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Three-Dimensional Characterization of Isocenter Accuracy on Halcyon Linear Accelerator As a Function of Off-Axis Distance and MLC Layer

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ABSTRACT

Purpose:
To characterize the three-dimensional (3D) isocenter behavior of Halcyon linear accelerator as a function of off-axis distance and multileaf collimator (MLC) layer, and to evaluate the need for spatially resolved isocenter metrics beyond a single-value specification.

Methods:
Winston–Lutz images were acquired for 5 ball bearings (BBs) embedded in a phantom positioned at 0, 3.6, 5.4, 7.7, and 9.9 cm from isocenter. For each BB, the radiation field was independently shaped by the distal and proximal MLC layers and eight gantry, and four collimator angles were sampled at each location. Isocenter displacement vectors were reconstructed for gantry, collimator, and combined gantry–collimator rotations. Mean isocenter offset, root-mean-square (RMS) deviation, and maximum 3D deviation radius were calculated. Three-dimensional displacements were further decomposed into gun–target (beam-axis) and lateral (in-plane and cross-plane) components.

Results:
Across all BBs and MLC banks, maximum deviation did not exceed 1 mm. For combined gantry–collimator motion, the maximum 3D isocenter offset did not increase significantly for the proximal MLC bank, but 0.025 mm/cm for the distal MLC bank. Directional decomposition revealed isocenter walkout was predominately in gun-target direction as opposed to transverse plane. Distal MLC layer produced larger deviations (+0.27 mm at 10 cm) than proximal as off-axis distance increased.

Conclusion:
Halcyon off-axis isocenter walkout is not strongly dependent on off axis distance within 10 cm of isocenter. Differences in behavior between proximal and distal banks may warrant independent evaluation of delivery accuracy.

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INTRODUCTION

- Treating targets out of isocenter is frequently employed when using the Varian Halcyon linear accelerator to treat multiple targets with a single field or avoid bore/patient collision in highly lateral targets.
- Halcyon uses two sets of 1 cm wide (at isocenter) stacked and staggered multileaf collimators (MLCs) to shape the radiation field.
- The goal of this study was to measure the mechanical accuracy of Halcyon delivery as a function of off-axis distance and MLC layer.

METHODS AND MATERIALS

- A phantom slab consisting of 9 ball-bearings (BB) embedded in epoxy resin was designed and manufactured to mimic a multi-target single-isocenter geometry (figure 1).
- One BB was placed at the center of the phantom while four were located at 3.6, 5.4, 7.7 and 9.9cm away from the central BB. The additional 4 BBs were used to support phantom alignment.
- MLC defined Winston-Lutz (W-L) images were acquired for the central BB and the daily setup errors reported by RIT were removed to accurately position the phantom at the radiation isocenter.
- W-L images shaped independently by proximal and distal MLC banks were then acquired at the off-center locations using 11 beams per BB (4 different collimator angles at gantry 0°, and 7 different gantry angles).
- Measurements were repeated 4 times in total by two different physicist.
- Root means square (RMS) and maximum 3D offset between mechanical and radiation field was investigated against the 0.75mm average and 1mm maximum tolerance for SBRT treatments.

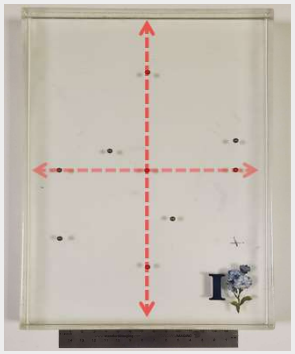
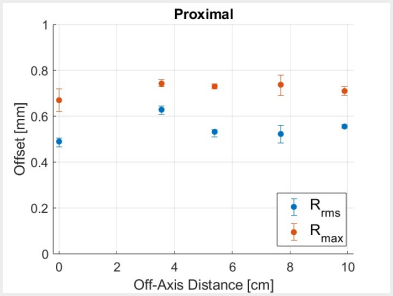


Figure 1. Custom multi-target phantom.

RESULTS

- Figures 2 and 3 show the maximum and average offset as a function of BB distance from the isocenter for distal and proximal MLC banks. Values are displayed in table 1.
- RMS average offset was within 0.75 mm and maximum offset within 1mm for all BB measurements.
- Linear regression of the proximal MLCs showed no significant or strong correlation between off-axis distance and maximum 3D offset. The distal MLC bank maximum offset showed a significant ($p<0.05$) but low 0.02 mm/cm (R^2 = 0.36) increase with off-axis distance.
- Differences in maximum offset ranged from 0.01-0.25 mm between proximal and distal banks and generally increased with off-axis distance.
- Mean RMS Offset in "Gun Target" direction exceeded offset in BEV transverse plane "lateral" across all BBs and both proximal (0.48mm vs 0.26mm) and distal (0.49mm vs 0.27mm) MLC banks.
- The projection responsible for maximum deviation was within gantry angles between 180°-270° or with collimator rotation for 62% of measurements. This behavior was consistent across most BBs and distal and proximal banks.



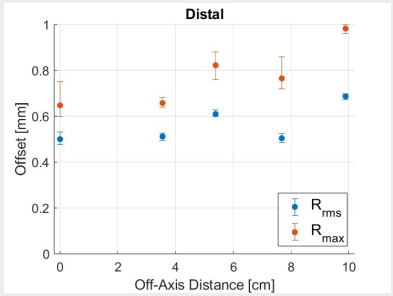


Figure 3 and 4. Proximal (left) and Distal (right) RMS and Maximum deviations averaged across 4 experimental setups. Error bars display the maximum and minimum values across all 4 experiments

Table 1. Proximal (left) and distal (right) RMS and maximum deviations averaged across 4 experimental setups

BB Distance [cm]	Proximal RMS deviation [mm]	Distal RMS deviation [mm]	Proximal max deviation [mm]	Distal max deviation [mm]
0	0.49	0.50	0.67	0.65
3.6	0.63	0.51	0.74	0.66
5.4	0.53	0.61	0.73	0.82
7.7	0.52	0.50	0.74	0.77
9.9	0.56	0.69	0.71	0.98

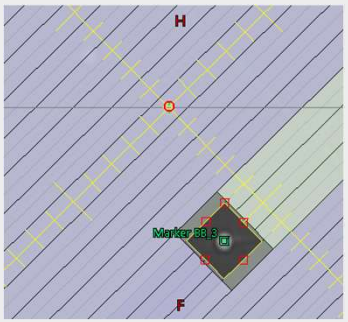


Figure 2. Example off-axis imaging field from beam's eye view (BEV)

CONCLUSIONS

- Proximal-layer isocentricity remained stable across the evaluated off-axis range, whereas distal-layer maximum and RMS deviations increased with distance, but continued to remain below 1 mm.
- Distal maximum deviation increased by approximately 0.018 mm/cm and reached 0.98 mm at 9.9 cm, compared with 0.71 mm for the proximal layer. These findings indicate layer-dependent off-axis behavior and support separate characterization of the proximal and distal MLC layers when assessing of-axis geometric accuracy
- Because each distance was represented by a BB in a different spatial direction, the observed relationship reflects the sampled off-axis locations and cannot be attributed to radial distance alone. Additional phantom orientations are needed to separate distance-dependent from direction-dependent effects.

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