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Evaluation of Delivered Dose in Brain Radiosurgery using an Anthropomorphic Phantom: An End-to-End Dosimetric Assessment

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KEYWORDS

Radiosurgery, Dosimetry, Stereotactic Techniques, Treatment Planning, Quality Assurance, Brain Phantom

ABSTRACT:

This study evaluates the accuracy of delivered dose in brain radiosurgery using stereotactic techniques with a 6 Flattening Filter-Free (FFF) beam energy. An end-to-end quality assurance (QA) process was performed using an anthropomorphic phantom and nanoDots dosimeters. The workflow included Computed Tomography (Computed Tomography (CT)) simulation, treatment planning, and dose delivery using advanced medical imaging and radiation therapy systems. Dosimetric measurements were conducted to assess dose distribution, target coverage, and healthy tissue sparing.

Results demonstrated close agreement between the planned and delivered doses for three simulated lesions, with average delivered doses of 8.25 ±0.14 Gy, 8.33±0.16 Gy, and 8.30 ±0.15 Gy, and a maximum hotspot dose of 8.60 ±0.19 Gy. The accuracy of dose distribution was verified with a gamma index conformity of 99.5%. This study emphasizes the importance of end-to-end QA in stereotactic radiosurgery, especially in regions with tumor sizes under 1 cm, where careful dose planning is critical to minimizing the risks of complications such as necrosis and damage to surrounding healthy tissues.

Introduction

Brain tumors, including glioblastomas, are among the most aggressive and challenging conditions to treat, often requiring multimodal approaches for effective management **(1).** The latest World Health Organization (WHO) Classification of Tumors of the Central Nervous System identifies over 100 distinct types of primary brain tumors, emphasizing the complexity and diagnostic challenges associated with these conditions **(2).** Radiation therapy (RT) remains a cornerstone in treating central nervous system (CNS) tumors, offering a non-invasive yet highly effective modality for tumor control **(3)**. Advances in RT techniques have significantly enhanced precision, allowing for highly conformal radiation delivery that minimizes exposure to surrounding healthy tissues and critical structures such as organs at risk (OARs) **(4)**

Among these innovations, stereotactic radiotherapy (SRT) stands out as a critical approach for managing small to medium-sized lesions. Delivered as single-fraction stereotactic radiosurgery (SRS) or fractionated stereotactic radiotherapy (FSRT), SRT achieves superior dose conformity and rapid dose fall-off outside the target region compared to conventional techniques like three-dimensional conformal radiation therapy (3-D CRT) or intensity-modulated radiation therapy (IMRT) **(5,6).** This high precision makes SRT particularly effective in treating tumors located in anatomically complex regions

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or those smaller than 1 cm. However, the high doses required—often reaching up to 20 Gy per session—pose risks such as tissue necrosis or damage to surrounding healthy structures, necessitating meticulous treatment planning and evaluation of potential complications **(1).**

Understanding the current landscape of SRT requires a thorough review of prior advancements and techniques. Recent studies highlight the importance of integrating advanced imaging and treatment planning systems to achieve optimal clinical outcomes. Simultaneously, quality assurance (QA) remains central to radiation therapy programs, ensuring that patients receive the prescribed dose with high precision. Even minor deviations in dose delivery can lead to significant clinical consequences: underdosing may compromise tumor control, while overdosing can increase the risk of complications and morbidity **(7,8).**

Given the complexity of SRT, particularly for small targets, ensuring both geometric and dosimetric accuracy is paramount. While routine QA tests validate the functioning of treatment machines and planning systems, they often fall short in guaranteeing accuracy across the entire treatment workflow. This underscores the necessity of implementing comprehensive end-to-end (E2E) QA protocols, which validate the entire process, from imaging and treatment planning to dose delivery **(9).**

In this study, we present an in-house E2E QA test for a radiosurgery stereotactic volumetric modulated arc therapy (VMAT) treatment of microgliomas. Using an anthropomorphic head phantom embedded with NanoDot dosimeters, we evaluated the entire workflow from CT simulation and patient setup to radiation delivery by measuring the delivered dose. The findings aim to provide valuable insights into the effectiveness and accuracy of advanced stereotactic radiotherapy techniques, particularly in managing small lesions in complex anatomical regions

Material and Methods

1. Phantom characteristics

Accurate assessment of dose distribution is critical for ensuring the efficacy and safety of radiation therapy treatments. An anthropomorphic phantom, which closely replicates human anatomy, provides a reliable tool for evaluating the interaction of ionizing radiation with human tissues.

In this study, we utilized the CIRS ATOM 701-D anthropomorphic phantom for quality control verifications prior to patient treatment. The phantom is designed to simulate the anatomy of a standard adult male (173 cm height, 73 kg weight) and incorporates detailed internal structures. Its thoracic region measures 23 x 32 cm, calibrated to mimic the properties of soft tissues and internal organs. The model comprises 39 transverse slices, each 2.5 cm thick, allowing precise modeling of dose distribution at various depths.

To enhance measurement precision, we employed NanoDots dosimeters, which, as mentioned in Figure 1, are optically stimulated luminescence (OSL) detectors, to collect dose data. NanoDots were integrated into the CIRS ATOM phantom at critical locations, including the isocenter and peripheral regions, enabling detailed evaluation of dose distribution. Their use in small fields provided enhanced confidence in dose accuracy, crucial for validating stereotactic treatment plans.

Figure 1: Nano dots detectors

2. Calibration of Nano Dots Dosimeters

The calibration of nano Dots dosimeters was a critical step in ensuring the accuracy of dose measurements for the end-to-end quality assurance (QA) process. The following outlines the calibration protocol:

1. *OSLD System:*
2. The study utilized nanoDot® OSLDs (Landauer, Inc.), which consist of an Al_2O_3:C crystal (density: 1.41–2.45 g/cm³) encapsulated in a light-tight plastic case. These dosimeters measure the absolute point dose by converting the detector response (counts) into absorbed dose using a calibration factor
3. Calibration Setup:

- Beam Quality: A 6 MV photon beam was used for calibration.

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- Field Size: A 10 × 10 cm² field size was employed.
- Source-to-Surface Distance (SSD): 100 cm.
- Build-up Material: 1.5 cm of PMMA slabs for build-up and 10 cm of PMMA slabs for back-scattering.
- Reference Dosimeter: A Farmer-type ionization chamber (PTW-30113, 0.6 cm³), calibrated at the International Atomic Energy Agency (IAEA), served as the reference dosimeter **(11, 12).**

4. Calibration Protocol:

- Dose Levels: OSLDs were irradiated at three dose levels: 100 MU (1 Gy), 200 MU (2 Gy), and 300 MU (3 Gy).
- Detector Placement: For each irradiation session, 5 OSLDs were placed at the beam axis and off-axis positions to account for beam profile uniformity **(13).**
- Repetition: Each dose level was repeated twice, with 10 OSLDs used per session (2 groups of 5 detectors).
- Reading Process: Each OSLD was read 5 times using a microStar reader (Landauer, Inc.) to reduce statistical errors. The average reading and standard deviation (SD) were calculated **(14).**

5. Calibration Factor Calculation:

- The calibration factor ND,w was determined using the formula:

$$ND,w=\frac{D0(cGy)}{M0,corr(counts)}$$

Where $D0$ is the absorbed dose measured by the ionization chamber, and $M0,corr$ is the corrected detector response **(15,11).**

6. Correction Factors:

- The study accounted for various correction factors, including dose linearity, fading, beam quality, angular response, and element sensitivity. However, since the calibration conditions were consistent, most correction factors were set to 1, except for the angular correction factor $k\theta$ **(15, 16).**

7. Dose Linearity:

- A dose linearity curve was plotted for doses ranging from 0 Gy to 3 Gy, covering the dose range used in the treatment plans.
- The coefficient of determination R^2 was greater than 0.9999, indicating excellent dose linearity within the used dose range **(13, 14).**

8. Uncertainty Analysis:

- The combined standard uncertainty σ was calculated to account for all uncertainties in the dose measurement process, including those from the ionization chamber and OSLD readings **(11, 15).**
- The coefficients of variation (CV) for OSLD readings at each dose level were 0.024, 0.032, and 0.024, well within the vendor-recommended value of 0.05 **(13).**

SUM UP:

The calibration process ensured that the OSLDs provided accurate and reproducible dose measurements, which were crucial for validating the VMAT treatment plans **(10, 15).**the use of a Farmer-type ionization chamber as a reference dosimeter and the rigorous calibration protocol (including multiple readings and repetitions) minimized uncertainties in the dose measurements **(11, 14).**the high dose linearity and low coefficients of variation demonstrated the reliability of the OSLDs for clinical dosimetry in the context of VMAT QA **(13, 15).**

3. CT simulation ,dosimetry and treatment

The head phantom was scanned using a General Electric Optima CT-660 scanner (128-slice axial reconstruction) to achieve improved visualization along the Z-axis. For accurate alignment, the phantom was positioned in a neck rest and immobilized. Separate CT scans were conducted for each NanoDot insert to ensure precision.

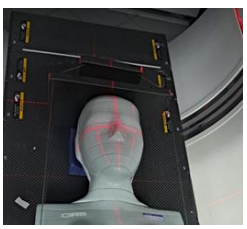

Figure 2: CIRS head phantom positioned in CT scanner

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The treatment plan was developed using the Monaco Treatment Planning System (TPS). Three spherical lesions, each 1 cm in diameter, were delineated as planning target volumes (PTVs). The treatment plan included four arcs for dose delivery:

- **Arc 1**: A complete 360° rotation with the treatment table at 0°.
- **Arcs 2-4**: Partial arcs covering 180°, with varied table positions to optimize dose distribution.

The plan was designed to ensure that 100% of the prescribed dose covered at least 95% of each PTV, adhering to clinical protocols. NanoDots were strategically placed within the lesions to record the delivered dose for comparison with the planned dose.

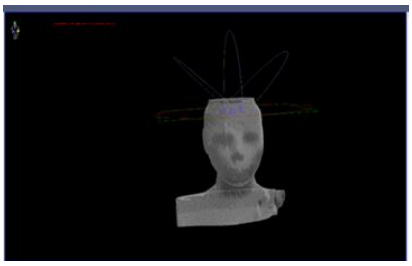

Figure 1: visualisation of the 4 arcs

The precise contours of the simulated lesions and the PTV were fundamental in the critical phase of treatment planning. To ensure the accuracy and validation of the expected dose distribution, we integrated data obtained from Nano Dots.

These Nano Dots, placed within each lesion, provided real-time measurements of the delivered dose, offering an empirical dataset for comparison. By incorporating these measurements into the planning process, we could evaluate and confirm the accuracy of the dose distribution predicted by the Treatment Planning System (TPS).

Utilizing the Monaco TPS, we created customized treatment plans for each lesion. The goal was to optimize the dose distribution within the lesions while minimizing exposure to surrounding tissues. The validation of our treatment plans was strengthened by comparing the real-time doses measured by the Nano Dots with the doses projected by the planning system.

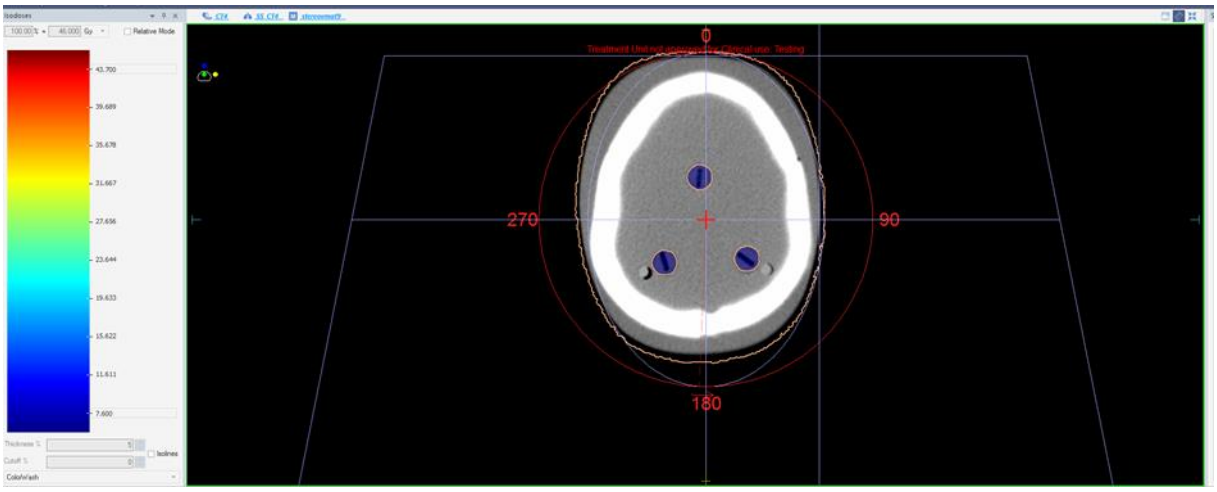

Figure 2: the dose distribution within the lesions is achieved using the stereotactic technique

To record the actual dose distribution, enabling validation of the agreement between the planned treatment dose and the dose actually administered to the patient an device called the Ptw Octavius check is positioned on the treatment table. Its essential role is to detect any discrepancies between the calculated dose and the delivered dose, thus ensuring a high level of safety and precision in stereotactic radiotherapy.

The PTW OCTAVIUS CHECK arc is a quality assurance dosimeter used in radiotherapy. It is specifically designed to measure the radiation dose distribution delivered during patient simulation and treatment.

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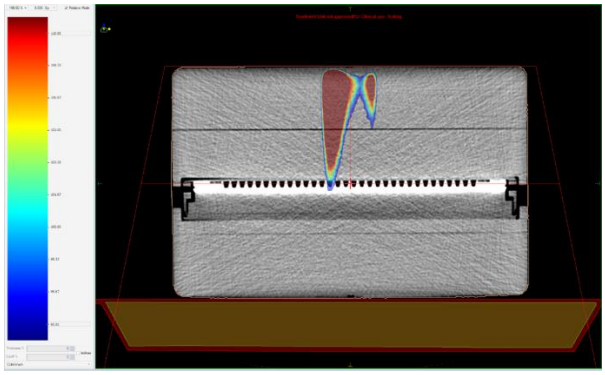

Figure 3 :the dose distribution within the ptw Octavius 4D

Results and discussion:

Reading NanoDot Results

Accurate evaluation of the doses delivered during treatment simulation is essential to ensure that the treatment plan meets expectations. The process of reading the results from the nanoDots begins with their extraction from the phantom after the treatment simulation. Each nanoDot is then inserted into a thermoluminescent reader, which can detect the signals emitted by the nano Dot crystals when exposed to ionizing radiation. The thermoluminescent reader converts these signals into dose values. These dose values for each nanoDot are recorded, allowing for an assessment of the dose distribution within each lesion.

Dose Comparison Curve with Max Hotspot Dose in Red

The statistical agreement between measured and planned doses reinforces the reliability of the treatment planning system.

1. Analysis of Obtained Data and Dose Characteristics with Max Hotspot Comparison

The data obtained from reading the nanoDots revealed essential dose characteristics for our evaluation. For the three simulated lesions, we obtained the following average values:

Lesion at position 1: D_average = 8.25 ±0.14 Gy
Lesion at position 2: D_average = 8.33 ±0.16 Gy
Lesion at position 3: D_average = 8.3 ±0.15 Gy

These results demonstrate the precision of the planned treatment, as the average doses closely match the values anticipated in the treatment plan. Additionally, the maximum hotspot dose of 8.6 ±0.19 Gy was compared to these measured doses.

This comparison indicates that the treatment simulation was successfully executed and that the lesions received doses consistent with clinical requirements. This analysis of the nanoDots data is a crucial component of our Quality Assurance evaluation, demonstrating the reliability of the simulation and treatment planning process in stereotactic radiotherapy.

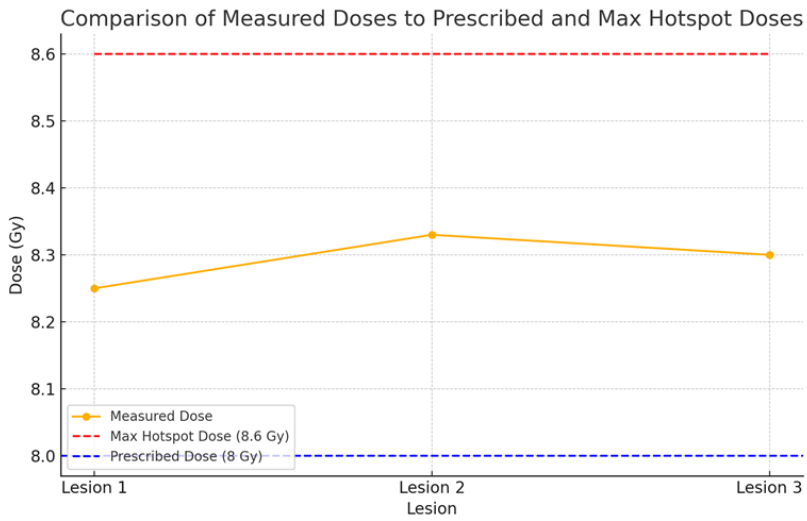

Figure 4 :comparing of measured dose with prescribed and max hotspot dose

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2. Quality Assurance before Treatment:

In this section, we will detail the steps of Quality Assurance (QA) before high-dose stereotactic radiotherapy treatment, highlighting the crucial role of the Arc CHECK PTW OCTAVIUS in this process.

a) Positioning of the Arc CHECK PTW OCTAVIUS: Quality Assurance begins with the precise positioning of the Arc CHECK PTW OCTAVIUS on the VERSA HD machine's treatment table. This step ensures that the dose control device is subjected to the same treatment conditions as the patient during the simulation, thereby providing an accurate assessment of the delivered dose.

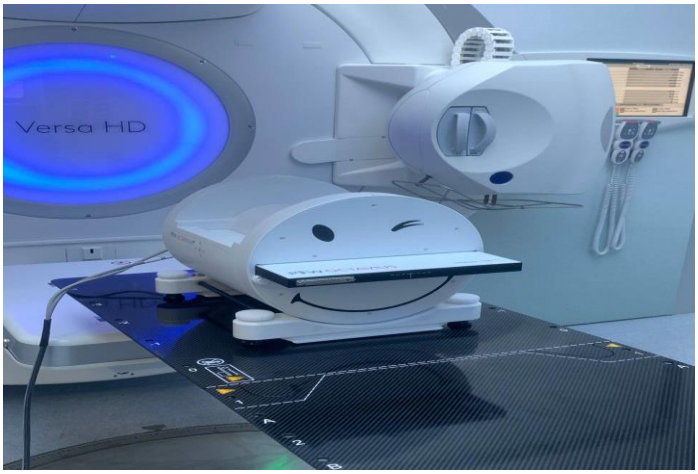

Figure 5: this simulation generated a simulated dose distribution, representing the theoretical dose that the phantom should receive during treatment (8Gy)

Comparison Between Simulated Dose and TPS Calculated Dose:

The comparison between the simulated dose distribution and the dose distribution calculated in the TPS was conducted using the Arc CHECK, which measured the actual dose distribution during the simulation. This process validated the accuracy of the treatment plan.

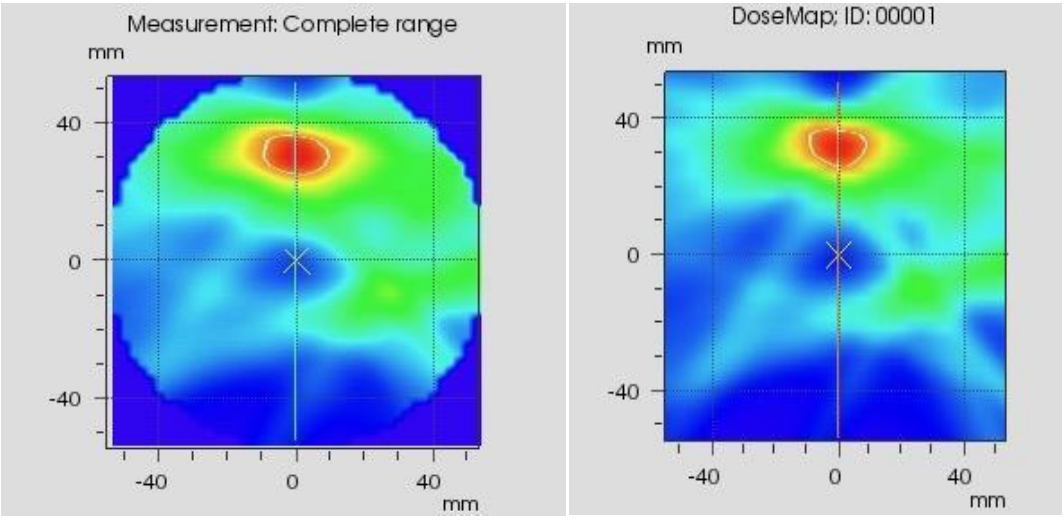

Figure 6: evaluation between the simulated dose distribution and the dose distribution calculated in the Treatment planning system

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Results of Gamma Index:

The matching results of these two dose distributions demonstrate excellent conformity between the simulated dose and the calculated dose, thereby validating the accuracy of the stereotactic radiotherapy treatment.

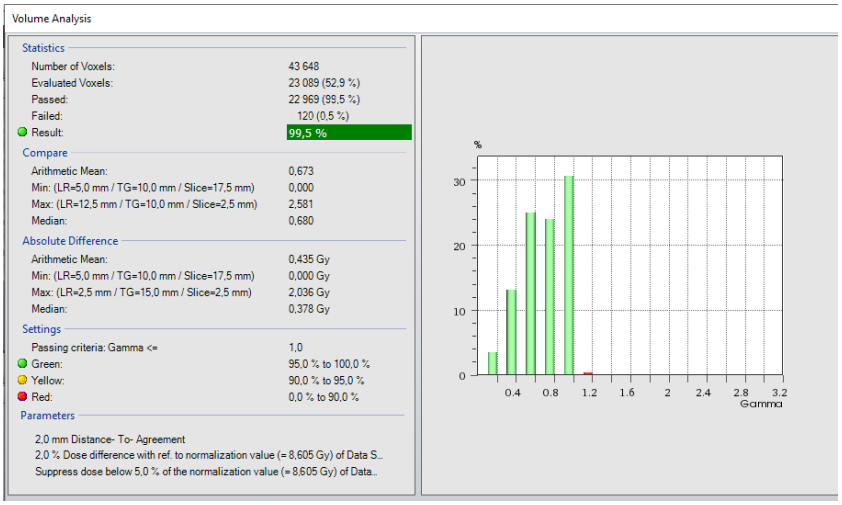

Figure 7: the matching results of the two dose distributions

The results of our study have significant clinical implications for high-dose stereotactic radiotherapy. The high precision of dose delivery, confirmed by gamma indices reaching 95%, underscores the effectiveness of Quality Assurance (QA) measures and highlights the crucial role of the ArcCHECK in maintaining patient safety. This precision is vital for maximizing the effectiveness of the treatment while minimizing damage to healthy tissues.

In our study, the comparison between the calculated dose by the Treatment Planning System (TPS) and the simulated dose measured by the ArcCHECK played a pivotal role in validating the treatment accuracy. The simulated dose distribution, representing the theoretical dose that the phantom should receive during treatment, was meticulously compared to the dose distribution calculated by the TPS. This comparison, facilitated by the ArcCHECK, provided real-time measurements of the delivered dose, enabling a direct assessment of the treatment plan's accuracy.

The high level of agreement between the simulated dose and the TPS-calculated dose, as evidenced by the gamma index analysis, demonstrates that the QA process is robust and reliable. This agreement confirms that the treatment simulation accurately reflects the planned treatment, ensuring that the actual dose delivered to the patient aligns with the prescribed dose. The gamma index results, showing a 99.5% conformity, are particularly noteworthy as they validate the precision of the stereotactic radiotherapy treatment.

Moreover, the ability to accurately evaluate doses on simulated lesions opens the door to more personalized treatments tailored to the individual needs of patients. This customization is essential in modern radiotherapy, where treatments must be both highly effective and minimally invasive. The Arc CHECK's role in this process cannot be overstated; it not only ensures that the planned dose is delivered accurately but also provides a means to continuously monitor and adjust treatment plans as needed.

However, challenges remain, particularly in the complexity of multiple treatments and the need to optimize treatment plans to minimize doses to healthy tissues. The intricate nature of high-dose stereotactic radiotherapy requires meticulous planning and constant vigilance to ensure that the dose delivery is both precise and safe. Future work should focus on enhancing the TPS algorithms and improving the integration of real-time dose measurements to further refine the treatment process.

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In conclusion, our study highlights the critical importance of rigorous QA processes and the use of advanced dosimetry tools like the Arc CHECK in high-dose stereotactic radiotherapy. The high degree of accuracy achieved in our dose delivery not only enhances treatment efficacy but also ensures patient safety, paving the way for more personalized and effective radiotherapy treatments.

Conclusion

This study rigorously validates the precision of stereotactic brain radiosurgery through an end-to-end quality assurance process using an anthropomorphic phantom. The high conformity between the planned and delivered doses, with minimal deviations, underscores the reliability of the treatment planning and delivery systems. The use of the ATOM 701-D model and nanoDots for dose measurement provided a robust framework for evaluating dose distribution accuracy, target coverage, and healthy tissue sparing.

The findings demonstrate the essential role of comprehensive quality assurance in ensuring patient safety and treatment efficacy in stereotactic radiosurgery. The high precision achieved, as evidenced by the close match between the planned and measured doses, highlights the effectiveness of the QA measures employed. This study also emphasizes the importance of integrating advanced imaging and dosimetric technologies for further refinement of treatment processes.

Future research should prioritize integrating real-time dose measurement technologies with enhanced treatment planning system algorithms and incorporating real-time dose measurement technologies to optimize treatment plans further. These advancements will contribute to the ongoing improvement of stereotactic radiosurgery, ultimately leading to better patient outcomes and more personalized treatment approaches.

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