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Comparative Analysis of Setup Error Sensitivity in Thoracic SBRT Across CyberKnife, Halcyon, and VitalBeam

Background & Purpose

Stereotactic body radiation therapy (SBRT) requires high geometric precision due to steep dose gradients. Small setup errors may significantly impact target coverage and dose to surrounding organs at risk. While multiple treatment platforms are used clinically, their relative sensitivity to setup error remains unclear. This study evaluates the dosimetric impact of translational setup errors across CyberKnife, Halcyon, and VitalBeam using a controlled phantom model.

Methods

An anthropomorphic thoracic phantom was used to eliminate respiratory motion and ensure reproducibility. A 1.5 cm spherical gross tumor volume (GTV) with a 5 mm isotropic expansion to planning target volume (PTV) was planned to 50 Gy in 5 fractions across CyberKnife, Halcyon, and VitalBeam. Rigid translational setup errors of ±1, ±2, ±3, and ±5 mm were applied in orthogonal directions. No reoptimization or renormalization was performed following shifts.

Dosimetric endpoints included PTV D95, D98, and Dmean, conformity index (CI), homogeneity index (HI), intermediate dose metrics (D2cm, R50), and organ-at-risk parameters. A mixed-effects model was used to evaluate platform and shift magnitude effects, with all endpoints reported as modeled change from baseline (Δ).

Results

Shift magnitude significantly affected dosimetric outcomes ($p < 0.0001$), with increasing setup error resulting in increasing magnitude of change in target coverage (ΔD95) and intermediate dose spillage (ΔD2cm). While numerical differences between platforms were observed, no significant platform-by-shift interaction was identified ($p = 0.9195$), indicating similar trends across systems. Dose conformity (R50) remained stable at small shifts but showed increasing change at larger magnitudes.

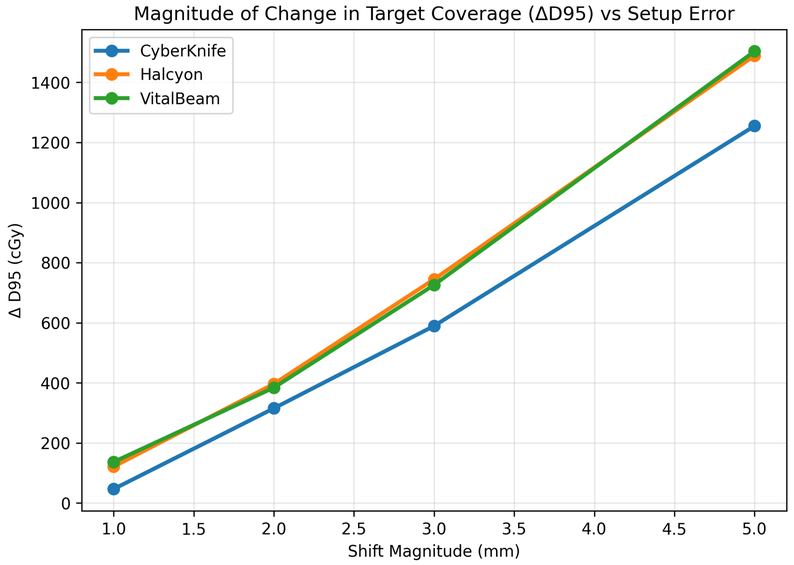

Figure 1. Modeled change in target coverage (ΔD95, cGy) increases in magnitude with increasing setup error across all platforms.

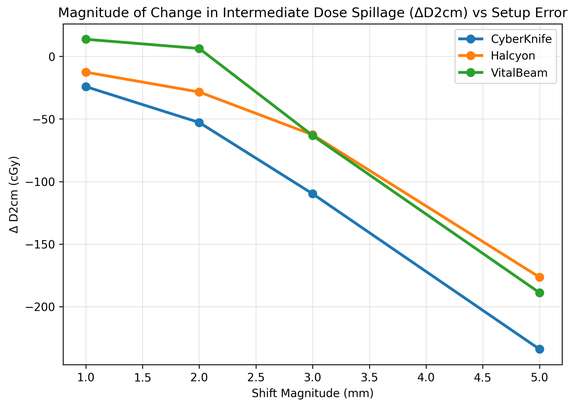

Figure 2. Modeled change in intermediate dose spillage (ΔD2cm, cGy) increases in magnitude with increasing setup error across all platforms.

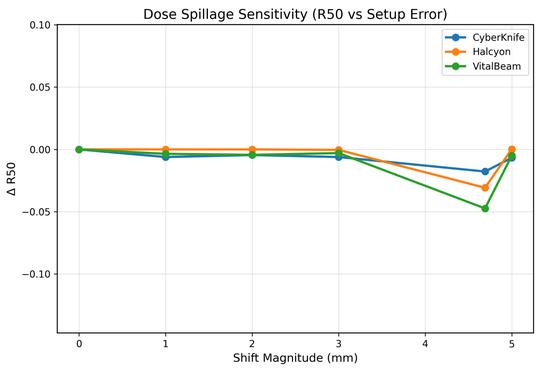

Figure 3. Modeled change in dose conformity (ΔR50) increases with larger setup errors across all platforms.

Discussion

Thoracic SBRT plans demonstrated strong sensitivity to translational setup error, with increasing shifts resulting in increasing magnitude of dosimetric change. Despite differences in delivery technique, all platforms showed similar responses. Although CyberKnife exhibited greater numerical variation in D2cm, these differences were not statistically significant, suggesting shift magnitude is the primary driver of dosimetric change.

Conclusion

Setup error significantly impacts thoracic SBRT dosimetry, with increasing shifts reducing coverage and increasing dose spillage. Similar trends across platforms highlight the importance of precise patient positioning and image guidance. Shift magnitude was the primary driver of dosimetric degradation.

Limitations

This study utilized a stationary phantom, which does not account for respiratory motion and may limit clinical generalizability. Only translational setup errors were evaluated, and rotational uncertainties were not included. Additionally, no adaptive replanning or reoptimization was performed following the introduction of setup shifts. The analysis was also limited to a single target size and location, which may not fully represent the range of clinical scenarios encountered in thoracic SBRT.

References

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