Clinical Neuroscience Research, 2024, Volume 2, Issue 4
http://ojs.bbwpublisher.com/index.php/CNR
Online ISSN: 2981-8133

Discussion on the Splitting Treatment Technique in Gamma Knife Treatment Plans

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Abstract: *Objective:* In clinical Gamma Knife treatment, when patients have multiple or large lesions, a single Gamma Knife plan may require extended treatment time, making it difficult for patients to complete the session. This study explores the proper application of the splitting treatment technique in Gamma Knife treatment plans to create segmented plans for patients. *Methods:* Utilizing the design and output functions of the radiotherapy planning system, this study examines the typical errors in clinical treatment plans designed for the Moonlight Gamma Knife. Different splitting approaches were analyzed by comparing beam-on time for each target and calculating beam-on time error rates. Based on this, the appropriate splitting treatment technique for Gamma Knife treatment plans was discussed. *Results:* Scenarios where dose curves of multiple lesions intersect were categorized into three types: complete intersection, partial intersection, and no intersection. Complete intersection cases were further divided into Type I and Type II complete intersections. For cases with completely intersecting dose curves, the Gamma Knife plans should be split using the upper-lower segmentation method. For cases with no intersection, plans can be split based on individual lesions. For partial intersection cases, either the upper-lower segmentation or lesion-based segmentation method may be used. However, careful handling of target weighting at the dose curve intersection is necessary to ensure dose accuracy. For large lesions, the upper-lower segmentation method is recommended. *Conclusion:* To meet clinical treatment requirements, the proper application of the splitting treatment technique in Gamma Knife treatment plans is essential. This ensures dose accuracy in radiotherapy, thereby guaranteeing treatment efficacy and patient safety.

Keywords: Gamma Knife; Splitting treatment plan; Beam-on time; Dose curve

Online publication: December 26, 2024

1. Introduction

Gamma Knife treatment, as a non-invasive radiosurgical technique, has achieved significant success in the field of neurosurgery since its inception. It uses precisely focused gamma rays to deliver high-dose radiation to lesions while minimizing damage to surrounding healthy tissues [1,2].

When patients have multiple or large lesions, using a single treatment plan for one session results in prolonged treatment time, making it difficult for patients to complete the session. Under the same prescribed dose, increasing the number of fractions reduces the single-session dose, which compromises the Gamma Knife's advantage of delivering a high single-session dose. The splitting treatment technique addresses this by ensuring efficacy while meeting the practical treatment needs of patients [3].

Plan splitting is often complex, requiring careful balancing of treatment doses and radiation coverage among different lesions [4]. This study explores the appropriate application of the splitting treatment technique in Gamma Knife treatment plans to facilitate segmented treatment for patients.

2. Materials and methods

2.1. Materials

This study utilized the planning design and output functions of the Xi'an Integrated Luna-260™ Gamma Knife Radiotherapy Planning System 3.0 (RTPS) to explore the splitting treatment technique for Gamma Knife treatment plans.

2.2. Research methods

Using the planning design and output functions of the radiotherapy planning system, typical clinical treatment plans prone to design errors in Luna-260™ Gamma Knife planning were identified. Plans were designed using different splitting methods, and the beam-on times for each target point were recorded. The beam-on time error rates were compared and analyzed to investigate the correct splitting technique for Gamma Knife treatment plans.

2.3. Principles of the splitting treatment technique

The splitting treatment technique for Gamma Knife treatment plans involves dividing a single treatment plan into two or more plans to meet the patient's treatment needs [5].

3. Clinical application of the splitting treatment technique

3.1. Typical clinical Gamma Knife treatment plan

A male patient with liver cancer and pulmonary metastases underwent Gamma Knife treatment at the hospital in October 2024. Two adjacent metastatic lesions in the lungs required treatment, as illustrated in **Figure 1**.

The combined treatment plan (Plan AB) for lesions 1 and 2 provides the most accurate beam-on time for each target point, serving as a reference for evaluating other splitting plans, as shown in **Figure 1AB**.

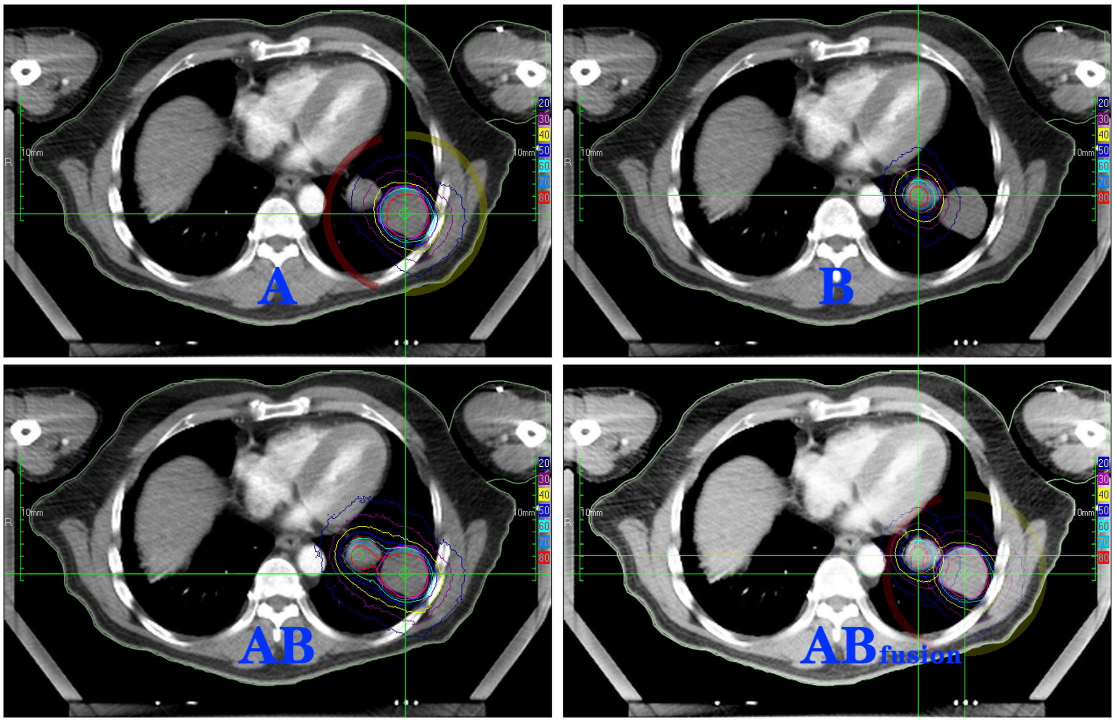

Figure 1. Dose curve diagram for two adjacent lesions (complete intersection type II). **Figure 1AB** represents the dose curve diagram for the combined treatment of lesions 1 and 2. **Figure 1A** represents the dose curve diagram for Plan A, which treats lesion 2. **Figure 1B** represents the dose curve diagram for Plan B, which treats lesion 1.

3.2. Evaluation of lesion-based splitting plans

For lesion-based splitting, lesions 1 and 2 were treated separately, with Plan A designed for lesion 1 (**Figure 1A**) and Plan B designed for lesion 2 (**Figure 1B**).

For a single treatment session with a prescription dose of 5 Gy at the 50% isodose line, the beam-on times for target points in Plans A, B, and AB are compared in **Table 1**.

Table 1. Comparison of beam-on times (seconds) across splitting methods

Plan	Target	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
AB		105	175	175	140	332	273	332	227	329	175	262	175	122	87	280
A	Split by lesion	137	/	/	182	/	356	/	297	/	/	342	/	160	114	365
B		/	201	201	/	383	/	383	/	379	201	/	201	/	/	/
EF		105	175	175	140	332	273	339	231	336	178	266	178	122	87	280
E	Split by upper-lower	105	175	175	140	333	273	/	/	/	/	/	/	/	/	280
F		/	/	/	/	/	/	353	241	351	187	277	187	127	91	/

(Note: Data in **Table 1** were collected from the typical clinical treatment plans listed. The prescribed single-session dose was 5 Gy at the 50% isodose line. The table compares beam-on times (in seconds) across different splitting methods. Data marked as "/" indicate that the plan does not include the corresponding target point.)

The error rates for beam-on times in Plan A compared to the original combined Plan AB for each corresponding target point are as follows: target point 1: (137–105)/105 = 30.48%, target point 4: 30%, target point 6: 30.4%, target point 8: 30.84%, target point 11: 30.53%, target point 13: 31.15%, target point 14: 31.03%, and target point 15: 30.36%. The average beam-on time error rate for all target points in Plan A is 30.6%.

For Plan B, the error rates for each target point are: target point 2: (201–175)/175 = 14.86%, target point 3: 14.86%, target point 5: 15.36%, target point 7: 15.36%, target point 9: 15.2%, target point 10: 14.86%, and target point 12: 14.86%. The average error rate for all target points in Plan B is 15.05%.

This indicates that splitting the plan in this manner introduces significant beam-on time errors, leading to inaccurate treatment doses.

Figure 1AB$_{\text{fusion}}$ shows the image resulting from merging **Figures 1A** and **1B**. The overlapping isodose lines for lesions 1 and 2 demonstrate that when lesion 1 is treated with Plan A and lesion 2 with Plan B, each lesion is influenced by the dose from the other's target points to varying degrees. This results in dose error rates that exceed beam-on time error rates, explaining the inaccuracy of this splitting method.

3.3. Evaluation of upper-lower splitting plans

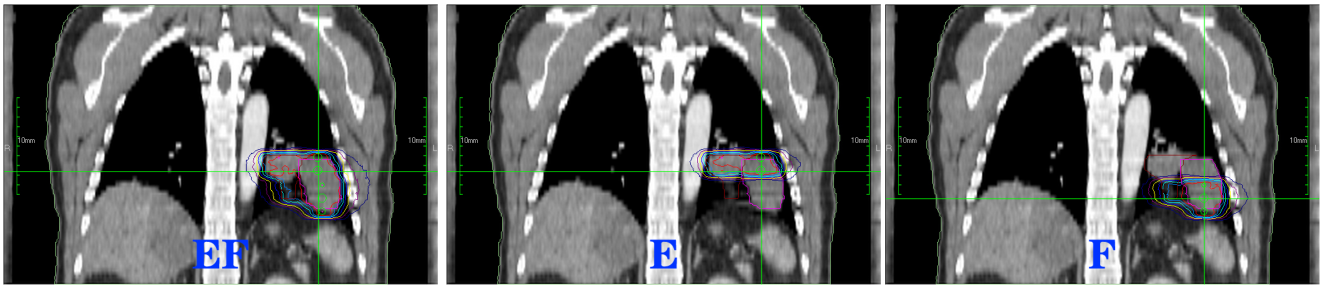

Figure 2. Coronal dose curve diagram for correct splitting plans. **Figure 2EF** represents the combined dose curve diagram for lesions 1 and 2, corresponding to the same plan as **Figure 1AB**. **Figure 2E** represents the dose curve diagram for Plan E, which targets the upper half of EF. **Figure 2F** represents the dose curve diagram for Plan F, targeting the lower half of EF.

First, lesions 1 and 2 were treated as a whole to design Plan EF (**Figure 2EF**). Then, the lesions were split into upper and lower parts along the cranio-caudal axis, resulting in two separate plans: Plan E (**Figure 2E**) and Plan F (**Figure 2F**).

The coronal dose curve diagrams in **Figure 2** illustrate the differences before and after splitting.

For a single-session prescribed dose of 5 Gy at the 50% isodose line, the beam-on times for Plans E, F, and EF are shown in Table 1. All beam-on times in Plan E are identical to those in Plan EF, resulting in an average beam-on time error rate of 0. For Plan F, the error rates for each target point compared to Plan EF are: target point 7: (353–339)/339 = 4.13%, target point 8: 4.33%, target point 9: 4.46%, target point 10: 4.46%, target point 11: 4.13%, target point 12: 5.06%, target point 13: 4.1%, and target point 14: 4.6%. The average beam-on time error rate for Plan F is 4.41%.

In summary, the lesion-based splitting method (Plan AB) resulted in an average beam-on time error rate of 23.34%. In contrast, the upper-lower splitting method (Plan EF) achieved a significantly lower average error rate of 2.35%. After splitting Plan EF into Plans E and F, Plan E showed no beam-on time errors, while Plan F retained minor errors due to the inherent uneven dose distribution in the original Plan EF. However, the splitting process improved dose uniformity between the upper and lower parts. Thus, Gamma Knife treatment plans for such cases should adopt the upper-lower splitting design. The use of the correct splitting technique is critical, as it directly affects dose accuracy, treatment efficacy, and patient safety [6].

4. Results

As a senior radiotherapy treatment planner (physicist), I have been designing Gamma Knife and accelerator treatment plans since 2006, having developed over 12,000 Gamma Knife treatment plans for more than 10,000 patients. This section provides a summary and experience-sharing regarding common errors in designing split treatment plans for Gamma Knife therapy. Feedback and corrections from experts and colleagues are welcome.

To correctly apply Gamma Knife treatment plan splitting techniques, it is first necessary to distinguish the intersection types of dose curves for multiple lesions. Based on the type of intersection, the appropriate splitting technique can be selected. Drawing on clinical experience in Gamma Knife treatment plan design, I categorize the possible intersection scenarios of dose curves for multiple lesions into three main types: complete intersection, partial intersection, and no intersection. The complete intersection type can further be divided into complete intersection Type I and complete intersection Type II, as illustrated in **Figure 3**.

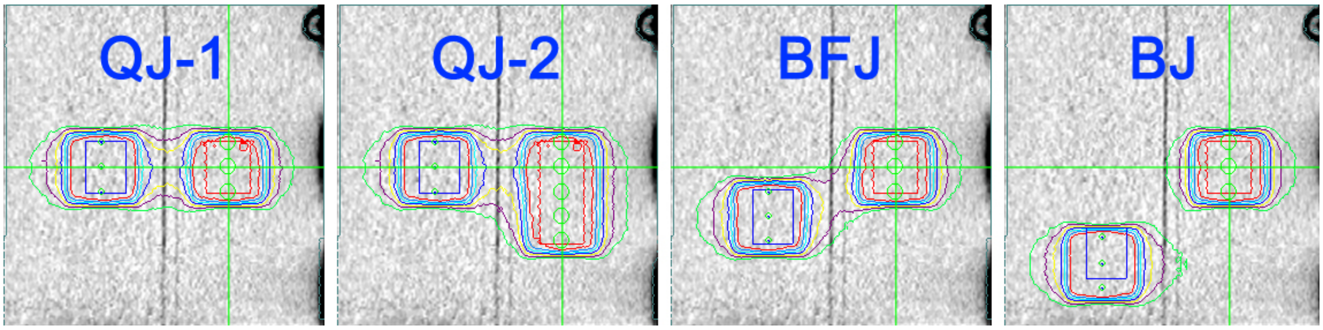

Figure 3. Intersection types of dose curves for multiple lesions. **QJ-1** represents complete intersection Type I, **QJ-2** represents complete intersection Type II, **BFJ** represents partial intersection, and **BJ** represents no intersection.

In clinical treatment plan design:

(1) For complete intersection types (as shown in **Figures 3 QJ-1** and **QJ-2**), the Gamma Knife plan should be split using the upper-lower splitting method.

(2) For no intersection types, the lesion-based splitting method is appropriate. In cases where a patient has multiple lesions, even if they are in the same transverse plane, they can still be considered a no-intersection type if the distance between the lesions is sufficiently large and their minimum dose curves do not overlap.

(3) For large lesions, the upper-lower splitting method should always be used.

(4) For partial intersection types (as shown in **Figure 3 BFJ**), the dose curves for various lesion parts may both intersect and remain separate. This type can be addressed using either the upper-lower splitting method or the lesion-based splitting method.

When handling multi-lesion treatment plans, errors are more likely to occur for inexperienced physicians or treatment planners. The most common mistake lies in misjudging the intersection type of dose curves for multiple lesions. Partial intersection types are often incorrectly classified as no intersection types, leading to the erroneous use of lesion-based splitting methods and resulting in dose deviations [7].

5. Discussion

When there is uncertainty in determining the intersection type of dose curves for multiple lesions, the treatment plan should first be designed as a whole. The dose curve intersection type should then be assessed, and the correct Gamma Knife treatment plan splitting technique should be applied [8]. The intersecting dose curves of multiple lesions significantly influence one another because overlapping dose curves (as shown in **Figure 1 AB$_{fusion}$**) increase the dose to adjacent lesions. This leads to dose deviations, which, in turn, affect the beam-on time for target points.

Advantages of Gamma Knife treatment plan splitting techniques:

(1) Improved dose accuracy for lesions: Splitting treatment plans ensures that each lesion receives an appropriate radiation dose.

(2) Enhanced flexibility for patient treatment: This technique allows for personalized treatment plans tailored to the patient's specific conditions, including lesion size, location, quantity, and overall health status.

(3) Ensured treatment efficacy and safety: By precisely controlling the radiation dose and its range, damage to surrounding normal tissues is minimized, reducing the risk of treatment-related complications [9].

Limitations of Gamma Knife treatment plan splitting techniques:

(1) Treatment time: Splitting the treatment plan may increase the total treatment time and number of sessions. However, this resolves the issue of prolonged single-session treatments that patients may struggle to endure, meeting treatment demands while ensuring efficacy.

(2) Technical expertise requirements: This technique demands high levels of experience and professional skills from radiation treatment planners (physicists), ensuring dose accuracy.

(3) Cost: Implementing this technique may increase treatment costs, including equipment use, human resources, and subsequent monitoring [10].

In clinical Gamma Knife treatments, when a patient has multiple or large lesions, a single Gamma Knife treatment plan often requires extended treatment time that patients may find difficult to endure. To meet patient needs, correctly applying Gamma Knife treatment plan splitting techniques enables phased treatment while ensuring the accuracy of the radiation dose. This approach ultimately ensures both the efficacy and safety of the patient's treatment.

Disclosure statement

The author declares no conflict of interest.

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