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Original Research Article

Dose Verification for LINAC-Based Stereotactic Radiosurgery Planned at Different Prescription Isodose Levels Using Delta4 Phantom+

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ABSTRACT

Background: Linear accelerator (LINAC)-based stereotactic radiosurgery (SRS) plans and their treatment are complex techniques that require a comprehensive quality assurance program before they are clinically implemented. To cope with this intricacy, clinics must comprehensively validate treatment plans to deliver precise doses and assure patients. The study aimed to verify the treatment planning dose to the dose delivered at the LINAC during the SRS treatment planned at different prescription isodoses with the new wireless Delta4 Phantom+.

Materials and Methods: Clinically accepted volumetric modulated arc therapy (VMAT) SRS plans made with the Stereotactic End-to-End Verification (STEEV) anthropomorphic phantom were created with six different prescription isodose level using 6 MV flattening filter free (FFF) beam. All these VMAT SRS plans were replicated on the Delta4 Phantom+ and delivered with Varian Truebeam LINAC. The planned and delivered dose showed excellent correlation, and this was evaluated using distance to agreement (2 mm), dose deviation (2%), and gamma-index passing rate.

Results: The results showed that the calculated treatment planning system (TPS) dose and the measurement with the Delta4 Phantom+were in excellent accord. The minimum gamma pass rate was 99.6% and the maximum 100%. The gamma passing rate above 95% for all plans and dose goals were achieved.

Conclusion: The verification with the Delta4 Phantom+ measurement depicted an excellent correlation with the dose of the SRS treatment plans for the different prescription isodose levels. The wireless Delta4 Phantom+ device is precise and consistent. It is a quickly set-up device, suitable for SRS treatment verification and allows for real-time measurement. However, we do recommend a stricter passing rate for VMAT SRS Plans.

Keywords – *Stereotactic radiosurgery, prescription isodose, treatment plans, Delta4 Phantom+, Gamma-index.*

INTRODUCTION

Stereotactic radiosurgery is minimally invasive or non-invasive type of external beam radiation therapy that operates behind the principle of using focal technique to deliver high radiation doses in one or few fractions by the help of multiple convergent beams of high energy photons to distinct small target volumes while sparing healthy surrounding tissues.[1,2] These treatments can be delivered using the Cyberknife, Gamma Knife, Novalis, Proton and LINAC-based systems.[3] LINAC-based systems for SRS are increasing and gaining ground in many centers. Nonetheless, the prescription isodose levels differ among different institutions.[4]

Utilizing flattening filter-free (FFF) beams and volumetric modulated arc therapy (VMAT), linear accelerator (LINAC)-based SRS enables the delivery of intricate dose distributions within a shorter timeframe. With only a few fractions, any slight deviation from the target could majorly affect tumour control. Thus, the accurate localization of targets and adherence to strict mechanical and dosimetric tolerances are crucial for precisely delivering LINAC-based SRS plans.[5,6]

The quality assurance (QA) of this LINAC-based SRS system is important for fully implementing this advanced technique. Mistakes committed in any of the stages in the radiotherapy chain may pose detrimental effects to patients. While some mistakes can be found through pre-treatment dose verification, called patient-specific quality assurance (PSQA), others during the acceptance and commission stage.[7,8]

Pre-treatment verification confirms that the treatment dose, position, and volume are as planned. In a broader sense, verification assures the quality of treatment implementation. Stereotactic radiosurgery (SRS) is a well-established technique that delivers larger doses of radiation to small intracranial targets, usually in a single session. This therapy has stood the test of time and has evolved with technological advances.[9] Initially developed within a fixed frame system with point-based measurements of target coordinates, SRS has progressed to frameless systems with image-guided target localization. Dynamic modulated arc therapy with the LINAC has also increasingly gained ground in delivering SRS. Considering this, it is undoubtedly true that technological advances have reduced set-up inaccuracies and uncontrolled errors in delivering SRS. However, these innovations have made treatment delivery an increasingly complex process, and there is an ultimate need for assurance that the exact dose is delivered to the right target and that maximal sparing of the adjacent normal critical organs is held.[3,10]

Nowadays, a couple of methods are used for PSQA. These include point or transmission dose verification, 3D dose reconstruction methods, and other dedicated phantoms.[11] Dosimeters such as diodes, ionization chambers, and radiochromic films are widely used but their area of functioning differs. Some may not be ideal for smaller fields because of large sensitive volumes.[12]

Film dosimetry is commonly used for pre-treatment verifications. However, mistakes can occur during the calibration and reading process.[13] While a diode detector is appropriate for small field measurements as mostly used in SRS, in big fields, it over-response due to high Z material.[14,15] A recent study found that synthetic diamond detectors performed well when measuring point doses in stereotactic radiation beams. However, single-element detectors also offer limited information regarding the dose distribution.[13]

In this study, the authors aimed to establish congruence between LINAC-based SRS VMAT Plans at different prescription isodose levels to measurement done with the Delta4 Phantom+ and to validate the use and appropriateness of this phantom for pre-treatment verification.

MATERIALS AND METHODS

All Treatment Planning and Phantom measurements were performed at the Centro riferimento di Oncologico (CRO), Aviano-Italy. The measurements were done on Varian TrueBeam LINAC and with the new wireless Delta4 Phantom+ (Figure 1).

The treatment plans were generated using the Varian Eclipse 15.0 treatment planning system (TPS). Clinically accepted VMAT SRS plans made with Computed Tomography (CT) images of the Stereotactic End-to-End Verification (STEEV) anthropomorphic phantom with six different prescription isodose levels (50, 55, 60, 65, 70, and 80),

a prescribed dose of 18Gy in a single fraction and using 6 MV FFF beam were created. The treatment plans were done with five arcs and three different planning target volume margins (0 mm, 1 mm, 2 mm).

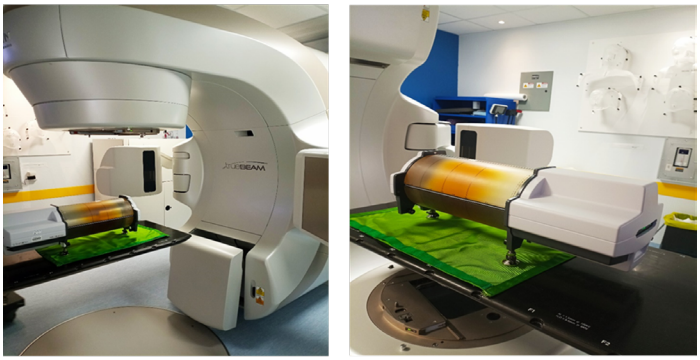

FIGURE 1. The set-up position of the Delta4 Phantom+ on the couch of the Truebeam LINAC.

The Delta4 Phantom+ is a new wireless system that allows highly accurate patient-specific QA of advanced radiotherapy techniques like IMRT, VMAT, SRS, Halcyon, and TomoTherapy. It uses a three-dimensional (3D) detector array with 1069 detectors to assess the full dose distribution in the isocentric region, rather than just a single planar measurement.[16] This comprehensive 3D verification ensures the treatment is given as exactly planned. The Delta4 Phantom+ comprises two planar circuit boards built in an orthogonal crossed array pattern. These boards feature radiation-detecting elements of p-type and Si diodes, with a 0.5 cm spacing in the central high-resolution region and a 1 cm spacing elsewhere (Figure 2).

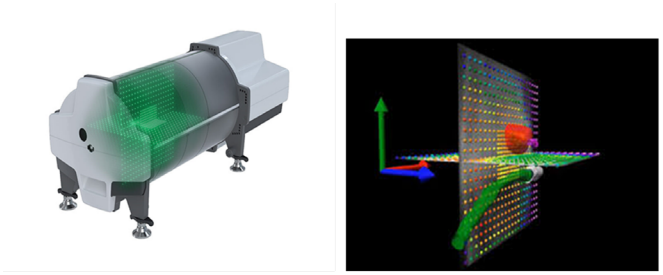

FIGURE 2. The operation of the Delta4 Phantom+ showing the interior of the radiation-detecting elements.[16]

The high-resolution region of the boards is located in the central 6 cm × 6 cm area, while the overall detector plane region measures 20 cm × 20 cm. The cylindrical phantom is 22 cm in diameter and 4 cm in length. The material is composed of PMMA and has a 1.19 g/cm^3 of mass density. The Delta4 Phantom+ has a dose resolution of 0.1 mGy, allowing for precise measurements. It can detect doses as low as 1 mGy, without any upper limit. The phantom is entirely wireless, without any cable connections. It effortlessly transfers data using Wi-Fi and operates on battery power, ensuring a seamless and convenient set-up and usage experience.[17]

The Varian TrueBeam LINAC is a modern medical linear accelerator that revolutionizes radiotherapy treatment. It has photon energies of 6, 10, and 15 MV, 6 and 10 FFF, and electron energies of 6, 9, 12, 15, and 18 MeV. It has a round edge, millennium multi-leaf collimator (MLC) with middle 20 pairs of width 0.5 cm, peripheral 20 pairs of width 1 cm, and an enhanced dynamic wedge. MV imaging has 2.5 MV photon energy; in addition, it has kV CBCT and a-Si 1200 portal imaging. This allows for image-guided radiotherapy and various high-end treatments like SRS and Stereotactic Body Radiotherapy (SBRT).[18]

The treatment plans were modelled onto the Delta4 Phantom+ CT scan within the TPS for dose calculation. The dose distribution was recalculated, and the planning data, including the original plan's beam parameters, were the same. These plans were then transferred to the True beam LINAC and delivered (Figure 3).

The Delta4 Phantom+ software is an integral component of the Delta4 Phantom+ system. The software provides an intuitive and easy-to-navigate interface, allowing users to quickly set up and perform measurements. It supports DICOM structure import functions, allowing for seamless integration with existing treatment planning systems (TPS). The Delta4 software enables real-time acquisition of dose distribution data during treatment delivery, providing instant feedback on treatment accuracy. It offers a range of tools to analyze the disparities between measurement and calculated TPS dose effectively. [17] An analysis utilized the key parameters distance to agreement (DTA), dose agreement (DA), and the gamma pass rate. The concept of gamma analysis was initially proposed by Low et al.[19]

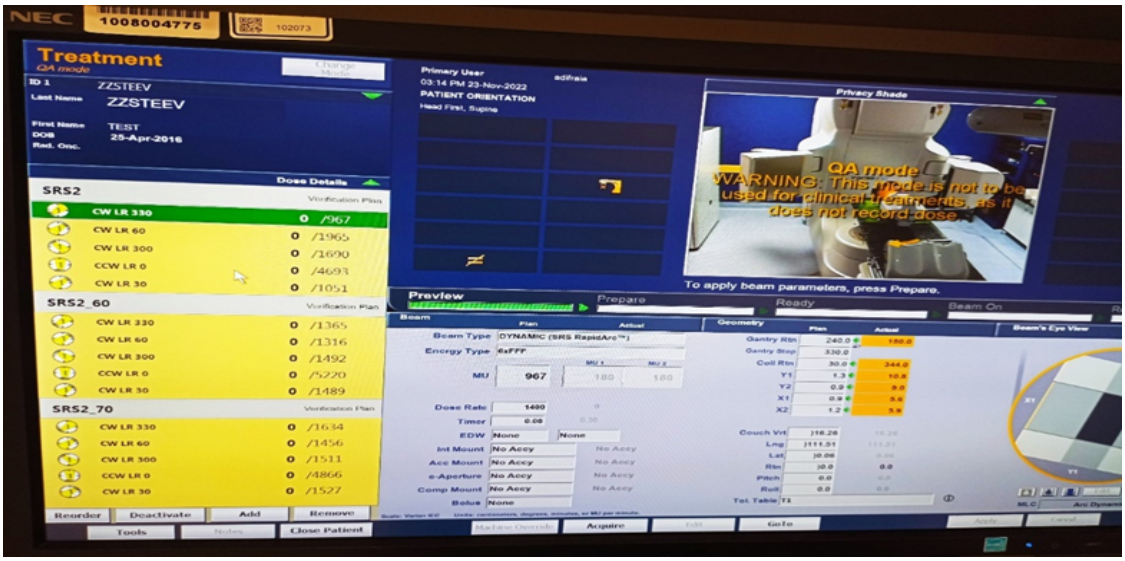

FIGURE 3. Truebeam LINAC monitor interface during measurement.

as a means to compare dose distributions that have been calculated and measured quantitatively. This utilizes the physical distance and dose difference, then normalizes them based on the acceptability criteria.[20]

The DTA, dose deviation (DD), and gamma-index passing rates were all calculated by the software.[19] The criteria for acceptance used in this center was DTA of 3 mm, dose difference of 3%, and the gamma-index passing rate of 95% and 90% for IMRT and VMAT SRS, respectively based on the AAPM TG-218 action limit8 but in this study a 2% dose difference, 2 mm DTA and the gamma-index passing rate of 95% were used. Isocenteric set-up position was used for the Delta4 Phantom+ in measurement. A four-field box technique measuring 10 × 10 cm^2 was measured for the correction factor.[16]

RESULTS

The analysis of all plans included using the three most suitable parameters: the DA (with a limit of 2%), DTA (with a limit of 2 mm), and gamma passing rate.

Table 1 summarizes the results of the gamma passing rate, distance to an agreement, and DD of all plans with the different prescription isodose levels. Overall, in all cases, excellent agreement was seen between the measurement and calculation of TPS doses. The minimum gamma passing rate was 99.6% and the maximum was 100%. The gamma passing rate for all plans was higher than 95% using 2%/2 mm DD/DTA. Our criteria of 95% for the gamma-index was met for all plans with all the different prescription isodose levels used. The correction factor was found to be 1.01.

TABLE 1. Kappa values for qualitative variables showing good agreement between two devices.

Assessment Parameters	Margin Used	Prescription Isodose Level					
		50	55	60	65	70	80
Gamma-Index passing rate 2%/2 mm	0 mm	99.7%	99.8%	99.9%	99.9%	100%	100%
	1 mm	99.6%	99.7%	99.9%	99.7%	99.8%	100%
	2 mm	99.9%	100%	100%	100%	99.8%	99.8%
Dose deviation (DD)	0 mm	76.0%	76.0%	79.1%	80.3%	81.1%	83.4%
	1 mm	76.1%	76.1%	79.5%	80.7%	81.5%	83.7%
	2 mm	76.2%	76.2%	79.9%	80.9%	81.7%	83.9%
Dose to time agreement	0 mm	100%	100%	100%	100%	100%	100%
	1 mm	100%	100%	100%	100%	100%	100%
	2 mm	100%	100%	100%	100%	100%	100%

DISCUSSION

In this study, the use and suitability of the wireless Delta4 Phantom+ were assessed for treatment verification of LINAC-based SRS plans made with different prescription isodose levels. We compared measurements made with phantom and treatment planning dose. We found the wireless Delta4 Phantom+ as an easily set-up device with minimal positional errors that provides consistent and comprehensive QA suitable for SRS plans. Its functionality is identical to the plug-in Delta4 Phantom+ with a few exceptions.[21] The wireless system, real-time results, waterproof construction, and ease of use make it well-suited to measuring small fields and composite SRS plans.

Delta4's first calibration and commissioning procedure must be completed with rigorous and precise measurements to assure patient-specific QA testing accuracy. It enables complete analysis of data and a quicker approach to conduct measurements without the need for additional QA systems. Measurements are taken on the phantom's two planes, and the software generates a 3D dose distribution using an interpolation approach[16] (Figure 4).

There is documented evidence of the use of other detectors in SRS, such as ionization chambers, alanine pellets, plastic scintillators, Sun Nuclear Corporation (SNC) ArcCHECK, SNC SRS MapCHECK, IBA Matrixx Resolution, electronic portal imaging device (EPID) and IBA myQA SRS but their scope of operation varies.[6,22]

The gamma-index is a valuable tool in dosimetric verification analysis, allowing for a comparison between the TPS plan and the measurement (Figure 5).

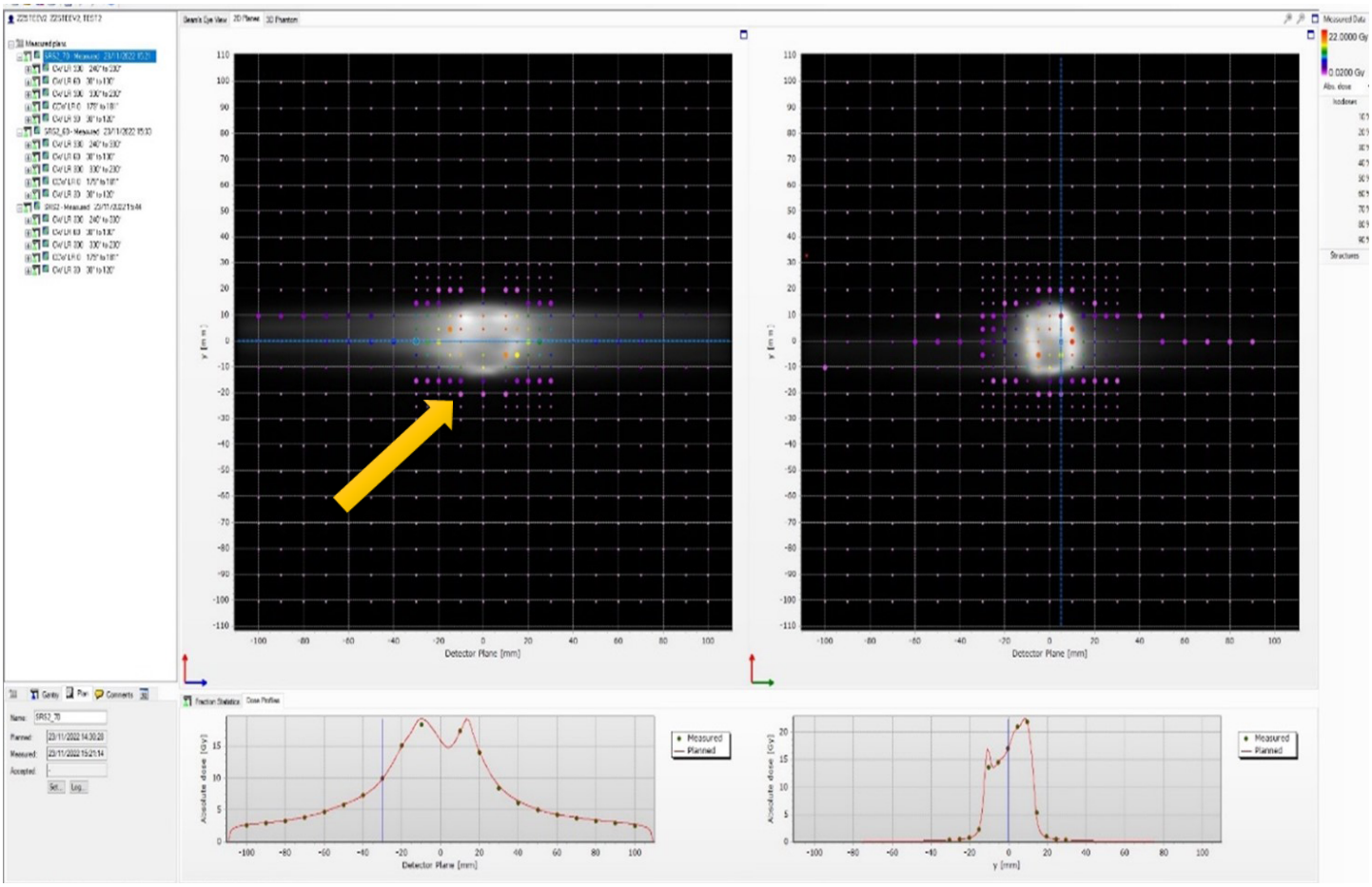

FIGURE 4. The Delta4 Phantom+ software displaying the result. The absolute dosage is shown in two diode arrays in three dimensions on the top panel, with color coding used to indicate the dose (yellow arrow).

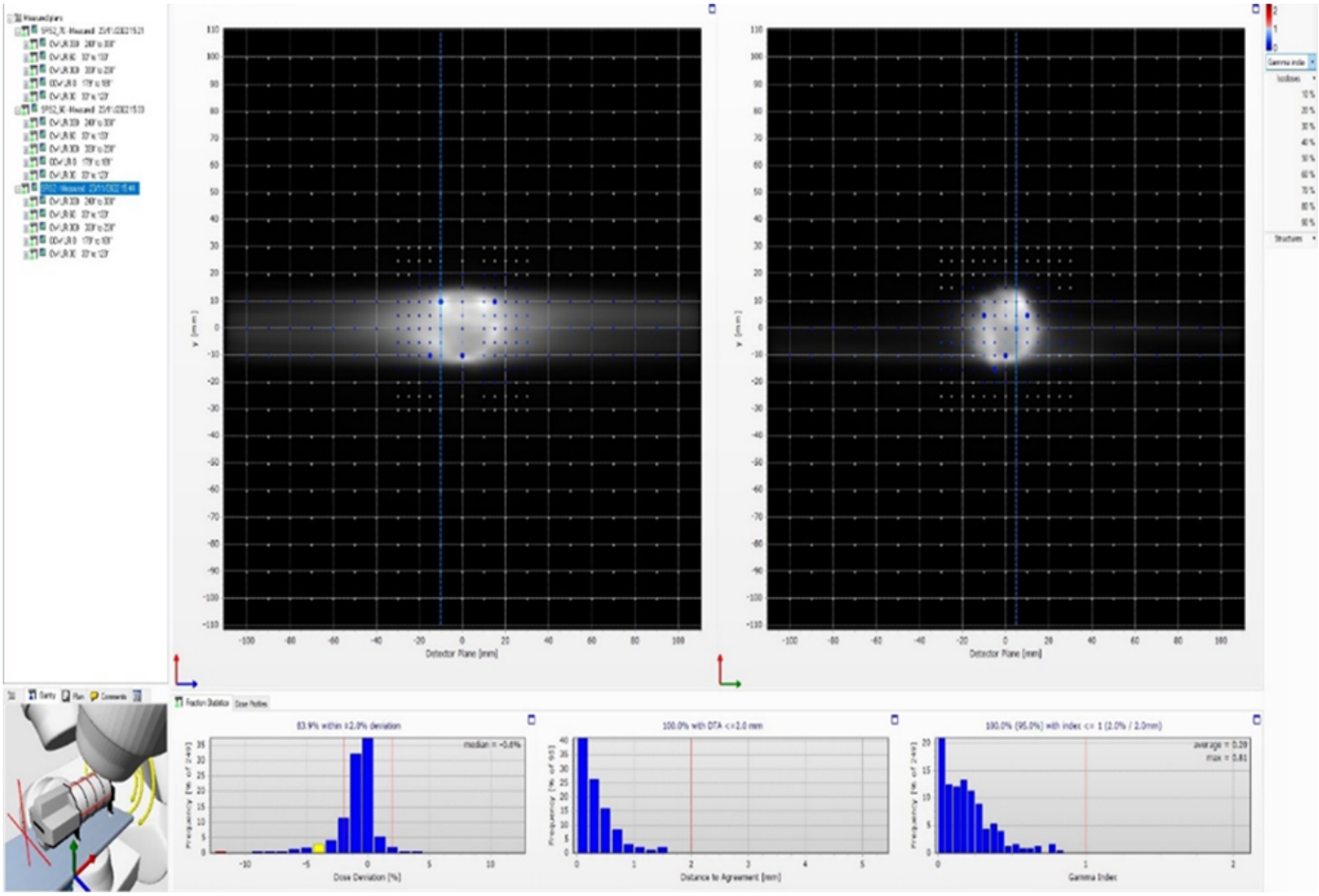

FIGURE 5. The Delta4 Phantom+ software displaying three histograms: distance to agreement, dose deviation, and gamma-index.

It provides a metric to assess the level of agreement in dose. It is commonly utilized for PSQA. The minimum gamma pass rate was 99.6%, and the maximum was 100%. The gamma passing rate was above 95% for all plans as seen in Table 1. Dose goals were also achieved. Developing a center-specific protocol is crucial, as the treatment planning and set-up influence the gamma-index. Various factors can impact the final result, such as the detector's type and sensitivity, TPS algorithm, LINAC output, and clinical judgment of dose tolerance level.[23]

It is important to mention that the DTA and DD criteria utilized for gamma analysis are not entirely independent. They have a connection to the dose gradient factor. It is widely accepted that a passing rate of 90% with a 3 mm/3% clinical significance is commonly used for most highly advanced treatment techniques.[24] This study used a different gamma passing rate of 95% with a 2 mm/2% due to the sharp dose gradient in SRS. However, should our gamma-index passing rate be less than 95%, further verification would be necessary with any of the other detectors such as gafchromic film. According to Nelms et al., gamma passing rates using the criterion of (3%, 3 mm) are insensitive to clinically meaningful patient dose mistakes on a field-by-field basis.[25]

Sadagopan et al. validated the accuracy and reproducibility of the Delta4 device by comparing its results to measurement with film and an ion chamber.[26] Similarly, Bedford et al. found that Delta4 demonstrated a slightly stronger correlation between calculated and measured doses than the film. This may be due to the absolute nature

of Delta4 measurements in contrast to the relative nature of film dosimetry.[27]

Our measured pass rates were comparable with those of other detectors using the same pass criteria when used for treatment verification for VMAT Plans. The minimum gamma passing rate in our study was higher when compared to EBT-XD Film 96.70%, EPID 95.93%, SRSMapCHECK 96.76%, and myQA SRS 97.91% using the same passing criteria 2%/2mm.[6] Furthermore, in a study by Desai et al.,[28] the Delta4 Phantom+'s performance was evaluated by measuring 36 clinical cases using a ViewRay MRIdian linac. The findings were identical to those obtained utilizing a Sun Nuclear ArcCHECK. Both devices met the institution's 95% pass rate for a 3%/3 mm gamma requirement. Still, the use of 2%/2 mm gamma passing rates revealed subtle variances among the devices, with the Delta4+ being a little superior in terms of the results.[28]

Applying 2%/2 mm as a gamma parameter provided excellent sensitivity and minimum fluctuation. The detector's resolution allows for good visualization of the gamma distribution graphically on the software. This is a precious visual tool for identifying regions of overdose and underdose.[29]

Our final measured gamma pass rates may be influenced by some factors such as the True beam LINAC output variability, user configuration, and detector settings. However, it is challenging to separate these factors from the final findings. Moreover, selecting an SRS QA detector is contingent upon several elements that vary between institutions. These considerations include prior expertise, financial resources, user-friendliness, and the sensitivity and specificity requirements that align with the institution's unique SRS QA criteria.[2,6] Hence, it is important to interpret the gamma pass rates presented in this study as a validation of the Delta4 Phantom+ as suitable for SRS treatment verifications rather than as a direct method for comparing it with the other detectors. Furthermore, although we recommend using 2%/2 mm because of the great degree of agreement our investigation was able to attain, other tight gamma parameters such as 2%/1 mm or 1%/1 mm could be explored due to the high dosimetric accuracy of stereotactic treatments.[8]

CONCLUSION

The Delta4 Phantom+ and software system provide efficient set-up, precise real-time measurement, and comprehensive three-dimensional analysis, making it well-suited for the intricate nature of modulated irradiation such as VMAT SRS on the LINAC. The findings suggest that good agreement between measurement and TPS was achieved irrespective of the prescription isodose and planning target volume margins used. The use of Delta4 Phantom+ demonstrates efficacy and efficiency in PSQA. Accuracy is crucial in every aspect of treatment delivery for SRS plans; however, despite meeting the gamma-index rate used, we recommend a stricter passing rate for VMAT SRS Plans. The comparison of Delta4 Phantom+ with other QA verification systems was not conducted due to time constraints and the unavailability of different QA systems in the department. There is potential for further expansion of the work.

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None.

CONFLICTS OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest.

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