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Research Article

Quality Assurance for Image- Guided Radiation Therapy IGRT-QA

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A B S T R A C T

Image-Guided Radiation Therapy (IGRT) is a technique that utilizes imaging during each treatment session to enhance the precision and accuracy of radiation therapy. By guiding the delivery of radiation to the planned target volume, IGRT ensures that the intended dose is accurately administered while sparing surrounding healthy tissues. Quality Assurance (QA) for IGRT6 on a linear accelerator (linac) is crucial to verify that the system is functioning correctly and delivering the prescribed dose effectively. The American Association of Physicists in Medicine (AAPM) Task Group 179 (TG-179) recommends periodic QA9,10 to maintain the integrity of IGRT systems. Key components of IGRT QA for linacs include ensuring the alignment of the radiation beam with the target by verifying the accuracy of the gantry, collimator and couch movements. Assessing the quality of images used for guidance, such as those from kilovolt (kV) or megavolt (MV) cone-beam CT (CBCT), is essential for precise patient positioning. Customizing the QA process for individual patients, taking into account anatomical changes and setup errors, is also important. Regularly evaluating the performance of the IGRT system, including the calibration of imaging devices and the accuracy of dose delivery, ensures consistent performance. Additionally, ensuring that the IGRT system adheres to regulatory standards and safety guidelines is crucial for maintaining safety and compliance. By implementing a comprehensive QA program4, healthcare providers can ensure the consistent and reliable performance of IGRT systems, ultimately improving patient outcomes.

Keywords: Image-Guided Radiation Therapy (IGRT), Quality Assurance (QA), Linear Accelerator (Linac), Varian TrueBeam, Elekta Infinity, Isocenter Verification, Winston-Lutz Test, MC2 Varian Mobius Phantom, Catphan Phantom, Cone-Beam CT (CBCT), On-Board Imaging (OBI), Doselab Software, Geometric Accuracy, Image Quality, Patient-Specific QA, System Performance, Safety Interlocks, AAPM TG-179

1. Introduction

This paper outlines the IGRT QA protocol implemented at our institution for Linear Accelerators. Quality Assurance (QA) ensures the safe and efficient application of technologies. Common QA tests include Imaging System QAs such as kV 2D, MV EPID and kV CBCT, with the machine isocenter serving as the reference point.

Safety Checks: Daily safety checks are recommended to prevent collisions between imaging equipment and the couch or patient. Monthly IGRT QA encompasses image quality checks, scale checks orientation accuracy, uniformity, noise, high contrast spatial resolution and low contrast detectability. Annual QA checks include CT number accuracy and stability, imaging dose and imaging system performance (specifically kV system checks like kVp and mAs accuracy and stability).

2. Materials and Methods[7-9]

At our clinic, patient treatments are administered using two advanced linear accelerators: the Varian TrueBeam Linear Accelerator and the Elekta Infinity Linear Accelerator. To maintain precise and reliable image-guided radiation therapy (IGRT), we have established a comprehensive quality assurance (QA)[1] protocol that encompasses daily and monthly and annual checks, as well as safety interlock assessments.

2.1. Daily QA procedures

For daily machine performance evaluations, we utilize specialized phantoms for each linear accelerator. The Varian TrueBeam system is assessed using the Isocal Phantom, which ensures the accuracy and stability of imaging and treatment parameters. For the Elekta Infinity system, we employ the QUASAR™ Penta-Guide Phantom, which is specifically designed to evaluate the performance of Cone Beam Computed Tomography (CBCT) imaging systems. These daily checks help identify any deviations early and maintain consistent imaging quality and treatment accuracy.

2.2. Monthly QA Procedures

Our monthly QA procedures involve more detailed imaging quality assessments. For both megavoltage (MV) and kilovoltage (kV) imaging systems of the Varian TrueBeam and Elekta Infinity we use the MC2 Varian Mobius Phantom. This phantom facilitates thorough testing of imaging performance, including spatial resolution, contrast and geometric accuracy. To verify the CBCT image quality on both systems, we use the Catphan Phantom, which provides objective metrics for image quality such as uniformity, noise and low-contrast detectability.

2.3. Isocenter Verification

We perform the Winston Lutz test to ensure accurate isocenter alignment. This test uses a Cube Phantom containing a precisely positioned 2mm sphere at its centre, allowing for high-precision analysis of the congruence between the radiation isocenter, the mechanical isocenter and the imaging isocenter. Additionally, we use a marker block with a central fiducial and four internal discs to assess geometric accuracy and scaling, contributing to accurate patient positioning and dose delivery.

2.4. Collision checks and safety interlocks

Safety is a critical aspect of our IGRT protocols. We conduct collision checks to verify the functionality of safety interlocks in both kV and MV imaging systems. These interlocks are designed to automatically halt system operations if there is a risk of a collision between moving components, such as the gantry and the patient table. In particular, if a collision is detected between the kV/MV systems and the KVS arm pedal or device body, the motion of the arm, gantry, couch and On-Board Imager (OBI) console will be immediately stopped **(Figure 1)**. This safety mechanism is vital to protecting both patients and clinical staff by preventing accidental hardware collisions during imaging and treatment.

2.5. OBI check

On-Board Imaging (OBI) systems play a crucial role in modern radiation therapy by facilitating precise patient positioning and ensuring accurate treatment delivery. These systems integrate both kilovolt (kV) and megavolt (MV) imaging capabilities, allowing for high-resolution imaging and verification of treatment parameters before and during the therapy sessions. Maintaining the performance and accuracy of OBI systems is fundamental to achieving optimal clinical outcomes and enhancing patient safety.

Figure 1: KVD, KVS and MVD.

2.6. Isocenter verification procedure

The isocenter verification process is designed to confirm the precise alignment of the radiation beam with the target treatment area. This verification is critical for maintaining the congruence of the mechanical, radiation and imaging isocenters, thereby minimizing discrepancies that could affect treatment accuracy. The verification begins with the setup of a specialized cube phantom on the treatment couch. This phantom, featuring a 2mm sphere positioned at its center, is meticulously aligned with the laser or light field markers to establish a baseline for imaging accuracy. Ensuring this alignment is critical, as even minor misplacements can lead to significant deviations in treatment delivery. Following the setup, images are captured using both the kV and MV imaging systems at multiple gantry angles, specifically at 0, 90, 180 and 270 degrees. These varied perspectives provide a comprehensive assessment of the imaging system's alignment with the treatment beam and help identify potential discrepancies that could arise from mechanical or imaging system inaccuracies **(Figure 2)**. The acquired images are then subjected to detailed analysis. The goal is to verify that the 2mm sphere at the centre of the phantom appears in a consistent position across all images, regardless of the imaging modality or gantry angle. To achieve this, we utilize the Doselab QA analysing software (Varian Medical Systems), which offers robust image processing and comparison tools. The analysis is conducted with a stringent tolerance of ±1 mm, ensuring that only minimal and clinically acceptable variances are permitted. Any discrepancies beyond this threshold prompt a detailed investigation and necessary calibration of the imaging system.

2.7. Quality Assurance (QA) procedure for the marker block with fiducial and discs

In addition to isocenter verification, our clinic employs a QA procedure involving a marker block with a central fiducial and four internal discs. This test serves as an additional layer of validation for the geometric accuracy and scale of the imaging systems, which is critical for precise patient positioning and treatment targeting. The process begins by positioning the marker block on the treatment couch. Special attention is given to ensure that the fiducial is centrally located and the four discs are correctly oriented within the block. Proper positioning of the marker block is essential to establish a reliable reference point for imaging assessments. After setup, kV and MV images are captured to assess the alignment of the imaging system with the marker block. These images are carefully analyzed to identify any discrepancies between the expected and observed positions of the fiducial and discs. Consistency between the kV and MV images indicates accurate system calibration, while discrepancies could signal the need for further adjustments.

To test the imaging system's performance under dynamic conditions, a controlled table shift is performed. The treatment couch is moved to a known offset position and a new set of images is acquired. This step evaluates whether the fiducial and discs maintain their expected positions relative to the isocenter, even when the patient positioning changes. Such testing simulates real-world treatment scenarios where patient movement or positioning adjustments may occur. The next step involves quantifying any discrepancies between the expected and actual positions of the fiducial and discs. Precise measurements are taken to determine whether these differences fall within the acceptable tolerance, typically within 1mm (Refer to Fig. 3). If the discrepancies exceed this threshold, adjustments are made to the alignment of the imaging system or the treatment couch to restore accuracy.

Once adjustments are implemented, the verification process is repeated to confirm that the system is performing within the established QA criteria. This iterative approach ensures that any issues are fully resolved before the imaging system is cleared for clinical use.

2.8. Significance of QA for marker block with fiducial and discs

Maintaining a rigorous QA process for the marker block with fiducial and discs offers several critical benefits:

2.8.1. Accuracy: By ensuring the radiation beam is precisely targeted at the fiducial and discs, the QA process directly contributes to the accuracy of radiation delivery to the intended treatment area.

2.8.2. Consistency: The procedures help maintain consistent treatment delivery across multiple sessions, which is especially important for fractionated treatment plans where reproducibility is key.

2.8.3. Safety: The QA process minimizes the risk of unintended irradiation of healthy tissues surrounding the target area, enhancing overall patient safety. Through adherence to these detailed QA protocols, our clinic upholds the highest standards of accuracy, consistency and safety in radiation therapy treatments. This meticulous approach not only enhances treatment efficacy but also reinforces our commitment to patient care and safety.

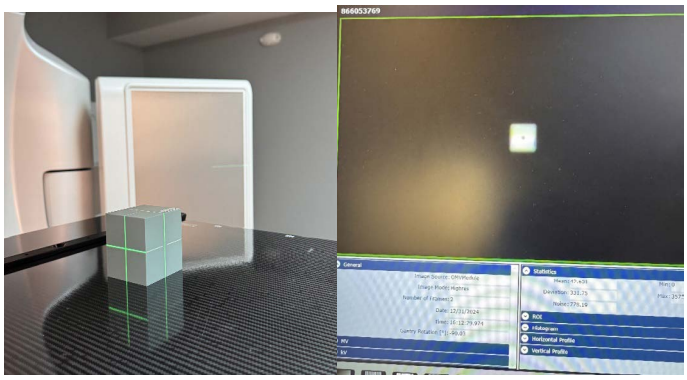


Figure 2: Cube phantom with 2mm sphere at the centre.

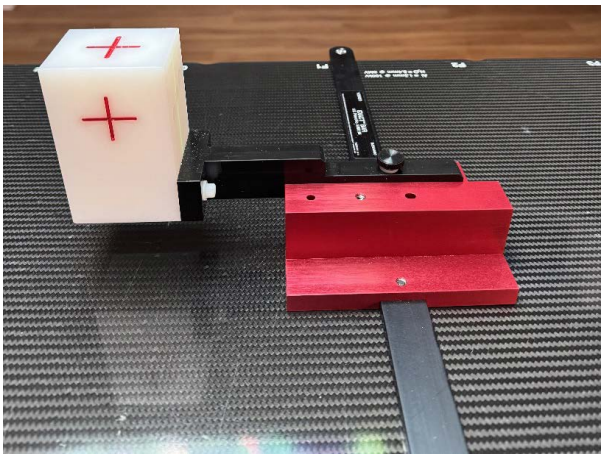


Figure 3: Marker block with 1 fiducial at the center and four discs inside the block.

2.9. Machine Performance Check (MPC)[2,3,9]

The Machine Performance Check (MPC) is a critical application developed by Varian to verify the mechanical and dosimetric performance of the TrueBeam Linear Accelerator. This integrated, image-based tool is a cornerstone of daily quality assurance (QA) practices, ensuring that the linear accelerator (linac) operates with optimal accuracy and reliability. Regular use of MPC not only supports high treatment precision but also enhances patient safety by identifying potential issues before clinical use.

The MPC process begins with the placement of the IsoCal phantom within the treatment room. This phantom is strategically positioned at a predefined location, serving as a reference object for various geometric and dosimetric evaluations. The IsoCal phantom is specifically designed to facilitate comprehensive system checks, including the verification of imaging alignment, radiation beam properties and mechanical accuracy of the linac components **(Figure 4a and Figure 4b)**.

Once the phantom is in place, the system initiates data acquisition by capturing a series of images with and without the IsoCal phantom at specific positions. These images include both kilovoltage (kV) and megavoltage (MV) modalities, providing a dual-perspective assessment that is crucial for performing accurate geometric and dosimetric checks. The use of both imaging modalities allows for cross-verification of measurements and enhances the robustness of the QA process.

2.10. Automated geometric checks

The MPC system performs a series of automated geometric checks that assess the mechanical accuracy and alignment of

critical components of the linac. The treatment isocenter, which represents the focal point where the radiation beams converge, is thoroughly evaluated to confirm its size and location relative to the imaging devices. Maintaining a precise treatment isocenter is essential for delivering radiation to the intended target area while avoiding healthy tissues.

The imaging isocenter coincidence check is another vital aspect of the geometric evaluation. This check ensures that the kV and MV imaging systems are accurately aligned with each other. Misalignment between these imaging systems could lead to discrepancies in patient positioning and impact treatment accuracy.

In addition to isocenter evaluations, the MPC system verifies the collimator rotation offset to ensure the accuracy of the collimator's rotational movements. The collimator shapes the radiation beam and any deviation in its rotation could affect the treatment field's geometry. Similarly, gantry positioning is assessed to verify that the gantry moves to the correct angles during treatment delivery.

The treatment couch, which can move in up to six degrees of freedom, undergoes checks to confirm its positioning accuracy. These checks are crucial for patient positioning, especially when complex treatment plans require precise couch adjustments. The Multi-Leaf Collimator (MLC) leaf positions are also evaluated for accuracy and reproducibility, as the MLC is responsible for modulating the radiation beam shape according to the treatment plan. The jaw positioning, which further defines the treatment field, is checked to ensure it meets the expected parameters.

2.11. Automated dosimetric checks

In addition to geometric evaluations, MPC conducts automated dosimetric checks that focus on the consistency and stability of the radiation beam. One of the primary checks involves measuring the beam output constancy. This test assesses whether the radiation dose delivered by the linac remains consistent over time, which is crucial for achieving the prescribed treatment dose.

The beam profile constancy is also evaluated to ensure that the radiation intensity is uniform across the treatment field. Any changes in the beam profile could affect dose distribution and potentially lead to under- or over-treatment of certain areas. The beam centre shift check verifies whether there are any shifts in the central axis of the radiation beam, which could affect the alignment with the target area.

2.12. Analysis and reporting

After completing the automated checks, the MPC system performs an analysis of the acquired images and data. This automated analysis compares the measured geometric and dosimetric parameters against predefined tolerances set by clinical protocols and manufacturer specifications. By automating this process, MPC minimizes the risk of human error and enhances the efficiency of the QA process.

The system generates a detailed report that summarizes the results of all checks performed during the MPC procedure. This report includes quantitative measurements, graphical representations of image analyses and indications of whether the parameters meet the acceptable limits. The report serves as a critical document for clinical record-keeping and for identifying any trends in system performance that may require attention.

2.13. Review and corrective actions

Once the report is generated, it is reviewed by a qualified medical physicist or a member of the QA team. This review process involves assessing whether all measured parameters fall within the established tolerance limits. If the results are within acceptable ranges, the linac is cleared for clinical use.

However, if any parameters are found to be out of tolerance, immediate corrective actions are implemented. These actions may include recalibrating the imaging system, adjusting mechanical components or performing additional tests to isolate the cause of the discrepancy. The goal of these corrective measures is to restore the linac's performance to optimal levels before it is used for patient treatments.

The MPC procedure is designed to be highly automated, which not only reduces the need for manual intervention but also enhances the consistency and repeatability of the QA process. By automating data acquisition, analysis and reporting, MPC ensures that the linac's performance is thoroughly evaluated on a daily basis with minimal variability in the QA outcomes.

Figure 4: a) Isocal Phantom b) MPC SET UP

2.14. Digital measurement accuracy for On-Board Imaging (OBI)

To verify the digital measurement accuracy of the On-Board Imaging (OBI) system, an additional procedure involving the blade calibration tool is conducted. The blade calibration tool is placed precisely at the isocenter of the treatment field, providing a reference for evaluating the digital measurement accuracy of the OBI system.

A kV image is acquired with the calibration tool in place. The image is then analysed using the measuring tools integrated into the OBI system. Specifically, the superior/inferior (S/I) and right/left (R/L) dimensions of a 10 cm x 10 cm square are measured. The expected measurement value is 10 ± 0.1 cm, providing a stringent criterion for digital measurement accuracy **(Figure 5)**.

By adhering to this procedure, the accuracy of the digital measurements taken by the OBI system is validated, supporting high-precision imaging and treatment delivery. This step is particularly important for maintaining spatial accuracy in patient positioning and ensuring that the treatment plan is executed as intended.

Through the comprehensive execution of the MPC and digital measurement accuracy procedures, our clinic maintains a robust QA framework that underpins the safety, accuracy and reliability of our radiation therapy services. These practices reinforce our commitment to delivering high-quality care and achieving optimal treatment outcomes for our patients.

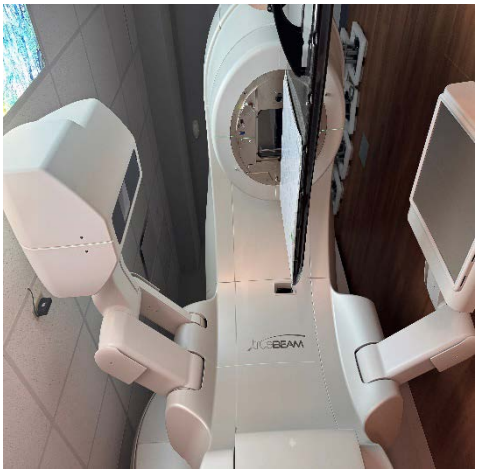


Figure 5: Digital Measurement Accuracy for OBI.

2.15. Mechanical position QA: KVD and KVS

The Mechanical Position Quality Assurance (QA) process for kilovolt detectors (KVD) and kilovolt sources (KVS) is an essential step in maintaining the precision of imaging systems used in radiation therapy. One of the critical components of this process is the mechanical centre check, which ensures that the imaging components are accurately aligned with the treatment isocentre.

To conduct the mechanical centre check, the gantry is first rotated to a 90-degree position at the coordinates (0,0,100). This specific positioning allows for precise measurement of distances relative to the isocenter. The QA procedure involves measuring the distance between the isocenter and the surface of the KVS, as well as the distance between the isocenter and the grid surface. These measurements are vital for verifying the alignment of the imaging components with the treatment beam. Maintaining a tolerance of ±2 mm for these measurements is crucial, as even small deviations can lead to inaccuracies in patient positioning and treatment delivery.

By routinely performing this mechanical center check, our clinic ensures that the KVD and KVS systems remain within acceptable operational parameters, thereby contributing to the overall accuracy and safety of radiation therapy treatments.

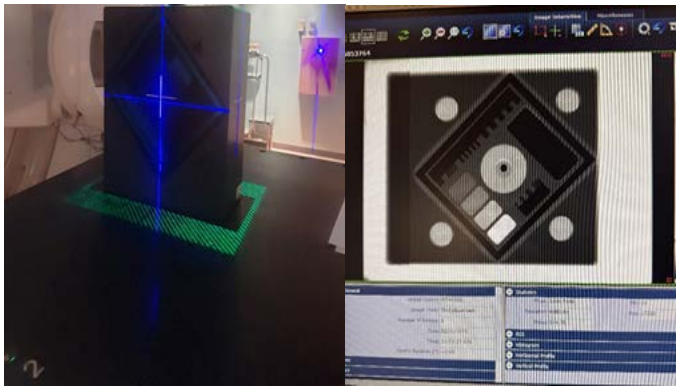
2.16. Image quality QA

Image quality assurance (QA) is a systematic process designed to ensure that imaging systems consistently produce high-quality images. This process involves regular data recording, analysis and evaluation to monitor image quality over time. By implementing a structured QA program, our clinic can identify potential issues early and make data-driven decisions to enhance image quality, which is critical for accurate diagnosis and treatment planning.

One of the primary tools used in our image quality QA process is the MC2 Varian Mobius Phantom. This phantom is specifically designed for both megavoltage (MV) and kilovoltage (kV) imaging QA, allowing for a streamlined approach to testing. During the QA process, the MC2 phantom is positioned within the imaging system according to established protocols **(Figure 6a)**. Since the phantom is compatible with both MV and kV imaging, only a single setup is required, which improves efficiency and reduces setup variability.

The imaging procedures involve capturing images with both MV and kV modalities. The MC2 phantom contains various test objects that assess critical image quality parameters, including resolution, contrast, noise, uniformity and image scaling. These parameters are indicative of the imaging system's ability to produce clear and accurate images under clinical conditions.

Once the imaging is completed, the acquired images are analysed using Dose Lab TG-142 software. This software is designed to automate the analysis process by comparing the imaging metrics against the TG-142 guidelines. It provides quantitative assessments of resolution, contrast, noise levels, image uniformity and scaling accuracy **(Figure 6b and 6c)**. The automated nature of the software minimizes human error and ensures a consistent evaluation of the imaging system's performance.



a) MC2 Varian Mobius Phantom b) KV Image

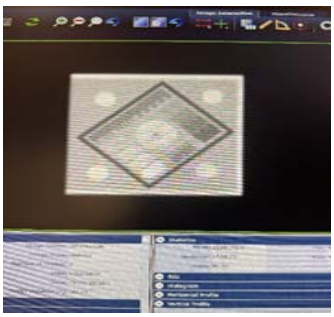


Figure 6: c) MV Image

3. CBCT Image Quality: Catphan CTP 604 Phantom

In addition to the MC2 Varian Mobius Phantom, Catphan phantoms are employed for cone-beam computed tomography (CBCT) imaging quality assurance. These phantoms are critical for evaluating CBCT systems' performance across a range of parameters, including uniformity, contrast, contrast-to-noise ratio (CNR), spatial resolution, slice thickness and geometric distortion.

The process begins by accurately positioning the Catphan phantom on the treatment couch following the manufacturer's guidelines. Two CBCT scans are performed as part of the QA protocol: a head scan at 100 kVp and 20 mA and a pelvis scan at 125 kVp and 80 mA. Both scans use a source-to-image distance (SID) of 150 cm, a reconstruction matrix of 512 x 512 and a slice thickness of 2.0 mm. These specific settings replicate clinical conditions and provide a thorough assessment of the imaging system's capabilities.

The images generated from these scans are then analyzed using Doselab Software **(Figure 7)**. The software evaluates uniformity across the entire field of view, which is critical for consistent image quality. It also measures the contrast resolution

to determine the system's ability to differentiate between varying tissue densities. The contrast-to-noise ratio (CNR) is assessed to gauge image clarity, balancing contrast with the inherent noise of the imaging system.

Spatial resolution tests are conducted to verify the system's ability to detect small anatomical details, which is crucial for identifying subtle changes in tissue. Slice thickness accuracy is measured to ensure that the z-axis representation of scanned objects is true to life. Finally, geometric distortion checks are performed to identify and correct any discrepancies in the image that might arise from system inaccuracies.

Figure 7: Catphan CTP604.

3.1. Image quality (EPID) for treatment verification[2,5,9]

Electronic Portal Imaging Devices (EPIDs) play a vital role in radiation therapy by providing real-time imaging to verify patient positioning and monitor treatment delivery. These devices use MV imaging, which offers the advantage of capturing images directly with the treatment beam, thereby aligning the treatment verification process with the therapeutic dose delivery.

To ensure high image quality with EPIDs, our clinic utilizes both the MC2 Varian Mobius Phantom and the Las Vegas Phantom **(Figure 8)**. The Las Vegas Phantom, in particular, is instrumental in evaluating the geometric accuracy and contrast resolution of MV images.

The QA process involves setting up the Las Vegas Phantom at the top of the MV detector (MVD). The phantom is carefully positioned to ensure it is entirely within the field of view of the imaging system. Planar MV images of the phantom are then acquired using the EPID. These images are analysed to assess geometric accuracy by examining the spatial arrangement of the holes in the phantom. Accurate positioning of these holes in the images indicates that the EPID is correctly aligned with the treatment isocentre.

In addition to geometric checks, contrast resolution is evaluated by analysing the visibility of holes with varying diameters and depths. This assessment helps determine the EPID's ability to differentiate between subtle contrasts in the imaging field. The results of the contrast resolution analysis are compared to the manufacturer's specified values for each energy level to ensure compliance with clinical standards.

By maintaining rigorous image quality QA protocols for both CBCT and EPID systems, our clinic ensures that all imaging modalities used in radiation therapy meet the highest standards of accuracy and reliability. This approach is integral to achieving precise patient positioning, effective treatment planning and safe delivery of therapeutic doses.

Through these meticulous QA processes, our clinic upholds a commitment to delivering high-quality care while minimizing risks associated with imaging and treatment delivery in radiation therapy.

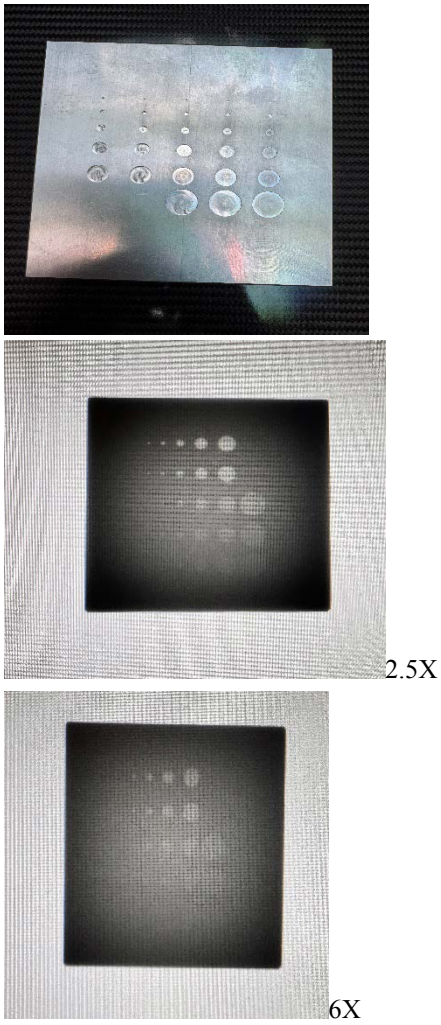


Figure 8: Las Vegas Phantom and MV Images for different Energies.

4. Results and Discussion

The comprehensive Quality Assurance (QA) analysis was conducted using DoseLab QA analyzing software, focusing on a range of imaging and mechanical performance parameters of our radiation therapy systems. By systematically evaluating these metrics, we aimed to ensure that all imaging systems, including On-Board Imaging (OBI), Cone-Beam Computed Tomography (CBCT) and Electronic Portal Imaging Devices (EPIDs), meet stringent clinical standards.

4.1. Winston-lutz test results

The Winston-Lutz test, a critical procedure for verifying the isocentric accuracy of the treatment machines, was conducted using the Varian cube phantom. This test involved acquiring images at various gantry, collimator and couch angles to assess the precision of the radiation beam's alignment with the treatment isocenter. The cube phantom, which features a 2mm sphere at its centre, served as the focal point for these evaluations. The images acquired during the Winston-Lutz test were analysed

using Dose Lab software, focusing on the displacement of the sphere relative to the treatment isocenter. The analysis revealed that the isocentric deviation remained within the acceptable tolerance of ±1 mm across all tested angles **(Figure 9a and 9b)**. This result indicates that both the Varian TrueBeam and Elekta Infinity Linear Accelerators are maintaining precise mechanical and imaging alignment, which is crucial for ensuring accurate treatment delivery and patient safety. The consistent results across different gantry, collimator and couch positions further demonstrate the stability of the imaging and treatment systems, reducing the risk of geometric uncertainties during clinical use.

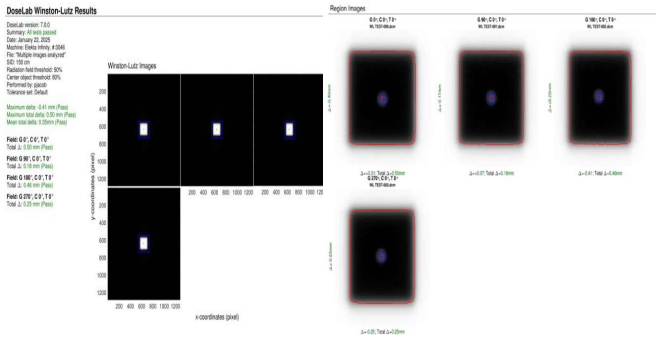


Figure 9: a) b)

4.2. Image quality QA: MV and kV imaging analysis

For the quality assurance of both megavoltage (MV) and kilovoltage (kV) imaging systems, the MC2 Varian Mobius Phantom was employed. This phantom offers a robust platform for evaluating multiple image quality parameters, including resolution, contrast, noise, uniformity and image scaling.

The QA procedure involved capturing both MV and kV images of the phantom under clinical conditions, followed by an in-depth analysis using DoseLab software. The software provided detailed metrics that allowed us to quantify the performance of the imaging systems.

The resolution assessment showed that the imaging systems could clearly distinguish fine structures within the phantom, indicating a high degree of spatial accuracy. The contrast evaluation confirmed that the systems could effectively differentiate between varying tissue densities, enhancing the visibility of anatomical structures. Noise levels were consistently low, contributing to clearer and more precise images.

Uniformity checks across the imaging field demonstrated a balanced and consistent image quality, which is vital for reducing variability in treatment planning. The image scaling results confirmed that the imaging systems maintained accurate geometric representation, ensuring that measurements taken from images are reliable for clinical decision-making **(Figure 10a and 10b)**.

These findings validate that both the MV and kV imaging systems are performing within the recommended guidelines, ensuring their readiness for clinical application and supporting high-precision patient treatments.

4.3. CBCT image quality evaluation[10].

The image quality of Cone-Beam Computed Tomography (CBCT) systems, integrated into both the Elekta Infinity and Varian TrueBeam Linear Accelerators, was also thoroughly evaluated. The CBCT QA process involved using Catphan phantoms, which are specifically designed to test various aspects of image quality. The CBCT imaging systems were subjected to rigorous testing across key parameters, including uniformity, contrast, contrast-to-noise ratio (CNR), spatial resolution, slice thickness and geometric distortion. These tests are integral to ensuring that CBCT images provide accurate and reliable data for patient positioning and treatment verification.

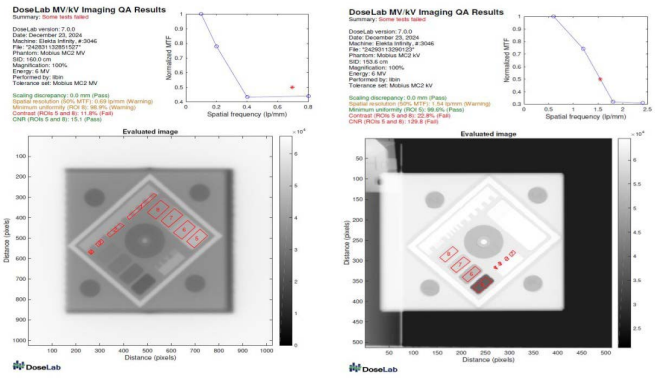


Figure 10: a) MV Image Analysis. b) KV image Analysis.

Uniformity analysis demonstrated that the CBCT systems maintained consistent image quality across the entire field of view, reducing the likelihood of image artifacts that could compromise treatment accuracy. The contrast and CNR evaluations highlighted the systems' ability to differentiate between different tissue types while maintaining clear and sharp images. Spatial resolution tests confirmed that the CBCT systems could accurately depict fine anatomical details, which is critical for precise treatment planning. The slice thickness analysis validated that the z-axis representation of scanned objects matched clinical specifications, contributing to accurate 3D reconstructions of patient anatomy.

Geometric distortion checks indicated minimal deviation, ensuring that CBCT images accurately represent the spatial relationships within the scanned volume. These findings align with clinical standards and reinforce the systems' suitability for use in daily clinical practice **(Figure 11)**.

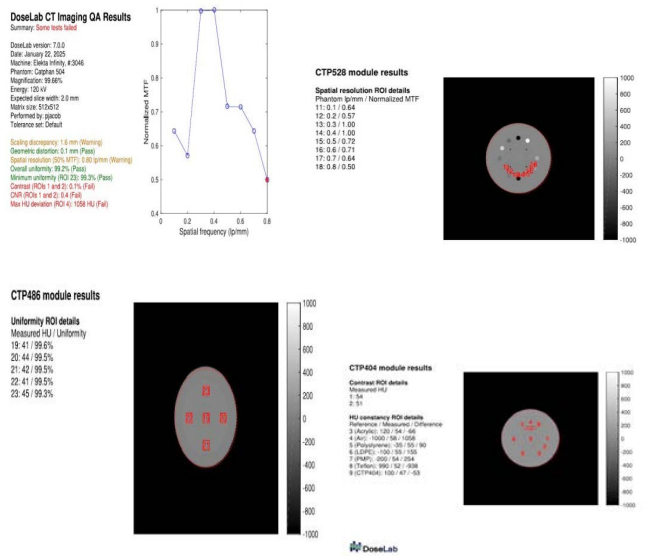


Figure 11: CBCT Image Quality Analysis.

5. Discussion: Clinical Implications of QA Results

The robust performance of our imaging systems, as demonstrated by the QA results, underscores the effectiveness of our QA protocols. Maintaining image quality within specified

tolerances is critical for achieving precise patient positioning and treatment accuracy, which directly impacts clinical outcomes.

The success of the Winston-Lutz test with deviations well within the ±1 mm tolerance highlights the mechanical precision of our linear accelerators. This precision is essential for ensuring that the radiation beam accurately targets the treatment area, minimizing the exposure of healthy tissues.

The excellent performance of the MV and kV imaging systems, particularly in terms of resolution, contrast and noise management, enhances the accuracy of patient setup and treatment verification. These imaging modalities play a crucial role in Image-Guided Radiation Therapy (IGRT), where accurate image quality translates to improved treatment delivery.

CBCT systems, with their demonstrated high-quality imaging metrics, provide an additional layer of accuracy by allowing for 3D visualization of the treatment area. This capability is particularly beneficial for adaptive radiation therapy, where treatment plans may be modified based on daily imaging results.

Overall, the consistent and high-quality performance of our imaging systems contributes to a safer and more effective radiation therapy environment. These results not only validate our current QA practices but also reinforce our commitment to maintaining rigorous standards in clinical imaging and treatment processes.

By continuously monitoring and analysing QA data, we can proactively address any emerging issues, ensuring that our systems remain reliable and that patient treatments are delivered with the highest possible accuracy. These efforts ultimately enhance patient safety and improve treatment outcomes, aligning with our clinic's mission to provide exceptional care in radiation oncology.

6. Conclusion

Establishing a comprehensive Quality Assurance (QA) program is essential for monitoring the mechanical stability and image quality of Image-Guided Radiotherapy (IGRT) systems. Regular and systematic testing is crucial for detecting any performance deficits that may arise. Although the specific implementation, frequency and tolerances of QA tests can vary depending on the institution and equipment, having a well-defined set of guidelines is imperative. These guidelines ensure that the system performance remains consistent and reliable, ultimately contributing to the safety and efficacy of patient treatments.

A robust QA program should include daily, monthly and annual checks, each targeting different aspects of the IGRT system. Daily checks focus on immediate safety and operational readiness, while monthly checks delve into more detailed image quality and mechanical accuracy assessments. Annual checks provide a comprehensive evaluation of the system's overall performance, including dosimetric accuracy and long-term stability. By adhering to these guidelines, institutions can maintain high standards of treatment delivery, minimize the risk of errors and ensure that patients receive the best possible care. Continuous monitoring and timely corrective actions based on QA findings are key to sustaining the optimal performance of IGRT systems.

7. Reference

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