Phantom-Based Evaluation of Treatment Accuracy for Lung-like Targets in Ultrahypofractionated Stereotactic Treatments using Elekta Unity 1.5 T MR-Linac

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Purpose: The integration of magnetic resonance imaging with linear accelerators (MR-Linac) has introduced a significant advancement in precision radiotherapy, especially for small field lung treatments where air-tissue interfaces present substantial dosimetric complexities. This study investigates the accuracy of dose calculation and delivery in ultrahypofractionated stereotactic body radiotherapy (SBRT) for lung-like targets using the Elekta Unity 1.5 T MR-Linac, supported by comprehensive phantom-based dosimetric evaluations.

Methods: Four identical spherical targets (1.5 cm in diameter) were placed within rectangular air cavities of a heterogeneous plastic water-equivalent phantom to simulate lung-like conditions. Two targets were placed at the center of the cavities and two were positioned at off-axis corners of the cavities adjacent to high-density phantom slabs. Each target was prescribed a mean dose of 650 cGy in a single fraction, with steep dose gradients beyond the target, reflecting ultrahypofractionated SBRT protocols. Treatment planning was performed using Monaco v6.2 with the GPU-based Monte Carlo Dose (GPUMCD) algorithm, employing eight equidistant isocentric coplanar beams and step-and-shoot intensity modulated radiotherapy (IMRT) delivery. Automatically segmented IMRT fields consisted of 4–20 segments with areas ranging from 0.279 to 9.975 cm^2 (mean: 3.124 cm^2). Dosimetric validation was conducted using a PTW microDiamond (MD) detector placed in a water-filled plastic phantom insert for direct dose measurements (five repetitions per target) and EBT4 Gafchromic films for entrance and exit dose verification. Measurement data were compared with GPUMCD calculations using mean percentage differences with standard deviations (MD detector) and gamma analysis with 3%/3 mm and 2%/2 mm criteria (EBT4 films).

Results: PTW microDiamond measurements demonstrated strong concordance with Monaco GPUMCD dose calculations. Off-axis targets yielded mean dose deviations of $+1.2\% \pm 0.3\%$ and $-0.9\% \pm 0.2\%$, while central targets showed slightly greater, yet clinically acceptable, differences of $+1.7\% \pm 0.6\%$ and $-1.8\% \pm 0.5\%$. EBT4 film-based gamma analysis demonstrated a minimum passing rate of 96.7% (3%/3 mm) and 94.6% (2%/2 mm) across all measured planes. Localized dose perturbations up to 4.2% were observed in regions immediately adjacent to air-tissue interfaces, consistent with the expected electron return effect (ERE).

Conclusions: This comprehensive dosimetric validation confirms that the GPUMCD algorithm delivers clinically acceptable dose calculation accuracy for small targets (≥1.5 cm) treated with small-field ultrahypofractionated protocols on the 1.5 T Elekta Unity MR-Linac. Target dose discrepancies remained below 2.5%, and gamma analysis consistently exceeded 94% pass rates, surpassing conventional clinical acceptance thresholds. The slightly higher deviations observed for centrally placed targets and at air-tissue interfaces highlight the necessity of meticulous treatment planning and robust quality assurance for anatomically complex regions. These results support the clinical feasibility of MR-guided SBRT for lung-like targets and establish baseline metrics to inform future quality assurance frameworks.

Keywords: MR-guided radiotherapy, MR-Linac, small field dosimetry, EBT4 gafchromic film, Air-tissue interface