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The Effect of Upper Limbs on Dosage in Gamma Knife Treatment

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Abstract: *Objective:* To study the effect of the upper limbs on dosage in Gamma Knife treatment. *Methods:* The design function of the Luna-260^{TM} Gamma Knife Radiotherapy Planning System was utilized, using a body phantom to simulate conventional treatment sites. Twenty sampling points were set for irradiation locations. Using five different collimator sizes commonly used in body treatments, treatment plans were designed under conditions with and without upper limbs, and sampling point irradiation time comparison data was collected to calculate and analyze dose error rates. *Results:* Across the 20 sampling points, the dose error range was from -16.09% to 0 when comparing treatment plans without upper limbs to those executed with upper limbs present, and from 0 to 19.75% in the reverse comparison. With the same prescription dose, location, and collimator size, dose error increased as the irradiation site moved closer to the upper limbs and decreased as the distance increased. *Conclusion:* In Gamma Knife treatment, the dose error decreases as the irradiation site is further from the upper limbs and increases when closer. Consistency in upper limb positioning is essential during Gamma Knife localization, planning, and execution. Although small, the upper limbs can significantly impact dosage, requiring stringent quality control to ensure the precision of treatment doses, thus safeguarding the effectiveness and safety of patient treatments.

Keywords: Gamma Knife; Upper limbs; Radiotherapy planning; Dosage

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1. Introduction

In radiotherapy planning, delineation is a critical step and includes contouring of the target area, sensitive tissues, organs, and the body surface. The upper limbs, as a minor part of the body, are often overlooked by radiotherapy personnel and are commonly contoured as part of the body surface in treatment plans. Few studies in the literature, both domestic and international, focus on the effect of the upper limbs on dosage, with most research involving linear accelerators and CyberKnife technology [1,2]. Currently, no studies on this aspect using the Gamma Knife have been identified.

This study aims to simulate scenarios with and without the upper limbs to collect and compare corresponding data, analyzing the impact of upper limbs on dose in different irradiation locations. Using clinical case data, the study further examines the extent of dose deviation due to the upper limbs under varying conditions. This aims to raise awareness among radiotherapy personnel regarding the importance of upper limb positioning for dose accuracy, thereby enhancing treatment efficacy and patient safety.

2. Materials and methods

2.1. Research tools

A homogeneous body phantom with a density close to human tissue was used to simulate positioning and capture CT localization image data. The Xi'an ET Medical Luna-260™ Gamma Knife Radiotherapy Planning System 3.0 (hereafter referred to as "RTPS 3.0") was used to conduct clinical research on the impact of the upper limbs on dosage.

2.2. Research methods

Using the body phantom on the Luna-260™ Gamma Knife body positioning bed and a GE large-aperture 4D-CT simulation machine, the body phantom was positioned and scanned, and the localization images were transmitted to RTPS 3.0 over a network.

In the treatment planning system, the intersection of all beam axes serves as the focal point [3]. The focal points of the Gamma Knife radiation on the body phantom were used as sampling points to design a comparative treatment plan simulation. All sampling points had target points set so that the arc path passed through the simulated upper limbs to obtain comparison data. The simulation of standard treatment sites on the body took 20 positions as sampling points, with scenarios created for both the presence and absence of upper limbs, as shown in **Figure 1**.

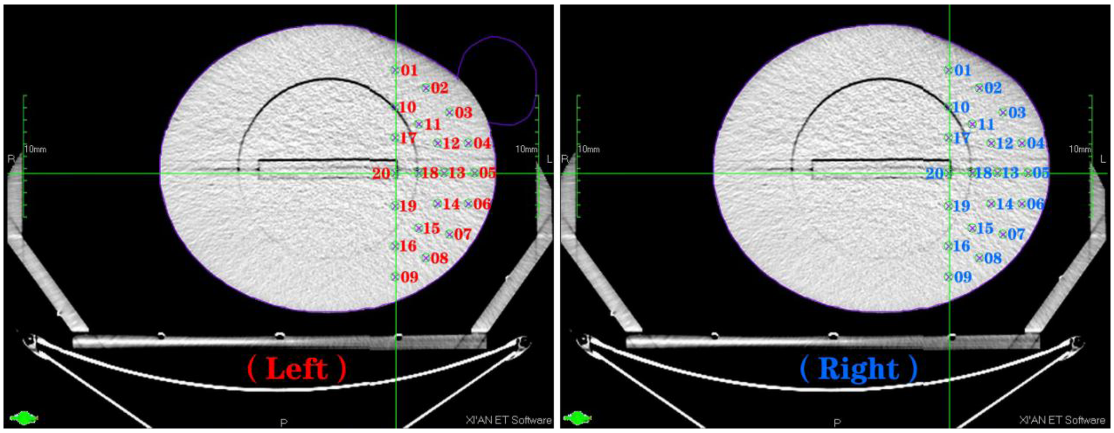

Figure 1. Comparison of sampling points with upper limb **(left)** and without upper limb **(right)**.

In **Figure 1 (left)**, the purple contour line on the upper right corner represents the simulated upper limb, based on typical limb size; **Figure 1 (right)** shows the absence of the upper limb.

2.3. Method for collecting comparative irradiation time data

The prescription dose was set at 50% of 1000 cGy in a single large dose treatment. Using RTPS, five different collimator sizes (2#, 3#, 4#, 5#, and 6#) commonly used in body treatment were selected, as the 1# collimator was excluded due to its small irradiation field not being applicable in body treatments. The data collection method is shown in **Figure 2**.

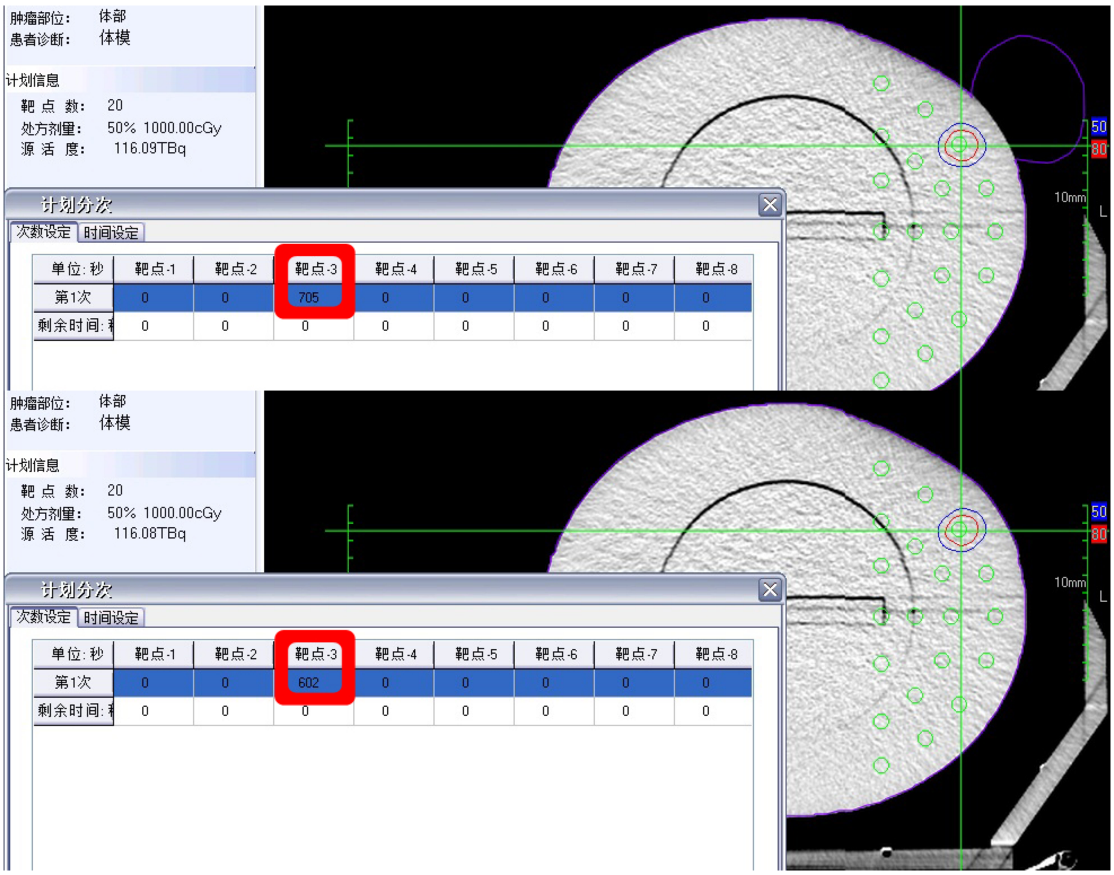

Figure 2. Comparison of irradiation times at sampling points with and without upper limbs for the same prescription dose, collimator, and location

Figure 2 illustrates the irradiation time collected at sampling point 03 using the 4# collimator, with a prescription dose of 50% of 1,000 cGy in a single dose. The upper image shows 705 seconds with the upper limb present, while the lower image shows 602 seconds without the upper limb.

3. Results

3.1. Irradiation time data

Using the data collection method shown in **Figure 2**, a total of 200 treatment plans were designed with 5 collimators, and 200 corresponding irradiation time data points were collected at sampling points with and without the upper limb, as shown in **Table 1**.

Table 1. Comparison of irradiation times for the same dose with different collimators at sampling points with and without the upper limb (irradiation dose: 50% of 1,000 cGy)

Collimator no.	2#	3#	4#	5#	6#	2#	3#	4#	5#	6#
Sampling point ID	Irradiation time with upper limb (s)					Irradiation time without upper limb (s)				
01	760	690	673	642	627	719	653	635	592	586
02	775	706	698	664	646	697	632	621	592	580
03	802	700	705	678	667	687	625	602	593	557
04	725	653	643	594	586	649	596	583	540	530
05	699	618	615	530	505	657	594	581	560	549
06	694	618	611	531	515	675	608	594	521	501
07	707	650	640	580	557	694	639	634	574	546
08	767	678	673	587	563	751	672	666	578	555
09	812	722	726	626	607	812	715	719	625	606
10	879	799	799	761	747	830	754	746	705	694
11	879	779	769	743	728	814	722	720	676	665
12	844	743	741	707	695	780	692	680	646	637
13	808	721	716	679	668	765	694	681	641	638
14	829	723	718	674	669	809	704	699	655	651
15	851	752	749	704	698	836	739	735	699	685
16	886	794	799	747	740	876	785	782	735	729
17	949	856	855	815	798	897	817	810	768	754
18	905	800	791	760	746	879	769	766	719	713
19	964	856	861	815	799	942	837	842	789	781
20	979	889	873	837	817	944	858	848	807	788

3.2. Data processing principle and dose error rate results

The irradiation dose is equal to the focal point dose rate multiplied by the irradiation time [4]. Within the same time frame, the focal point dose rate is identical. The irradiation time comparison data collected at the same location on each sampling point differ only by the presence or absence of the upper limb, with all other conditions constant. Therefore, the irradiation dose is proportional to the irradiation time, meaning the comparison of irradiation time data in **Table 1** also reflects the dose error rate for each irradiation position.

For the same prescription dose and collimator size at the same sampling point:

Dose error rate for irradiation without upper limb relative to with upper limb = (Dose without upper limb - Dose with upper limb) / Dose with upper limb = (Irradiation time without upper limb - Irradiation time with upper limb) / Irradiation time with upper limb.

For example, for a prescription dose of 50% of 1,000 cGy using the 4# collimator, the dose error at sampling point 03 without the upper limb compared to with the upper limb = (602 - 705) / 705 = -14.61%. Another example: at sampling point 09, the dose error for the same prescription dose with the 4# collimator is (719 - 726) / 726 = -0.96%. This calculation method yielded 100 comparative dose error rate data points for irradiation without the upper limb relative to with upper limb, as shown in **Table 2**.

Table 2. The dose error rate for irradiation without the upper limb relative to with upper limb

Collimator no.	2#	3#	4#	5#	6#
Sampling point ID	**Dose error rate without upper limb relative to with upper limb**				
01	-5.39%	-5.36%	-5.65%	-7.79%	-6.54%
02	-10.06%	-10.48%	-11.03%	-10.84%	-10.22%
03	-14.34%	-10.71%	-14.61%	-12.54%	-16.49%
04	-10.48%	-8.73%	-9.33%	-9.09%	-9.56%
05	-6.01%	-3.88%	-5.53%	5.66%	8.71%
06	-2.74%	-1.62%	-2.78%	-1.88%	-2.72%
07	-1.84%	-1.69%	-0.94%	-1.03%	-1.97%
08	-2.09%	-0.88%	-1.04%	-1.53%	-1.42%
09	0.00%	-0.97%	-0.96%	-0.16%	-0.16%
10	-5.57%	-5.63%	-6.63%	-7.36%	-7.10%
11	-7.39%	-7.32%	-6.37%	-9.02%	-8.65%
12	-7.58%	-6.86%	-8.23%	-8.63%	-8.35%
13	-5.32%	-3.74%	-4.89%	-5.60%	-4.49%
14	-2.41%	-2.63%	-2.65%	-2.82%	-2.69%
15	-1.76%	-1.73%	-1.87%	-0.71%	-1.86%
16	-1.13%	-1.13%	-2.13%	-1.61%	-1.49%
17	-5.48%	-4.56%	-5.26%	-5.77%	-5.51%
18	-2.87%	-3.88%	-3.16%	-5.39%	-4.42%
19	-2.28%	-2.22%	-2.21%	-3.19%	-2.25%
20	-3.58%	-3.49%	-2.86%	-3.58%	-3.55%

3.3. Data analysis

Based on the comparison data in **Table 2**, dose error rate curves were generated for each collimator, comparing irradiation without the upper limb relative to with the upper limb, as shown in **Figure 3**.

Areas with larger dose error rates for each collimator primarily occurred near the upper limb, such as at sampling points 01, 02, 03, 04, 10, 11, and 12, while regions with smaller error rates were further from the upper limb, such as sampling points 07, 08, 09, 15, 16, and 19. Collimators 5# and 6# at sampling point 05 did not match the overall dose error rate curve trend, likely due to their very large irradiation fields, which are not used in clinical practice; therefore, they are excluded from further analysis.

In the range of the 20 sampling points, the dose error rate for irradiation without the upper limb relative to with the upper limb was -16.09% to 0. The inverse calculation of this rate yields a dose error range of 0 to 19.75% for irradiation with the upper limb relative to without.

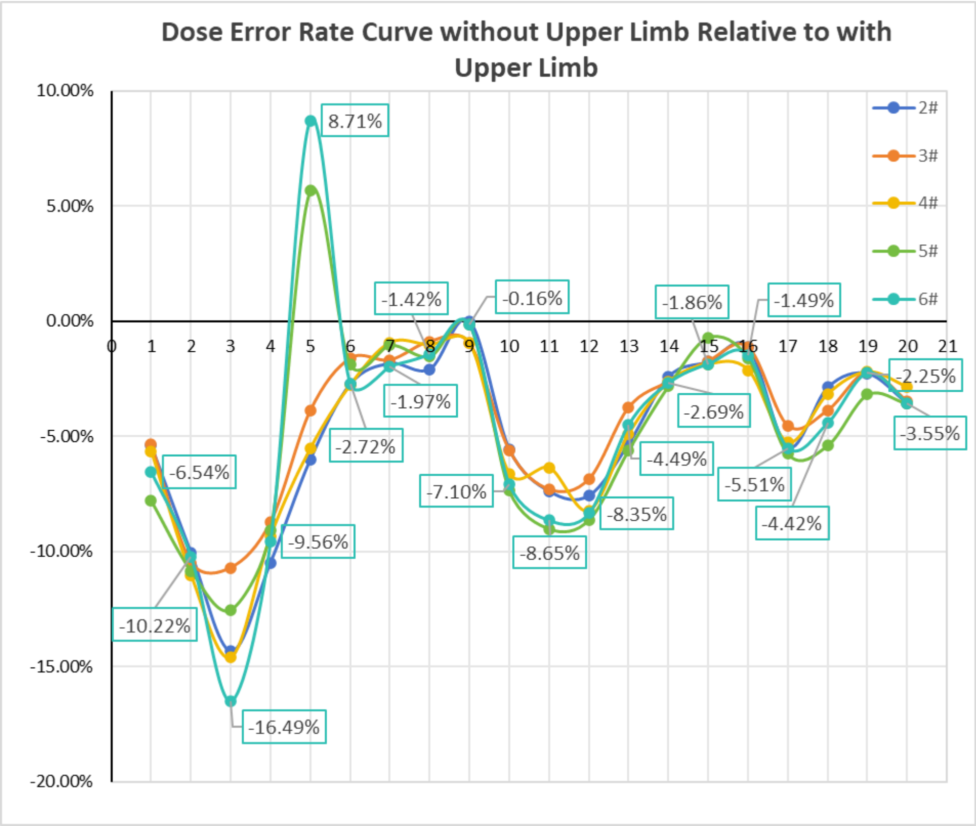

Figure 3. Dose error rate curve without upper limb relative to with upper limb. Note: The horizontal axis represents 20 sampling points on the phantom, and the vertical axis represents the dose error rate percentage. The curves show the dose error rates for collimators 2#, 3#, 4#, 5#, and 6# for irradiation without upper limb relative to with upper limb

4. Clinical plan analysis

A review of representative clinical plans at our Gamma Knife Center was conducted to validate the feasibility of using phantoms to study dose effects with and without the upper limb. This verification also assesses the clinical reference value of dose error rate ranges within sampling points when accounting for the presence or absence of a limb.

4.1. Clinical plan 1

Patient Ou, female, 86 years old, with liver metastasis from breast cancer, received Gamma Knife treatment in February 2023. The total treatment dose was 3,200 cGy at the 50% isodose line, administered over seven sessions. The patient was positioned using a vacuum bag for CT localization. To prevent interference with the CT imaging quality due to her upper limb, she held the limb on the liver side close to her chest, ensuring image clarity. During the treatment planning process, this arm was not visible in the positioning images and therefore could not be contoured, as shown in **Figure 3 (left)**. However, during the actual treatment, if the patient was unable to maintain the exact positioning due to prolonged treatment times, she would naturally place her upper limb on the liver side. In clinical practice, if the upper limb is not immobilized, this phenomenon is likely to occur. The opposing upper limb was used to simulate the scenario with the limb present during actual treatment, as depicted in **Figure 3 (right)**.

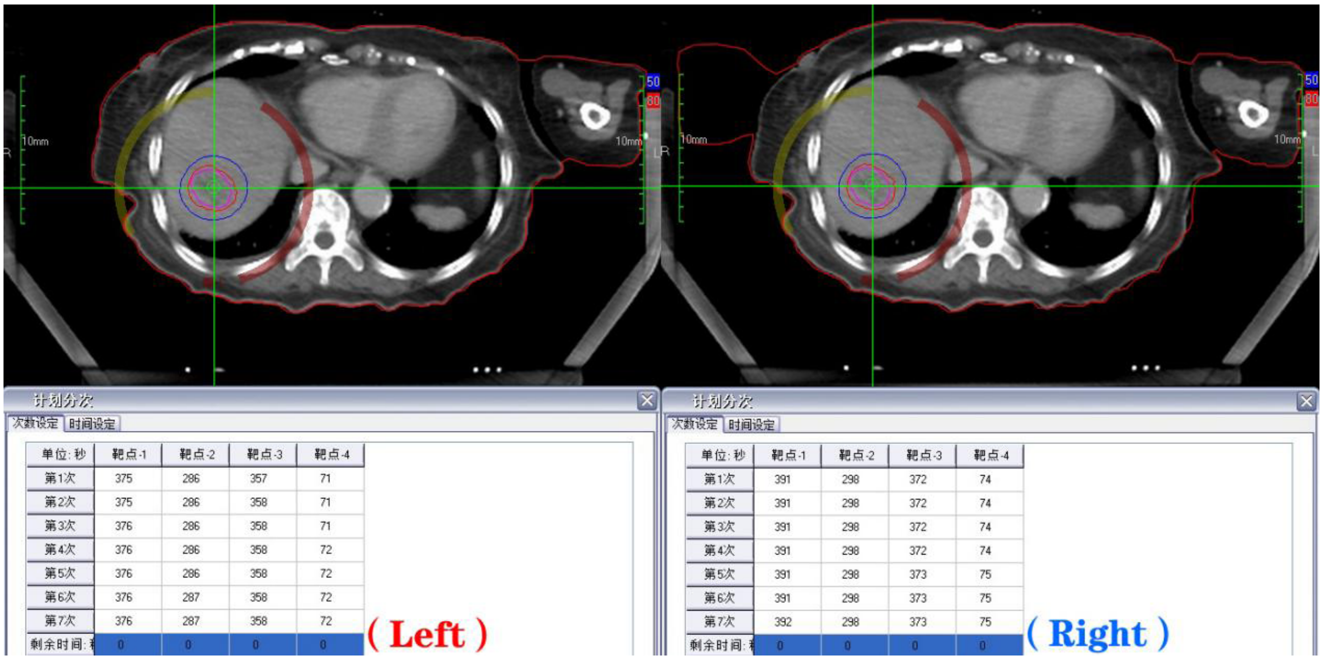

Figure 3. Comparison of planned irradiation times without the upper limb versus actual treatment with the upper limb. Note: In the actual CT localization image during patient positioning, the right upper limb is absent in **Figure 3 (left)**, while the upper limb on the left side is contoured based on the size and position of the contralateral limb to simulate its presence in **Figure 3 (right)**

By comparing the output irradiation times of each plan, the impact of the upper limb on lesion dose was analyzed. In this comparison, target points 1, 3, and 4 used the 4# collimator, while target point 2 used the 5# collimator. The dose error rate without the upper limb relative to the actual treatment with the upper limb was -4.09% for target 1, -4.68% for target 2, -4.03% for target 3, and -4.11% for target 4.

Due to varying distances from each target point to the upper limb, the dose error rates differed, with an average error rate of -4.23%. This indicates that the actual irradiation dose was 4.23% less than the prescription dose, equating to 3,064.64 cGy at the 50% line. In treatment planning, the actual presence of an unmodeled upper limb results in a similar situation, signifying that the actual irradiation dose would fall short of the prescribed dose.

4.2. Clinical plan 2

Patient Li, male, 62 years old, with primary liver cancer, received Gamma Knife treatment in November 2022. The total treatment dose was 3,500 cGy at the 50% isodose line, administered over seven sessions. During positioning with a vacuum bag CT, the patient's arms were normally positioned at his sides. During treatment planning, this arm was contoured as part of the body surface, as shown in **Figure 4 (left)**. However, in actual treatment, if the patient could not maintain the positioning due to prolonged treatment times, he would move his arm away. This occurrence is more common in patients with limited self-control who do not cooperate fully during treatment. For this plan, the other upper limb's size and position were used to simulate the scenario without the arm in the actual treatment, as depicted in **Figure 4 (right)**.

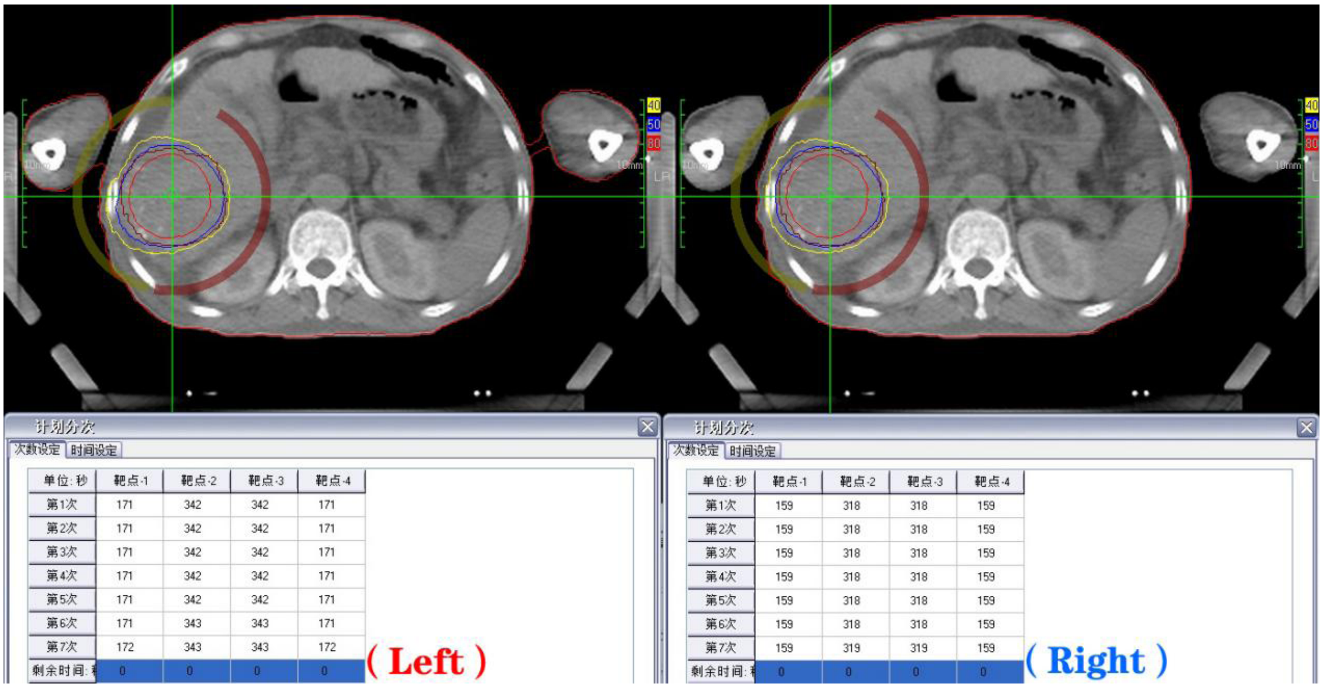

Figure 4. Comparison of planned irradiation times with the upper limb versus actual treatment without the upper limb. Note: The right upper limb is present in **Figure 4 (left)**, while **Figure 4 (right)** simulates the arm being moved out, with no contouring of the arm as part of the body surface

In this comparison, target point 1 used the 5# collimator, while target points 2, 3, and 4 all used the 6# collimator. The dose error rate for irradiation with the upper limb relative to actual treatment without it was 7.55% for target points 1, 2, 3, and 4. If the patient fully moved the arm away during treatment, the actual irradiation dose would increase by 7.55% relative to the prescribed dose, reaching 3,764.25 cGy at the 50% line. As the irradiation site is very close to the skin, this also indicates an increased skin dose. Given that the dose error fluctuates maximally in relation to the closest sampling point with an upper limb, even minor repositioning of the arm can alter the dose. Excessive dose errors may cause the dose for skin or adjacent organs at risk of exceeding critical values, potentially affecting treatment safety under severe circumstances.

5. Discussion

A recent study examined the dosimetric effects of arm positioning on CyberKnife radiotherapy for spinal tumor patients, concluding that even with extreme bilateral arm positions, arm movement had minimal impact on dosimetry during CyberKnife-based spinal tumor radiotherapy [5,6]. Typically, both domestic and international research methods use parameters from the Dose-Volume Histogram (DVH) within conventional plan evaluation tools to assess dose impact [7,8]. Although arm positioning can affect dose in specific cases, the influence is generally minor. The limited range of treatment sites in these studies restricts their ability to comprehensively reflect the dose impact of arm positioning on different tumor locations. Additionally, the varying irradiation methods of different devices may affect the degree of influence from the upper limb, warranting further research [9,10].

This study utilized the Luna-260^{TM} RTPS planning design function and employed phantoms to simulate a broader range of conventional irradiation sites, providing a more comprehensive assessment of the upper limb's impact on dose in Gamma Knife treatments. By combining the sample point positions from **Figure 1** with the dose error rate curve in **Figure 3**, it is evident that when the Gamma Knife target irradiation path intersects with the upper limb, the further the sample point is from the limb, the smaller the dose error rate; conversely, the closer the sample point, the greater the dose error rate.

Using two distinct types of clinical case plans, this study simulated situations where inconsistent arm positioning between radiotherapy planning and execution could occur if treatment phases were not meticulously controlled. This allowed calculation of the dose error rate between the prescription and the actual delivered dose, determining the patient's actual irradiation dose. The study thus validates the accuracy and practicality of this research method.

6. Conclusion

In summary, when the Gamma Knife target irradiation path intersects with the upper limb, the farther the irradiation point from the limb, the smaller the dose error, while proximity increases the error. It is crucial to maintain consistent arm positioning across Gamma Knife positioning, treatment planning, and execution. Not only must patients cooperate, but staff must also be carefully coordinated to ensure that radiation oncologists, treatment planners (physicists), and technicians diligently oversee every phase of radiotherapy. As Gamma Knife is a form of precision radiotherapy, even small arm-related dose impacts cannot be overlooked. Strict quality control is essential to ensure dose accuracy, which is vital for both the effectiveness and safety of patient treatment.

Disclosure statement

The authors declare no conflict of interest.

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