Optimizing Stereotactic Spinal Radiosurgery Planning with MR-Linac Treatment in Comparison to CT-Linac Treatments

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Introduction

Spinal stereotactic radiosurgery (SSRS) plans are commonly dose-limited by the constraints on the spinal cord. Treating with an MR-Linac allows for improved visualization of the spinal cord and the potential to gate treatment based on spinal cord motion. However, due to MR-Linac restrictions including IMRT fixed fields, fixed collimator, and larger MLC leaves, it is important to determine whether clinically acceptable plan quality is still achievable. Real-time gating of spinal cord motion with the MR-Linac has great potential for controlling spinal cord dose, but plan quality must be ensured. The purpose of this prospective study is to compare SSRS plans that were planned in Monaco for an MR-Linac to those planned in RayStation for a Linac using CT imaging.

Methods

Our research is a prospective study that collected 10 patients enrolled in a clinical trial (NCT05709782) approved by the MDACC institutional review board (PA22-0589), evaluating whether MRL-based SSRS improves treatment response and quality of life. Research plans were created in Monaco and imported into RayStation for comparison with their associated clinical plans. Data regarding tumor coverage, TV, maximum dose, minimum dose, PIV, mean dose and normal tissue sparing (dose fall-off, HI, TVR, EI, PCI, GI) were analyzed. GraphPad Prism was used for descriptive statistics (mean, standard deviation, and range) and analytical statistics (D'Agostino & Pearson test and two-tailed p-value) to calculate significance between Monaco and RayStation plans.

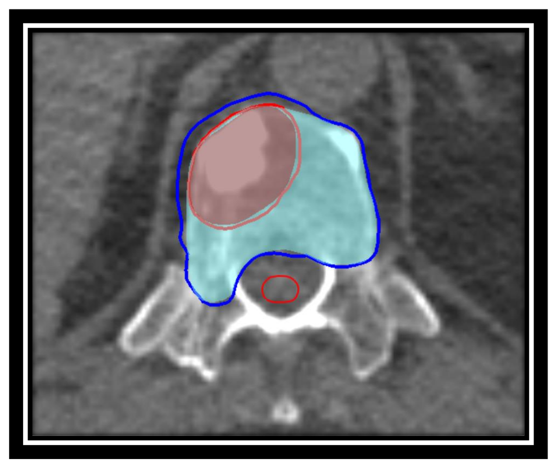


Figure 1 - RayStation

Figure 1 represents an axial slice of the coverage for the GTV (Red) and the CTV (Azure) by the 18 Gy and 16 Gy ISL respectively, for a RayStation planned case.

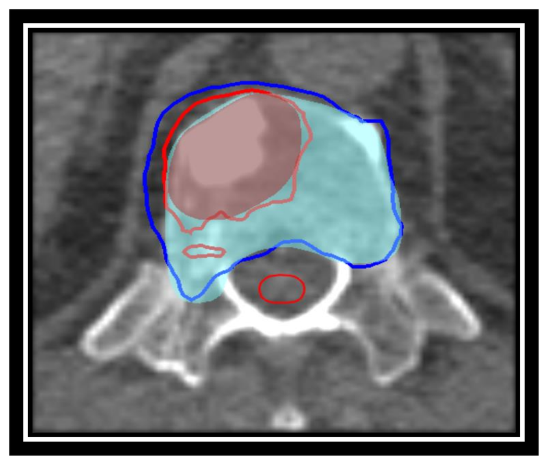
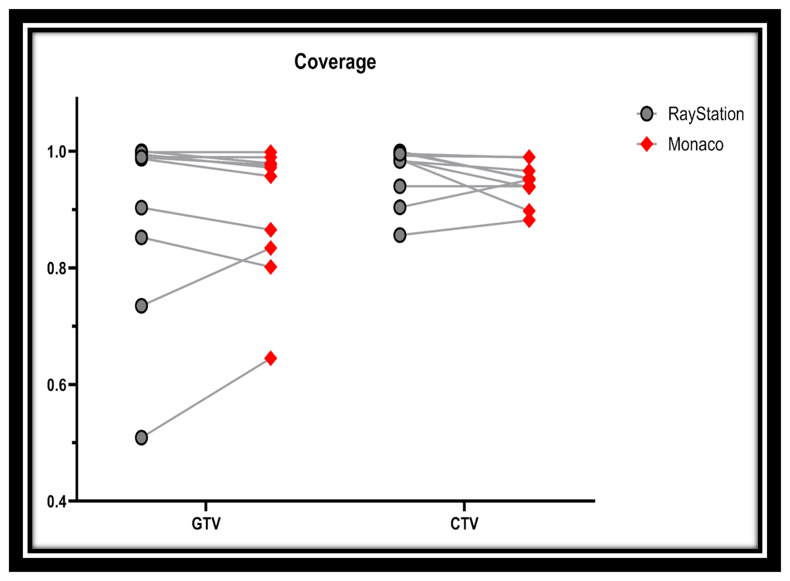
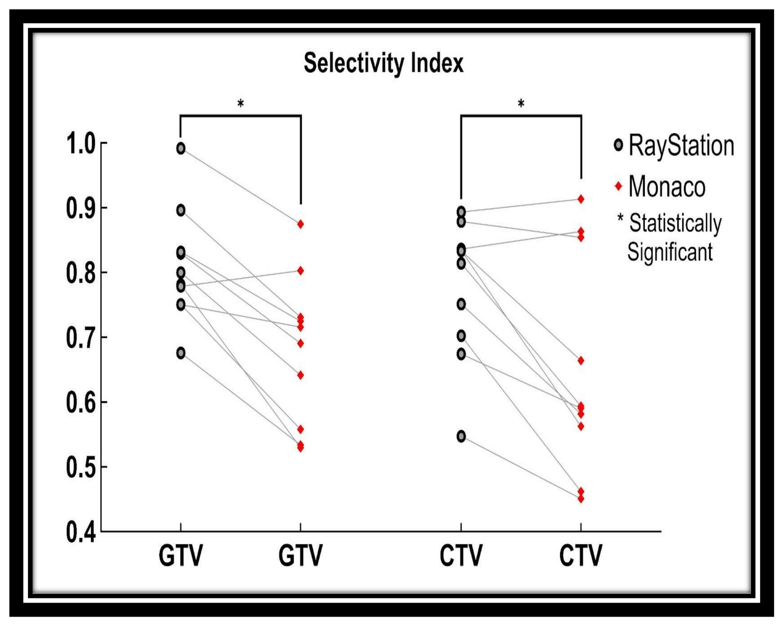


Figure 2 - Monaco

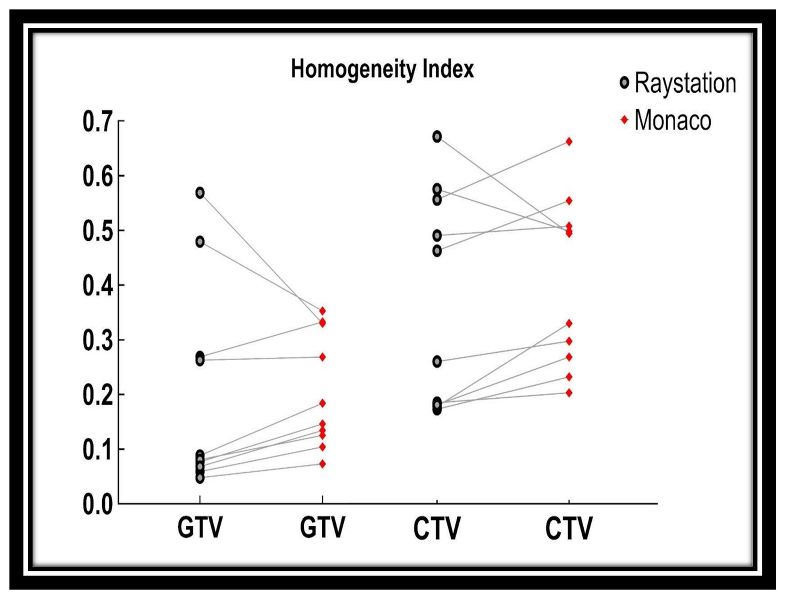
Figure 2 represents an axial slice of the coverage for the GTV (Red) and the CTV (Azure) by the 18 Gy and 16 Gy ISL respectively, for a Monaco planned case.



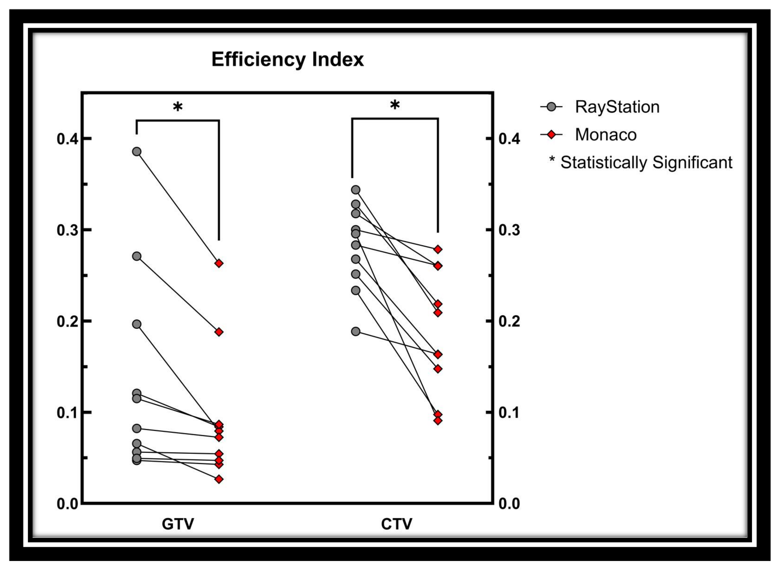
Coverage Graph



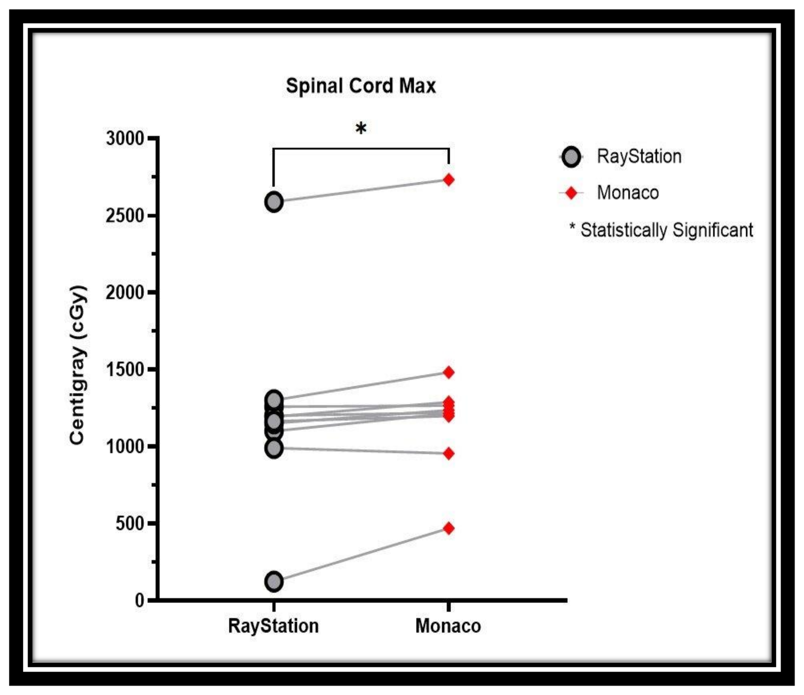
Selectivity Index Graph



Homogeneity Index Graph



Efficiency Index Graph



Spinal Cord Max Dose Graph

Results and Discussion

- Coverage

Monaco plans achieved GTV and CTV coverage comparable to RayStation, which is promising since GTV coverage (Dmin, D98, D95) has been linked to local relapse.

- GTV/CTV Min Dose

GTV and CTV minimum doses did not differ significantly between Monaco and RayStation, suggesting comparable tumor control. Prior studies report similar findings, likely reflecting optimization strategies that achieve consistent clinical goals across different dose calculation algorithms. It should be noted that less conformal dosing and increased normal tissue exposure from Monaco's fixed collimator and larger MLC leaves may increase vertebral fracture risk at ≥20 Gy per fraction.

- GTV/CTV and Spinal Cord Max Dose

Monaco MR-Linac plans had higher maximum GTV/CTV and spinal cord doses than RayStation, likely from Monte Carlo modeling and magnetic effects. Most plans stayed within cord limits, but careful planning is needed to prevent overdosing.

- Conformity

Monaco plans deviated further from 1 than RayStation, indicating poorer normal tissue sparing. Prior studies similarly found tighter conformity with RayStation, possibly due to Monaco's fixed collimator angle and larger MLC leaves rather than the Monte Carlo algorithm itself.

- Paddick Conformity Index

(PCI) and Gradient Index (GI)
Monaco plans had a significantly lower PCI and a higher GI for GTV and CTV, likely due to fixed 80° collimator rotation and thicker 8 mm MLC leaves. This results in less conformal dosing and more normal tissue exposure.

- Homogeneity Index (HI)

The HI measures dose uniformity, with values near 0 indicating better homogeneity.
Monaco and RayStation showed similar results, suggesting comparable uniformity, though Monaco may produce hotter target doses.

- Selectivity Index (SI)

The SI (0–1) reflects how well radiation conforms to the target, with higher values indicating better sparing. Monaco plans had lower values than RayStation, showing poorer conformality and reduced normal tissue sparing.

Results and Discussion (Continued)

- Efficiency Index (EI)

The EI, which compares energy delivered to the target versus surrounding tissue (ideal = 1), was significantly higher for RayStation than Monaco, likely due to MR-Linac limitations like step-and-shoot delivery, fixed collimators, and larger MLC leaves.

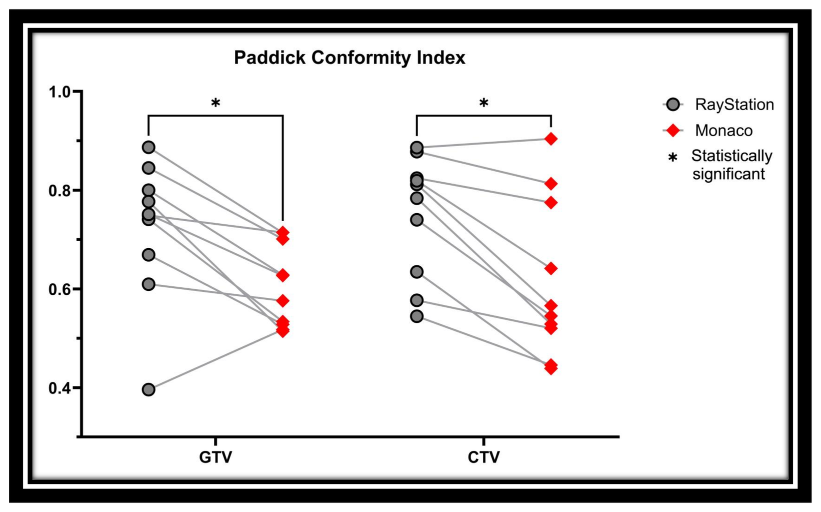
- Tumor Volume Ratio (TVR)

The TVR shows how much of the prescribed dose covers the tumor; lower values indicate better sparing of normal tissue. Tumor volumes were similar in Monaco and RayStation, but RayStation had lower ratios, indicating better tissue sparing likely due to MR-Linac limitations in Monaco, such as fixed collimators and larger MLC leaves.

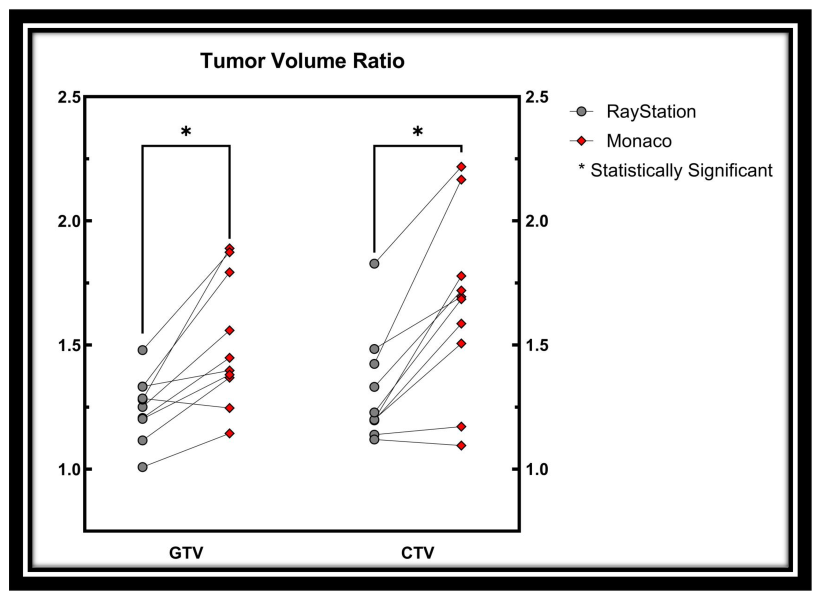
Index	Mean + Std. Dev. (RayStation)	Mean + Std. Dev. (Monaco)	p-value
Selectivity (GTV)	0.81±0.087	0.68±0.12	0.0006
Selectivity (CTV)	0.78±0.11	0.65±0.17	0.0057
Homogeneity (GTV)	0.20±0.19	0.21±0.11	0.0677
Homogeneity (CTV)	0.35±0.18	0.38±0.15	0.3269
Conformity (GTV)	1.38±0.36	1.12±0.25	0.0009
Conformity (CTV)	1.53±0.39	1.27 ±0.21	0.0273
Min Dose (GTV)	1689 cGy±218 cGy	1632 cGy ±308.9	0.3886
Min Dose (CTV)	1364 cGy±138 cGy	1355 cGy±160 cGy	0.9043
Max Dose (GTV)	2399 cGy ±493.8 cGy	2499 cGy ±491.9 cGy	0.0216
Max Dose (CTV)	2399 cGy ±493.8 cGy	2499 cGy ±493.6 cGy	0.0212
Tumor Volume Ratio (GTV)	1.510 ± 0.2616	1.249 ± 0.1286	0.001
Tumor Volume Ratio (CTV)	1.662 ± 0.3612	1.315 ± 0.2163	0.0009
Efficiency (GTV)	0.09442 ± 0.07394	0.1389 ± 0.1128	0.0072
Efficiency (CTV)	0.1890 ± 0.06711	0.2809 ± 0.04704	0.0033
Gradient Index (GTV)	13.75±6.73	16.77±8.18	0.1533
Gradient Index (CTV)	4.30±0.57	6.27±1.86	0.0049
Paddick Conformity Index (GTV)	0.72±0.14	0.61±0.083	0.0098
Paddick Conformity Index (CTV)	0.75±0.12	0.62±0.16	0.0016
Coverage (GTV)	0.90±0.16	0.90±0.11	0.5703
Coverage (CTV)	0.96±0.05	0.95±0.035	0.1309
Spinal Cord Max	1207±592.1 cGy	1306±569.7 cGy	0.0137

Figure 3 - Data

Figure 3 represents some of the analytical data acquired for several indexes.



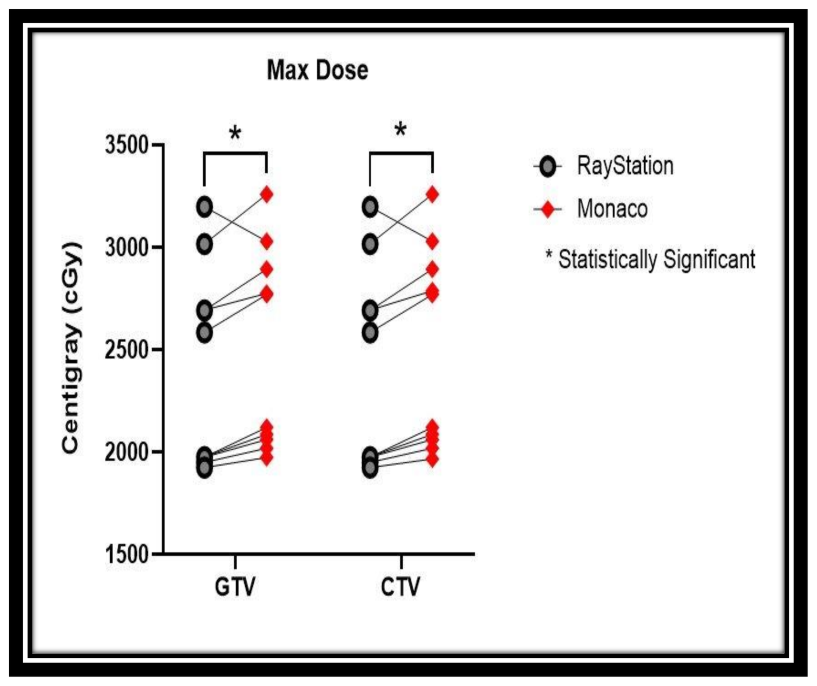
Paddick Conformity Index Graph



Tumor Volume Ratio Graph

Conclusion

- MR-Linac Monaco plans achieved equivalent target coverage, minimum dose, and dose homogeneity compared to TrueBeam-HDMLC RayStation plans, supporting dosimetric feasibility for spinal stereotactic radiosurgery.
- Monaco plans produced significantly higher maximum doses and reduced conformality (lower PCI/selectivity index, higher GI/TVR), attributable to the MR-Linac's 8 mm MLCs, fixed collimator, and step-and-shoot delivery.
- Spinal cord doses remained within published tolerance thresholds in 9 of 10 patients across both platforms.
- The MR-Linac's real-time soft tissue visualization and spinal cord gating may offset conformality trade-offs where precise cord delineation is critical to treatment safety.
- Larger prospective studies investigating optimized gating protocols, patient selection criteria, and algorithm-specific planning strategies are needed to further define the MR-Linac's role in SSRS and bridge the conformality gap while preserving its soft tissue imaging advantages.
- These findings are clinically significant as they support expanding MR-Linac SSRS as a viable treatment pathway for spinal metastases patients, a population where 30-40% of cancer patients present with spinal disease and precise cord sparing directly impacts quality of life.



GTV/CTV Max Dose Graph

References

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