Sector Intensity Modulated (SIM) Gamma Knife Stereotactic Radiosurgery

In this study, we proposed a novel concept of Sector Intensity Modulated (SIM) Gamma Knife plan. The key component of this innovation is to add more degrees of freedom for the gamma knife planning by dynamically allowing the beam-on time of each individual sector to be weighted independently. We showed that our proposed prototype system is efficient in providing better conformal plans while retaining full target coverage and minimizing dose to healthy tissues compared to the commercial based clinical plan.

This innovative concept was tested on multiple pituitary adenoma cases (one example shown in Fig.1), as they are usually difficult to plan. They require: 1) extremely high radiation dose to target, 2) very conformal dose distributions to spare critical structures, 3) absolutely no more than 8Gy to the optic nerve and chiasm. The prescription dose is 28 Gy to the 50 % isodose for hormone secreting tumors, and 14Gy for non-hormone secreting tumors. The anatomic structure and dose matrices from each sector for every shot as in Fig.3 were first obtained from the Gamma Knife planning workstation. The beam-on time of each individual sector varied independently with original beam-on time (T0) decomposed into different discrete levels, e.g. 10 interval levels with sector 1 open 0.6xT0, sector 2: 0.1xT0 etc. An in-house coded planning system with brute force algorithm was used to search optimized plans. Six quantitative numbers were utilized to evaluate the treatment plan quality, Coverage: \( \frac{Vol (PIV \cap TV)}{Vol (TV)} \), Gradient: \( \frac{Vol (PIV 50\%)/Vol (PIV 25\%)}{Vol (PIV \cap TV)} \), Conformality: \( \frac{Vol (PIV)^2\times Vol (TV)/Vol (PIV \cap TV)^2}{Vol (TV)} \), and Maximum dose to critical structure(s) including Gland, Stalk, Optical Nerve (ON) and Chiasm if applicable. As shown in Fig.2, TV in red is target volume, PIV in yellow (or PIV 50% if prescription dose is at 50%) is the prescription isodose volume, PIV in green is half of the prescription isodose (PIV 25% if prescription dose is 50%), PIV \( \cap \) TV in blue dash is the proportion of the prescription isodose volume inside the target volume. Better plan were reached with lowering in all quantitative indices as Gradient, Conformality, V8, V12 and Maximum dose to critical structure(s) while retaining at least 99% Coverage of the target. The resulting SIM plans were then re-entered into the Gamma Knife planning workstation and further compared with the commercial based clinical plan by an experienced oncologist.

The results for different pituitary adenomas even with small sizes from 200 - 500 mm\(^3\) consistently showed the SIM improved the plan quality with all quantitative numbers better than original clinical plan. Results were also confirmed by oncologist’s reading. One example is given in Fig. 4, the prescription isodose line (yellow) from both the original and SIM plan showed 99% coverage of the tumor target (in red) and optical nerve/chiasm (cyan) received less than 8Gy (green). However, the SIM plan gave better conformality, which can be clearly seen from coronal view as the prescription isodose line (yellow) covered less healthy tissue. It also showed steeper drop off the dose outside the prescription dose (between yellow and green) on sagittal view. In particular, up to 20% decrease in volume receiving higher than 8Gy was observed as shown in Fig. 4(d). The better quality plans were reached with more discrete decomposition levels of the beam-on time. The absolute volume reduction could reach up to 0.61cc while the original volume receiving over 8Gy was of only 3.12 cc (3120 mm\(^3\)). This may translate into clinically observable reduction in acute/late toxicities, which is particularly true for pituitary adenomas as delivering more than 8Gy to optic nerve would lead blindness to patients.

Overall, our preliminary results show that Sector Intensity Modulated (SIM) Gamma Knife plan offers exceptional degrees of dynamics for achieving unparalleled dose conformality in brain radiosurgery. More cases with diversified tumor volumes up to 4-cm in diameter for different brain diseases are needed to validate our work. Further research including adding more freedoms as the dynamic shot location and dynamic shot shaping are under investigation.
Fig 1: An in-house built Matlab® program showing (a) axial (b) sagittal, (c) coronal views of one pituitary adenoma case on MRI, with target tumor outlined in red, critical structures as stalk in green, gland in magenta, optic nerve and chiasm in cyan. Color-coding was the same for all figures.

Fig 2: Zoom-in view with dose map overlay to target showing definitions of objective terms used in optimization.

Fig 3. The dose maps corresponding to the contribution of each sector with the same amount of beam-on time from the original plan were shown, (a) dose map overlay to the MR image from one shot of the original plan, (b) dose map from sector 1 at the same location of that shot, (c) dose map from sector 2.

Fig.4 One example showing the original plan and Sector Intensity Modulated (SIM) Gamma Knife plan from (a) axial, (b) sagittal, (c) coronal view, respectively. The tumor target is outlined in red, and prescription isodose line is in yellow, while 8 Gy isodose line is in green. The quality of SIM plan normalized to the original clinical plans is shown in (d), lower indices better plan.