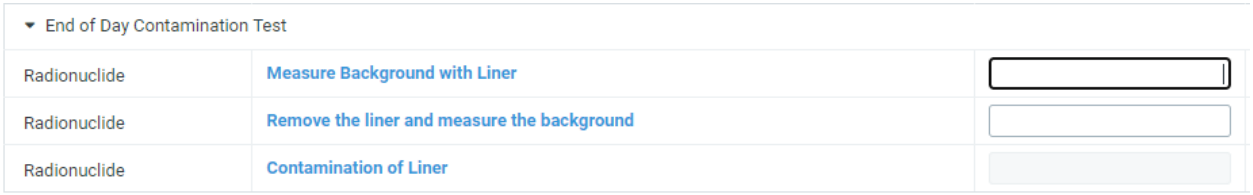


Figure 47. End of Day Contamination Test. Liner contamination is assessed at the end of each day following the well counter's use.

Figure 48. End of the Day Wipe Test. Wipe tests to detect low radiation contamination are conducted at the end of each day. Measurements are recorded for the HDR vault survey (i.e., infusion vault), hot lab, bathroom, and cart.

5.3 Implementation and Customization for Equipment and Hot Lab Test List

RadMachine support created the equipment calibration test list before I began integrating RadMachine. However, entering calibration factors and certificates was my responsibility.

RadMachine does not currently support RPT QA tests, so I created all the tests to record RPT QA results. The chief physicist keeps a written record of end-of-day wipe tests and surveys. After discussing with state inspectors, they showed interest in recording these results in RadMachine. They appreciated how organized the results were and how quickly they could review them.

I am responsible for inputting data into RadMachine. Creating tests for RPT QA highlighted a limitation of RadMachine. Python is used as its scripting environment; however, the tests created are limited to returning a single numerical value or a text string. There are situations where multiple values are preferred. For example, annually, the chi-square should be evaluated for the well counter. When performing a two-sided test, values from both the upper and lower tail critical values need to be compared. RadMachine cannot provide the probability range.

6 Future Applications

RadMachine is marketed for automating QA analysis for medical physicists, yet PRO has encountered setbacks that have hindered its full potential. These issues primarily stem from information technology (IT) and computer permissions. At present, physicists lack the administrative rights necessary to install software on their workstations, thus limiting their ability to fully utilize RadMachine's file automation capabilities. One initial complication arises with PRO’s monthly imaging tests using a test patient. RadMachine has the capability to query the ARIA database (i.e., Record and Verify system) for new images. "RadOrthanc" serves as the tool through which RadMachine communicates with DICOM PACS systems. Establishing a connection between RadOrthanc and ARIA involves installing RadOrthanc and configuring a connection using an AE Title, IP, and Port address. A similar process can be employed to link monthly QA CT sim images to RadMachine. Another challenge with RadMachine arises from PRO's status as a fully cloud-based site. Data files are stored in the cloud and cannot be accessed directly from local workstations without signing into the cloud. RadMachine utilizes a local agent stored on physicists' workstations to facilitate automation. Two types of files can be automatically uploaded into RadMachine: machine performance checks (MPC) and VMAT QA images, both saved to the Varian network folder. While MPC files can be reviewed offline, administrative permissions are required to install offline review software. This software allows data files from the MPC to be saved to a local folder accessible by RadMachine. VMAT QA images must be periodically copied to a locally accessible folder for RadMachine to collect. Although RadMachine streamlines the process of downloading files for analysis, its implementation in a fully cloud-based environment poses an IT challenge.

PRO is managed by Akumin. Akumin aims to implement RadMachine in all its clinics. PRO presented RadMachine to Akumin physicist in March 2024, which required RadMachine to be built and ready to showcase in two months. Akumin's next step is to install RadMachine local agent on a designated server. This should eliminate the complications of a local agent and cloud system communicating with each other, allowing each site to fully automate RadMachine as intended. However, there is no time table currently for the completion of a dedicated server for RadMachine.

The next step for PRO, utilizing RadMachine, involves initiating the tracking of service logs for the Varian Edge unit. Collaboration with service engineers will facilitate the tracking of machine maintenance and equipment inventory through RadMachine. Following service, engineers send reports to physicists. Yet, there is currently no established procedure for physicists regarding the maintenance of service records. RadMachine offers assistance in storing and tracking service hours. Additionally, a test list or QA test can be appended to service events. This details the procedures for specific tests to be conducted post-service and ensures the completion of required tests. Moreover, service engineers can manage inventory with RadMachine, saving time by readily identifying on-site parts for repairs.

The annual quality assurance test list still needs to be created. The chief physicist has a spreadsheet that will be used as a template. RadMachine suggested starting with daily QA and progressing to annual QA. However, I prefer to create the annual QA test list first. The reason for this preference is that many reference values are found during commissioning. PRO has not performed an annual QA yet, but an annual QA was essentially conducted before the machine was released for treatment. This data could have been inputted into RadMachine to serve as the

reference values for daily and monthly QA tests. Future users who have annual QA or commissioning results may want to create that test list first to provide values for other tests.

7 Conclusion

PRO implemented RadFormation's RadMachine, a cloud-based quality assurance (QA) data management application designed to streamline the entry, analysis, management, export, and monitoring of QA data for radiation therapy equipment. The primary aim is to replace physicist spreadsheets and standardize documentation practices. RadMachine enables physicists to set reminders for calibration and QA tests, generate charts, and share reports for collaborative review. Beyond physicists, therapists and service engineers also utilize the application. Therapists can complete their daily QA tasks in RadMachine, eliminating paper charts. Collaboration between service engineers and physicists facilitates tracking machine faults and equipment inventory for maintenance and repair. PRO requires therapists to complete daily QA tasks in RadMachine for physicist review. Physicists conduct monthly QA tests for the Varian Edge and Computed Tomography Simulation (CT sim) and record the results in RadMachine. Additionally, HDR Bravos QA tests are performed using RadMachine after source exchanges or on the day of treatment. RadMachine is also employed to record surveys for PRO's Radiopharmaceutical therapy program, offering a cloud-based data management system that is easily accessible and streamlined for regulatory review and covering physicists. The next step in implementing RadMachine is to fully utilize its automation capabilities. First, RadMachine must be integrated into the network server, allowing access from any workstation. This integration will enable QA image results to be imported into RadMachine automatically, without the need for physicists to manually insert the images. This automation will save valuable time, allowing physicists to focus on other essential duties.

References

1. Kutcher GJ, Coia L, Gillin M, et al. *Comprehensive QA for Radiation Oncology*. AAPM; 1994. doi:10.37206/45
2. Huq MS, Fraass BA, Dunscombe PB, et al. The report of Task Group 100 of the AAPM: Application of risk analysis methods to radiation therapy quality management. *Med Phys*. 2016;43(7):4209-4262. doi:10.1118/1.4947547
3. Svensson GK, Baily NA, Loevinger R, et al. *Physical Aspects of Quality Assurance in Radiation Therapy*. AAPM; 1984. doi:10.37206/12
4. Klein EE, Hanley J, Bayouth J, et al. Task Group 142 report: Quality assurance of medical acceleratorsa). *Med Phys*. 2009;36(9Part1):4197-4212. doi:10.1118/1.3190392
5. Nath R, Anderson LL, Meli JA, Olch AJ, Stitt JA, Williamson JF. Code of practice for brachytherapy physics: Report of the AAPM Radiation Therapy Committee Task Group No. 56. *Med Phys*. 1997;24(10):1557-1598. doi:10.1118/1.597966
6. Mutic S, Palta JR, Butker EK, et al. Quality assurance for computed-tomography simulators and the computed-tomography-simulation process: Report of the AAPM Radiation Therapy Committee Task Group No. 66. *Med Phys*. 2003;30(10):2762-2792. doi:10.1118/1.1609271
7. Siochi RA, Balter P, Bloch CD, et al. Report of Task Group 201 of the American Association of Physicists in Medicine: Quality management of external beam therapy data transfer. *Med Phys*. 2021;48(6). doi:10.1002/mp.14868
8. Hanley J, Dresser S, Simon W, et al. AAPM Task Group 198 Report: An implementation guide for TG 142 quality assurance of medical accelerators. *Med Phys*. 2021;48(10). doi:10.1002/mp.14992

9. Almond PR, Biggs PJ, Coursey BM, et al. AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams. *Med Phys*. 1999;26(9):1847-1870. doi:10.1118/1.598691
10. Binny D, Lancaster CM, Kairn T, Trapp JV, Crowe SB. Monitoring Daily QA 3 constancy for routine quality assurance on linear accelerators. *Phys Med*. 2016;32(11):1479-1487. doi:10.1016/j.ejmp.2016.10.021
11. Geary, Joseph. *Introduction to Lens Design With Practical ZEMAX Examples*. Willmann-Bell, Inc; 2002. https://img.optkt.cn/data/ueditor/php/upload/file/20200105/Introduction%20to%20Lens%20Design%20With%20Practical%20ZEMAX%20examples1578205135229846.pdf
12. Mahesh M. The Essential Physics of Medical Imaging, Third Edition. *Med Phys*. 2013;40(7):077301. doi:10.1118/1.4811156
13. Barrett HH. Foundations of Image Science. *J Electron Imaging*. 2005;14(2):029901. doi:10.1117/1.1905634
14. Gonzalez RC, Woods RE, Masters BR. Digital Image Processing, Third Edition. *J Biomed Opt*. 2009;14(2):029901. doi:10.1117/1.3115362
15. Ballrick JW, Palomo JM, Ruch E, Amberman BD, Hans MG. Image distortion and spatial resolution of a commercially available cone-beam computed tomography machine. *Am J Orthod Dentofacial Orthop*. 2008;134(4):573-582. doi:10.1016/j.ajodo.2007.11.025
16. Kerns JR. Pylinac: Image analysis for routine quality assurancein radiotherapy. *J Open Source Softw*. 2023;8(92):6001. doi:10.21105/joss.06001
17. Boyer A, Biggs P, Galvin J, et al. *Basic Applications of Multileaf Collimators*. AAPM; 2001. doi:10.37206/71

18. Keall PJ, Sawant A, Berbeco RI, et al. AAPM Task Group 264: The safe clinical implementation of MLC tracking in radiotherapy. *Med Phys*. 2021;48(5). doi:10.1002/mp.14625
19. Varian Medical Systems, Inc. Edge Radiosurgery System. https://protech-solutions.com.ua/assets/files/varian-edge.pdf
20. Xia P. LINAC and MLC QA for IMRT. Presented at: https://www.aapm.org/meetings/amos2/pdf/29-7911-53363-639.pdf
21. Ling CC, Zhang P, Archambault Y, Bocanek J, Tang G, LoSasso T. Commissioning and Quality Assurance of RapidArc Radiotherapy Delivery System. *Int J Radiat Oncol*. 2008;72(2):575-581. doi:10.1016/j.ijrobp.2008.05.060
22. RapidArc QA Test Procedures for TrueBeam.
23. Khan FM, Gibbons JP. *Khan's the Physics of Radiation Therapy*. Fifth edition. Lippincott Williams & Wilkins/Wolters Kluwer; 2014.
24. Nath R, Biggs PJ, Bova FJ, et al. AAPM code of practice for radiotherapy accelerators: Report of AAPM Radiation Therapy Task Group No. 45. *Med Phys*. 1994;21(7):1093-1121. doi:10.1118/1.597398
25. Simon TA, Kozelka J, Simon WE, Kahler D, Li J, Liu C. Characterization of a multi-axis ion chamber array. *Med Phys*. 2010;37(11):6101-6111. doi:10.1118/1.3505452
26. Meigooni A. ICRU Recommended Dose and Volume Specification for Reporting Interstitial Brachytherapy. Presented at: https://www.aapm.org/meetings/05SS/program/ICRU_Interstitial_Reporting.pdf

27. Tortorelli JP, Simion GP, Kozlowski SD. *A Compilation of Current Regulations, Standards and Guidelines in Remote Afterloading Brachytherapy*.; 1994:NUREG/CR--6276, EGG--2746, 10196713. doi:10.2172/10196713
28. Richardson SL, Buzurovic IM, Cohen GN, et al. AAPM medical physics practice guideline 13.a: HDR brachytherapy, part A. *J Appl Clin Med Phys*. 2023;24(3):e13829. doi:10.1002/acm2.13829
29. Kubo HD, Glasgow GP, Pethel TD, Thomadsen BR, Williamson JF. High dose-rate brachytherapy treatment delivery: Report of the AAPM Radiation Therapy Committee Task Group No. 59. *Med Phys*. 1998;25(4):375-403. doi:10.1118/1.598232
30. Rivard MJ, Coursey BM, DeWerd LA, et al. Update of AAPM Task Group No. 43 Report: A revised AAPM protocol for brachytherapy dose calculations. *Med Phys*. 2004;31(3):633-674. doi:10.1118/1.1646040
31. Das IJ, Francescon P, Moran JM, et al. Report of AAPM Task Group 155: Megavoltage photon beam dosimetry in small fields and non-equilibrium conditions. *Med Phys*. 2021;48(10). doi:10.1002/mp.15030
32. Sgouros G, Bodei L, McDevitt MR, Nedrow JR. Radiopharmaceutical therapy in cancer: clinical advances and challenges. *Nat Rev Drug Discov*. 2020;19(9):589-608. doi:10.1038/s41573-020-0073-9
33. Nickoloff E, Strauss K, Austin B, et al. *The Selection, Use, Calibration, and Quality Assurance of Radionuclide Calibrators Used in Nuclear Medicine*. AAPM; 2012. doi:10.37206/137

34. National Council on Radiation Protection and Measurements, ed. *Quality Assurance for Diagnostic Imaging Equipment: Recommendations of the National Council on Radiation Protection and Measurements*. The Council; 1988.
35. U.S. Nuclear Regulatory Commission. Title 10 Cofe of Federal Regulations. Part 35 - Medical use of byproduct material.
36. Jankovich J, LaFranzo M, Rogus R, Sepulveda L, Von Ahn K. NUREG-1556 Volume 3, Rev. 2 - Consolidated Guidance About Materials Licenses.
37. U.S. Nuclear Regulatory Commission. Title 10 Code of Federal Regulations. Part 20 - Standards for Protection Against Radiation.

Curriculum Vitae

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EDUCATION

University of Nevada, Las Vegas

- Professional Doctorate in Medical Physics August 2024
  - GPA: 3.2
  - Courses Completed: Accelerators in Nuclear Engineering, Advanced Health Physics, Bio-statistical Methods, Clinical Medical Physics, Dosimetry Aspects of Radiation Therapy Measurements/Outcomes in Rehabilitation, Radiation Protection, Radiation Safety and Quality Assurance, Radiation Risk Assessment, Radiation Therapy Physics: Brachytherapy, Radiation Therapy Physics: External Beam, Translational Research Design, Writing and Communication

- Master of Science Degree in Medical Physics Fall 2022
  - GPA: 3.4
  - Courses Completed: Advanced Health Physics, Advanced Radiation Biology, Applied Nuclear Physics, Biostatical Methods, Ethics of Medical Physicists, Health Physics Seminar, Measurements/Outcomes in Rehabilitation, Medical Imaging Physics, Radiation Detection, Radiation Dosimetry, Radiation Interactions, Radiation Oncology Physics Clinical Internship, Radiation Physics Instrumentation Lab, Radiation Risk Assessment, Radiation Therapy Physics, Sectional Anatomy, Therapy Physics Clinical Rotation and Lab, Translational Research Design

University of Nevada, Reno

- Bachelor of Science Degree in Physics Spring 2016
  - Minor in Mathematics
  - GPA: 3.0
  - Courses Completed: Astrophysics, Atmospheric Physics, Intro to Organismal Biology, Principles of Biological Investigation, Chemistry, Classical Mechanics, Intro to C++, Differential Equations, Electricity and Magnetism, Linear Algebra, Optics and Photonics, Social Psychology of Education, Theory of Relativity, Thermodynamics and Statistics, Quantum Mechanics and Applications

EXPERIENCE

Clinical Rotation – Personalized Radiation Oncology/Akumin Jan. 2024- Aug. 2024

- Adherence to Regulatory Compliance: stayed current on and complied with state and federal regulations and standards.
- Quality Assurance Management: Oversaw and upheld the quality of equipment and procedures. Gained Experience with Varian Edge LINAC, Varian Bravos Afterloader, Varian Eclipse, and Aria systems.
- Radiation Safety Implementation: Executed and ensured safety protocols for both patients and staff.
- Dosimetry Expertise: Measured and evaluated radiation doses for medical procedures. Worked with radiopharmaceuticals (Lu-177 Lutathera & Pluvicto) using a well counter and dose calibrator.
- Radiation Physics Mastery: Comprehended the principles and characteristics of radiation.

Clinical Rotation - Urology Nevada Aug. 2022- Dec. 2023

- Adherence to Regulatory Compliance: stayed current on and complied with state and federal regulations and standards.
- Quality Assurance Management: Oversaw and upheld the quality of equipment and procedures. Gained Experience with Varian TruBeam LINAC, Varian GammaMedplus Afterloader, Varian Eclipse, and Aria systems.
- Radiation Safety Implementation: Executed and ensured safety protocols for both patients and staff.
- Dosimetry Expertise: Measured and evaluated radiation doses for medical procedures. Worked with radiopharmaceuticals (Ra-223 Xofigo) using a well counter and dose calibrator.
- Radiation Physics Mastery: Comprehended the principles and characteristics of radiation.

Graduate Commons Assistant—UNLV Sept. 2018- Aug. 2022

- Greet and assist graduate/professional students checking into Graduate Commons.
- Make transactions and keep money deposits up to date.
- Enforce Graduate Common policies and report incidences if needed.
- Answer calls and take messages for the Graduate Commons manager.
- Ensure all stations and equipment are clean and sanitized.

Substitute Teacher/ Long Term Sub—CCSD Jan. 2017- Aug. 2022

- Create tests and lesson plans for courses.
- Track student progress and relay to their parents/guardians.
- Enforce school rules and work with administration.
- Explain new ideas and concepts to students ranging from pre-k to 12^{th} graders.

LEADERSHIP AND SERVICE

Graduate and Professional Student Association (GPSA) Fall 18'- Summer 22'

- GPSA Chief of Staff and Graduate Assistant (GA)
    - Assist President and Mentor/Manager with duties, such as but not limited to making agendas and minutes compliant, organize and file data, webpage building, lead awards committee.
- GPSA Council Member.
    - Representative for Health Physics and Diagnostic Sciences Graduate Students.
    - Serve on Intercollegiate Athletics Council.

Alpha Tau Omega (Leadership Development Fraternity) Fall 12' - Spring 16'

- Use leadership skills as the chapter's Historian.
- Help write for the chapter, highlighting the chapter's achievements.
- Aid in the organization of campus events to inspire community and promote diversity.
- Volunteer at community centers.
- Raise funds for organizations such as Three Square and Breast Cancer Research Foundation.