A dosimetric analysis of a spine SBRT specific treatment planning system

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Abstract
Purpose: The Brainlab Elements treatment planning system utilizes distinct modules for treatment planning specific to stereotactic treatment sites including single or multiple brain lesions as well as spine. This work investigates the hypothesis that an optimization tailored specifically to spine can in fact create dosimetrically superior plans to those created in more general use treatment planning systems (TPS).

Methods: Ten spine patients at our institution were replanned in Brainlab Elements, Phillips Pinnacle, and Elekta Monaco. The planning target volume (PTV) included the vertebral body (in either the thoracic or lumbar spine), pedicles, and transverse processes. In all plans, the target was prescribed 20 Gy to 95% of the PTV. Objectives for the study included $D_{5\%} < 25$ Gy and spinal cord $D_{0.035 cc} < 14$ Gy. Plans were evaluated by the satisfaction of the objectives as well total monitor units (MU), gradient index (GI), conformity index (CI), and dose gradient (distance between 100% and 50% isodose lines) in a selected slice between the vertebral body and spinal cord.

Results: All TPS produced clinically acceptable plans. The sharpest dose gradient was achieved with Elements (mean 3.3 ± 0.2 mm). This resulted in lowest spinal cord maximum point doses (6.6 ± 1.0 Gy). Gradient indices were also the smallest for Elements (3.6 ± 0.5). Further improvement in gradient index and spinal cord sparing were not performed due to the subsequent violation of the PTV $D_{5\%} < 25$ Gy constraint or the loss of conformity due to the loss of coverage at the PTV-spinal canal interface.

Conclusions: Brainlab Elements planning which relies on arc duplication to specifically optimize for spine anatomy did result in dosimetrically superior plans while holding prescription levels constant. While any planning system can improve upon specific dosimetric objectives, the simultaneous satisfaction of all constraints was best achieved with Brainlab Elements.

PACS
87.55.D-Treatment planning

KEY WORDS
Monte Carlo, spine, stereotactic body radiosurgery, treatment planning
1 | INTRODUCTION

Stereotactic body radiotherapy (SBRT) of spinal lesions has been increasingly utilized in radiotherapy for spine metastases as well as for primary tumors.\textsuperscript{1,2} It also has a role in the retreatment setting.\textsuperscript{3} The increased use of this technique can be attributed to advances in localization accuracy both in terms of immobilization devices and precise image guidance. Studies estimate the localization accuracy of cone-beam CT (CBCT), Cyberknife, and ExacTrac spine SBRT at sub-millimeter levels in each direction.\textsuperscript{4–7} With an expanded role for this treatment modality, treatment planning, and delivery efficiency as well as the ability to optimize ideal dose distributions are critical.

Brainlab has recently released Elements, its most recent treatment planning approach for stereotactic applications. The package includes tools for Cranial SRS, Multiple Brain Mets SRS, Spine SBRT as well as contouring tools for cranial and spine applications. Within these Elements are tools for image fusion, the correction of spatial distortions and spine curvature in MR scans, and automatic contouring tools. The Elements are designed specifically for the region being treated. For example, when contouring a gross target volume (GTV) for a spinal lesion, the anatomical mapping will automatically generate a CTV contour which expands to encapsulate the spinal region for a spinal lesion, the anatomical mapping will automatically generated treatment. 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arcs was set to 2 (4 total) for those cases in which Elements used arc splitting, and at 1 (2 total) for the cases where Elements did not. In the end, identical numbers of arcs were used between all plans. Minimum segment width was set to 0.5 cm and segment shape optimization was used.

The same planning strategy was used in these planning systems as in Elements. That is to say, starting optimization objectives included 95% coverage of PTV (“min DVH” in Pinnacle3, “target penalty” in Monaco), D5% < 25 Gy (“max DVH” in Pinnacle3, “quadratic overdose” in Monaco), spinal cord maximum dose of 14 Gy (“max dose” in both Pinnacle3 and Monaco). Ring structures were employed in Pinnacle3 for GI control but not in Elements as this is optimized behind the scenes invisible to the user. In Monaco, normal tissue sparing was accomplished with a maximum dose cost function with a shrink margin (avoiding penalizing voxels within some specified distance from a target). Weightings between optimization objectives were set manually in Pinnacle3, set to “auto” in Monaco, and controlled with slider bars in the Elements interface. The manual process of optimization refinement was performed by pushing harder on normal tissue sparing and spinal cord sparing before target coverage and heterogeneity were compromised.

In addition to assessing the ability to meet planning objectives, plan evaluation was performed by recording the total monitor units (MU), gradient index (GI) (volume of 50% isodose volume relative to PTV volume), conformity index (CI) (volume of 100% isodose volume relative to PTV volume), and dose gradient (distance from the 100% to 50% isodose lines in the anterior aspect of the interface between the PTV and spinal cord in the isocenter slice).

### RESULTS

In Brainlab Elements, the optimization created two VMAT arcs for four patients and four arcs for six patients. Target coverage at 20 Gy was achieved at 95.8 ± 0.3% in Elements and at exactly 95.0% in the other two planning systems. Spinal cord maximum dose objectives were easily met in all planning systems, but with much lower maximum cord doses in Elements. Table 1 summarizes the dosimetric evaluation criteria. Figures 2 and 3 summarize sample dose volume histograms (DVH) and dose distributions in all three TPS.

**Table 1** Summary of objectives and evaluation criteria of plans optimized in the three treatment planning systems. Values are averaged across the ten cases and the plus/minus numbers indicate standard deviations.

|                      | Elements | Pinnacle3 | Monaco |
|----------------------|----------|-----------|--------|
| Monitor units        | 7669 ± 1417 | 6836 ± 921 | 9177 ± 1189 |
| PTV coverage (%)     | 95.8 ± 0.3 | 95.0 ± 0.1 | 95.0 ± 0.0 |
| PTV D5% (Gy)         | 24.2 ± 0.3 | 24.5 ± 1.0 | 24.5 ± 0.7 |
| Spinal cord maximum dose (Gy) | 6.6 ± 1.0 | 10.4 ± 0.6 | 9.7 ± 1.1 |
| Gradient index (GI)  | 3.6 ± 0.5 | 5.2 ± 0.7 | 4.5 ± 0.5 |
| Conformity index (CI) | 1.1 ± 0.02 | 1.2 ± 0.1 | 1.2 ± 0.04 |
| Distance 20 Gy IDL to 10 Gy IDL (mm) | 3.3 ± 0.2 | 3.9 ± 1.0 | 4.1 ± 0.4 |

**Fig. 2.** Sample isodose curves from the three treatment planning systems are shown for three patients. The PTV and spinal cord as well as the 20 and 10 Gy isodose lines are shown.
In Elements, the spinal cord maximum dose and gradient index were lowered as much as possible while keeping the maximum dose in the PTV within tolerance and while keeping the CI near 1.1. In Pinnacle and Monaco, further lowering of spinal cord dose and dose gradient was prevented by the D5% nearing 25 Gy and conformity nearing 1.2, as can be seen in Table 1. As these evaluation criteria were nearing the edge of clinically acceptable plans, further optimization was halted. In the final analysis, both spinal

**Fig. 3.** Sample DVH graphs from the three treatment planning systems for three patients. The PTV and spinal cord are plotted.
cords maximum dose and gradient indices were significantly lower in Elements than in the other planning systems. Furthermore, the dose gradient (20 to 10 Gy isodose lines) was 0.6 mm sharper than Pinnacle and 0.8 mm sharper than in Monaco. Target coverage was mostly equal, while more monitor units were required in Monaco, but less in Pinnacle.

A two-tailed Wilcoxon signed-rank test (due to the low sample size) was also conducted to evaluate the null hypothesis of no difference between the TPS. No statistical difference was found for CI for Elements plans vs either Pinnacle or Monaco. For GI, the W-values were 0 for Elements plans vs both Pinnacle and Monaco, respectively, which is less than the critical value of 8 meaning the improvements in gradient index were statistically significant with Elements. Spinal cord maximum doses were also statistically different with W-values of 0. W-values of 5 and 0 were found for the distances from 100% to 50% isodose lines for Pinnacle and Monaco respectively.

4 | DISCUSSION

The main dosimetric findings include the lower GI and spinal cord maximum dose with similar conformity and dose heterogeneity. These results were compared with a study in the literature investigating spinal radiosurgery plans across systems and across institutions. In that study, with 95% PTV coverage, the average CI was 1.47 and ranged from 1.08 to 2.04. CI in this study is clearly on the lower end of this range. The ability to better spare normal tissues such as the spinal cord is made possible by the arc splitting concept employed by Elements. The benefit is not only due to the second pass to create more control points to meet objectives, but rather due to treating distinct sectors of the target in separate arcs particularly in regions of target concavity (such as the spinal cord). At gantry angles of 90 and 270, the optimizer is not forced to put fluence through the spinal cord to irradiate the bilateral transverse processes. If it is only asked to treat the proximal transverse process, the optimizer does not face as much conflicting penalty from cord dose overirradiation and distal transverse process underirradiation. A separate pass can focus on the contralateral side.

The physical dose gradient from 20 to 10 Gy isodose line was smaller in Elements, but it is difficult to determine if this is a conclusive finding since the differences were relatively modest. In patients not requiring as extensive treatment of the transverse processes, it is expected that the advantages of Elements would be smaller.

Based on the excellent spinal cord sparing, it may be possible to investigate dose escalation for such spine SBRT cases. In fact, Mousazadeh et al. have reported use of 24 Gy for SBRT with mean PTV volumes of 67.9 cc, approximately twice the PTV volume in this study. In that study, overall maximum dose to the spinal cord was 13.4 Gy. With a mean spinal cord maximum doses of 6.6 Gy in the Elements plans in this study, escalation to 24 Gy would be possible with even lower risks of spinal cord toxicities than in that study.

Calculation time is often a significant parameter for consideration of the efficiency of the treatment planning process, particular for stereotactic radiotherapy given the importance of the temporal gap between the MR study, CT simulation, and treatment. Calculation times are difficult to compare between planning systems given variations in computer hardware capabilities and calculation volumes among other complicating factors. Nevertheless, typical pencil-beam algorithm optimization times were on the order of a minute in Brainlab Elements, extending to several minutes for Monte Carlo optimization. Final planning times in Brainlab Elements after alteration of a several planning tools resulting in plan creation in 30–45 min.

Brainlab Elements is also characterized by a protocol-driven approach to treatment planning. Prescriptions, constraints to OAR, and relative importance of organs are set offline in protocols, moving much of the plan modification behind the scenes. Such a workflow moves into the automated treatment planning regime, displacing much of the time spent entering objectives and technical parameters from patient-specific planning to the initial commissioning of the software. Careful attention must be paid upfront, however, to the input of the physician and physicist so that clinical prescriptions and delivery approach can be settled before final commissioning of the treatment technique is performed.

5 | CONCLUSIONS

The spine module in Brainlab Elements was evaluated from a treatment planning standpoint on its ability to optimize spine SBRT dose distributions. Similar plans were generated in other commonly used TPS to determine if the anatomy-specific Elements plans are dosimetrically superior to others. Specifically, the spinal cord maximum dose, gradient index, and steepness of the dose falloff between the PTV and spinal cord were found to be improved in Elements plans.

CONFLICTS OF INTEREST

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REFERENCES

1. Chang UK, Lee DH. Stereotactic radiosurgery for spinal neoplasms: current status and future perspective. J Neurosurg Sci. 2013;57:87–101.
2. Hall WA, Stapleford LJ, Hadjipanayis CG, Curran WJ, Crocker I, Shu HKG. Stereotactic body radiosurgery for spinal metastatic disease: an evidence-based review. Int J Surg Oncol. 2011;2011:1–11.
3. Elbe E, Boyce-Fappiano D, Siddiqui S, Lee I, Rock J, Siddiqui F. Repeat courses of spine stereotactic radiosurgery (SRS): efficacy and toxicity. Int J Radiat Oncol Biol Phys. 2017;99:E518–E519.
4. Gerszten PC, Monaco 3rd EA, Quader M, et al. Setup accuracy of spine radiosurgery using cone beam computed tomography image guidance in patients with spinal implants. J Neurosurg Spine. 2010;12:412–420.
5. Quader MA, Novotny J, Flickinger JC, Huq MS, Gerszten PC. Evaluation of patient positioning accuracy during stereotactic spinal
radiosurgery using cone beam CT. *Int J Radiat Oncol Biol Phys*. 2008;72:S528.

6. Ho AK, Fu D, Cotrutz C, et al. A study of the accuracy of cyberknife spinal radiosurgery using skeletal structure tracking. *Neurosurgery*. 2007;60:ONS147–ONS156.

7. Chang Z, Wang Z, Ma J, O’Daniel JC, Kirkpatrick J, Yin FF. 6D image guidance for spinal non-invasive stereotactic body radiation therapy: comparison between ExacTrac X-ray 6D with kilo-voltage cone-beam CT. *Radiother Oncol*. 2010;95:116–121.

8. Cox BW, Spratt DE, Lovelock M, et al. International spine radiosurgery consortium consensus guidelines for target volume definition in spinal stereotactic radiosurgery. *Int J Radiat Oncol Biol Phys*. 2012;83:597–605.

9. Heron DE, Rajagopalan MS, Stone B, et al. Single-session and multi-session CyberKnife radiosurgery for spine metastases—University of Pittsburgh and Georgetown University experience. *J Neurosurg Spine*. 2012;17:11–18.

10. Moustakis C, Chan MKH, Kim J, et al. Treatment planning for spinal radiosurgery. *Strahlenther Onkol*. 2018;194:843–854.

11. Moussazadeh N, Lis E, Katsoulakis E, et al. Five-year outcomes of high-dose single-fraction spinal stereotactic radiosurgery. *Int J Radiat Oncol Biol Phys*. 2015;93:361–367.