An automated inverse planning optimization approach for single-fraction and fractionated radiosurgery using Gamma Knife Perfexion

Innovation/Impact: We propose a treatment planning optimization method to generate conformal single-fraction and fractionated stereotactic radiosurgery (SRS) plans for Gamma Knife® Perfexion™. The innovation in this work is that the current version of treatment planning system does not support inverse planning that takes into account organs-at-risk (OARs) or DVH-based criteria. Additionally, feasibility of delivering fractionated SRS can increase OARs sparing and allow for frameless treatments.

Introduction: The Leksell Gamma Knife® Perfexion™ units are typically used to deliver single-fraction SRS treatment plans. Fractionated SRS, in which a planning target volume (PTV) is considered to account for patient setup variations, can be an attractive alternative. In fractionated SRS it is essential that homogeneity is preserved because the PTV can have a large overlap with OARs.

Method and Materials: Our approach consists of two steps; First, we use a grassfire and sphere-packing hybrid to identify a good set of isocentre positions. Once the isocentres are selected, we use a mathematical optimization model to find the optimal combination of all collimator sizes as well as their intensities. The isocentre selection procedure is an iterative approach that at each iteration finds an isocentre based on a scoring method. At the selected isocentre, a sphere (as an estimation of a shot; the actual shot will be found later in the optimization step) is placed and the resulting covered area is deleted from the target volume. This iterative procedure continues until satisfactory coverage of the target is achieved. In the next step, the obtained set of isocentres is used in an optimization model to find the optimal shot shape (combination of collimator sizes) and their duration of irradiation. This sector duration optimization model is a penalty-based problem that minimizes the deviation of the delivered dose from the objective dose in all the structures, and is solved using a projected gradient algorithm.

In single-fraction SRS, a ring around the target is introduced to achieve conformal target coverage. In fractionated SRS, a higher weight is considered for dose homogeneity in the optimization model. Also fewer isocentres, and with a different scoring methods, are chosen in the overlap area of PTV and OARs.

Results: We have tested our approach on 7 clinical cases (comprising of 11 targets: four acoustic neuromas impinging upon the brainstem cases and seven variously sized brain metastases).

For single-fraction SRS, the clinical objective is $V_{100} \geq 98\%$ while dose to $1\text{mm}^3$ brainstem is under 15Gy. The obtained inverse single-fraction SRS plans are compared against manually-generated forward plans in Table 1. The results illustrate an improvement of +0.08 (range: 0.00 to +0.17) in Paddick and -0.12 (range: -0.27 to +0.03) in classic conformity indices in inverse plans. The mean dose to $1\text{mm}^3$ brainstem is 0.24Gy less in inverse plans (range: -2.4Gy to +2.0Gy). The beam-on time in inverse plans, however, is on average 33min longer. It is worth mentioning that beam-on time is not considered explicitly in our approach.

The clinical guideline for fractionated SRS plans is to achieve $V_{99} = 100\%$ for the gross target volume (GTV) and $V_{95} = 95\%$ for PTV, while keeping the dose to $1\text{mm}^3$ brainstem under 108% of the prescription dose (Rx). Table 2 shows the results for inverse fractionated SRS plans. As the table suggests, OARs could be spared with $1\text{mm}^3$ brainstem receiving a mean dose of 87.8% of Rx. In the case with the largest PTV overlap (case 7a), $1\text{mm}^3$ of brainstem receives only 8% higher than the Rx. Figure 1 illustrates the dose volume histogram and isodose-line figures for various cross-sections of a representative case (case 1). The maximum dose delivered for this case is less than 120% of Rx.
Figure 1: A fractionated SRS plan for a representative case with 55 isocentres shows good target coverage and OARs sparing. Cross-sectional figures show the conformal prescription isodose line (100% Rx) as well as 50%, 95%, and 110% Rx.

Table 1: Comparison of single-fraction SRS (Inv) plans with manually-generated plans (Fwd).

Table 2: Plan quality summary for fractionated SRS (Inv) and clinically delivered plans (Clin).

*: number of isocentres in inverse plans. †: maximum dose to 1mm³ of brainstem (in fractionated plans it is relative to Rx dose). ‡: beam-on time. BS=brainstem. Ch=Chiasm. Cl=Cochlea. **: percentage of PTV overlapping with each OAR.