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Use of Dynamic Lattice Structures to Optimize Biological Effectiveness of Spatially Fractionated Radiation Therapy in Brain Metastases

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ABSTRACT

Purpose: To evaluate the efficacy of dynamic lattice structures in Gamma Kinfe (GK) Spatially Fractionated Radiation Therapy (SFRT) and compare their performance against traditional static lattice designs. Plans were assessed using Equivalent Uniform Dose (EUD), Valley-Peak-Ratio (VPR), Target Mean Dose (TMD) and Therapeutic Ratio (TR).

Methods: CT images and target tumor contours were obtained from 20 patients with large brain metastases under an IRB-approved study protocol. For the GK planning system, SFRT vertices were generated using an in-house script and subsequently imported. Radiation shots were localized within a tumor volume retracted by 3mm margin, delivering a single fraction dose of 18Gy to the 70% isodose line. The treatment plan utilized a face-centered-cubic (FCC) lattice structure with 4 mm or 8 mm spheres. To maintain a consistent valley dose regardless of sphere sizes or number of spheres, an iterative optimization algorithm was employed to dynamically adjust lattice constants based on 3D dose profiles of the spheres.

Results: While static lattice plans exhibited significant metric variability between 4 mm and 8 mm sphere sizes, dynamic lattice placement demonstrated superior consistency. Specifically, EUD averages for static lattices were 4.6 (4mm) and 2.6 (8mm), whereas dynamic lattices yielded more uniform average of 3.9 and 4.1. This trend toward stability was mirrored in other metrics; TR averages were 1.5 and 1.0 vs 1.2 and 1.3; VPR values averaged 6.6 and 3.8 vs 6.2 and 5.1; and TMD values averaged 0.32 and 0.21 vs 0.26 and 0.33.

Conclusion: Dynamic lattice construction facilitates more robust planning by ensuring consistent EUD, VPR, TMD, and TR values independent of sphere size or quantity. This optimization approach represents a clinically viable and reliable method for SFRT planning.

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INTRODUCTION

SFRT utilizes extremely heterogeneous dose distributions to treat large tumors where a conventional, homogeneous, dose distribution may be possible (1). SFRT plans are prepared with some level of optimization but use fixed lattice constants when spacing the spheres. This research shows that plans of consistent quality can be produced regardless of tumor size using a dynamic lattice generation method.

METHODS AND MATERIALS

Using CT images and contours from 20 patients over 10 years with large brain metastases, sphere volumes were generated by in-house scripts, and the lattice is placed over the patient CT by experienced physicists to maximize the number of spheres in the target volume. Spheres were placed such that no part of any sphere was within 3mm of the surface of the target volume. The lattices used had a Face-Centered-Cubic (FCC) arrangement, chosen as it has the largest fill factor. The Gamma Knife shots were used as lattice points and were either 8 mm or 4 mm in size. An iterative optimization algorithm then modified the lattice constant, or spacing between the shots, to achieve consistent valley dose, and thus consistent plan quality, across the plans. For the 8mm dynamic lattice construction, if a shot would be excluded for existing within the 3mm subtraction of the target, it would be replaced by a 4mm shot. The target valley dose for all lattice types was below 33% of the prescription dose. Figure 1 demonstrates shot placement for the different types of lattices and shot sizes. Figure 2 demonstrates this in 3D and shows the process of replacing an 8mm shot with a 4mm where an 8mm shot would be on the boundary of the 3mm subtraction

To establish a metric for consistency, 4 mm shot plans were compared with 8 mm shot plans. The metrics used were Effective Uniform Dose (EUD), Therapeutic Ratio (TR), Target Mean Dose (TMD) and Valley-Peak-Ratio (VPR). TR was calculated for varying tissue types and tumor responses to radiation. P-analysis was conducted to evaluate changes in consistency when using a dynamic lattice constant. These consistency metrics were compared between the static and dynamic lattice plans.

RESULTS

The dynamic plans showed increased consistency in all metrics used. For static lattices EUD and TR values varied significantly more between the 4 mm shot plans and the 8 mm shot plans than the dynamic lattices. The p-values for dynamic lattice plans were also significantly higher than those for the static lattice plans which also shows greater consistency. Table 1 shows the average values for each parameter across all plans.

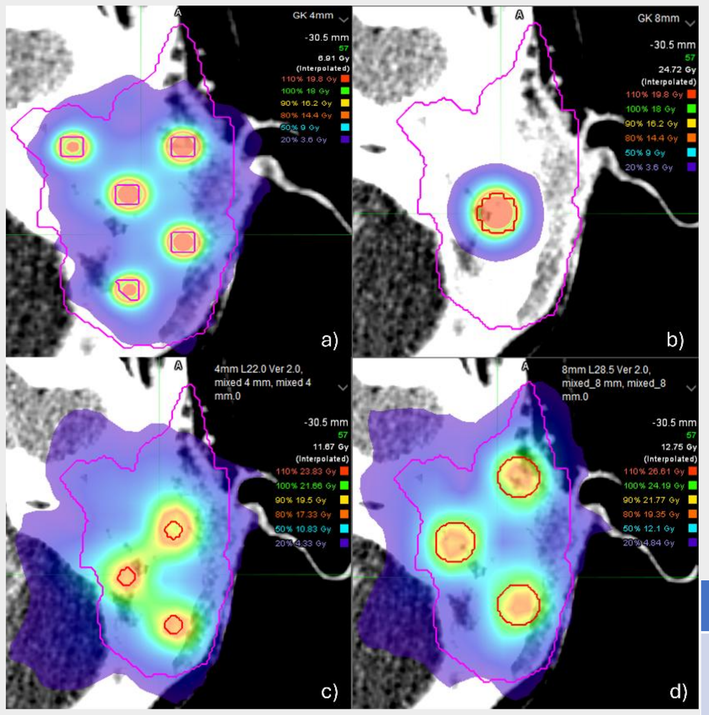

Figure 1. Demonstration of the generation of the static 4 mm lattice (a), static 8 mm lattice (b), dynamic 4 mm lattice (c) and dynamic 8 mm lattice (d). Target volume is highlighted in magenta.

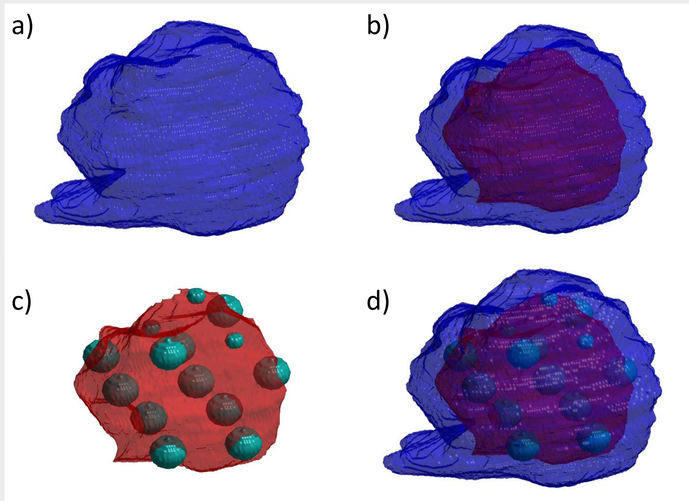

Figure 2. Shot placement in 3D. The target volume is shown in a) and the 3mm subtraction is highlighted in b). The placement of shots and replacement of 8mm shots outside of the subtraction is shown in c) and d) shows the final shot placement inside the target volume.

DISCUSSION

The lattices created with dynamic spacing performed most similarly to the static lattices using 4mm shot placements and had increased TR, EUD, TMD, and VPR compared to the 8mm static lattices. The goal of the algorithm that generated the dynamic lattices was to maintain a valley dose below 33% of the prescribed dose, which increased the spacing between shots as the number of shots also increased. As a result, larger tumors saw significantly larger lattice sizes than other tumors. This constraint led to the increased plan consistency.

Increased consistency in plan quality, regardless of shot size, **provides for further optimization** with other parameters such as lattice type. For example, the FCC lattice used in this research has a distinctly high packing ratio, but other lattices, such as close packed hexagonal (CPH) or body centered cubic (BCC) may produce similar or better results while decreasing delivery time. Lattice type may also be varied with shot size to achieve desired valley doses, such as using a BCC lattice with 8mm shots.

Parameter		4mm Static	8mm Static	p-Value Static	4mm Dynamic	8mm Dynamic	p-Value Dynamic
EUD	Normal	4.4	2.6	5.99E-13	**4.0**	**3.8**	0.258
	Sensitive	4.2	2.4	1.37E-12	**3.7**	**3.5**	0.331
	Semi-Resistant	4.8	2.7	4.52E-13	**4.2**	**4.0**	0.164
	Resistant	5.1	2.8	3.15E-13	**4.5**	**4.2**	0.105
TR	Sensitive	0.8	0.8	2.95E-09	**0.8**	**0.8**	3.60E-3
	Semi-Resistant	1.5	1.1	1.55E-10	**1.3**	**1.2**	4.50E-3
	Resistant	2.1	1.2	4.06E-10	**1.8**	**1.5**	1.40E-3
TMD		6.6	3.8	1.43E-12	**6.2**	**5.1**	9.76E-4
VPR		0.32	0.21	1.26E-11	**0.26**	**0.33**	3.60E-10

Table 1. Comparisons of several plan metrics for various tissue and tumor types across the different plans.

CONCLUSIONS

The use of dynamic lattice constants for spatially fractionated radiation therapy for brain metastases shows improved consistency across shot sizes which promotes further optimization of SFRT plans for large brain metastases.

REFERENCES

1.Cho YB, Yoon N, Suh JH, Scott JG. Radio-immune response modelling for spatially fractionated radiotherapy.
2.Hadfield, et. Al., Retrospective Planning Study for the Evaluation of Biological Effectiveness of Spatially Fractionated Radiation Therapy with Gamma-Knife Radiosurgery on Brain Metastases (in Review)

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