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Dosimetric evaluation of simplified intensity-modulated radiation therapy for thoracic tumors

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Abstract

To evaluate the feasibility of multi-parameters combined simplified intensity-modulated radiation therapy (sIMRT) planning in thoracic tumors and provide guidance for clinical practice. A total of 34 patients with thoracic tumors who underwent radiotherapy during 2019 to 2020 in our hospital were retrospectively analyzed. The same experienced medical physicist designed the sIMRT planning. The sIMRT planning limited the maximum number of segments per beam-field, the minimum segment area, and the minimum number of segment monitor units (MU), remaining consistent with the conventional intensity-modulated radiation therapy (IMRT). Comparative analysis of the difference in the irradiation dose to the tumor target area, and organs at risk, and delivery validate between 2 groups. The sIMRT slightly increased the tumor target area irradiation dose, but the homogeneity index was similar when compared with IMRT ($P > .05$). The sIMRT planning significantly reduced the low dose-volume area of the lungs (left lung, V_5: 2.5%; right lung, V_5: 3.1%; V_{10}: 1.8%; lungs, V_5: 3.2%; V_{10}: 1.5%, $P < .05$) and significantly increased the high dose-volume area of the lungs, heart, and esophagus, while meeting the clinical dose-restriction requirements. Moreover, the planning delivery validation showed that significantly reduced the treatment time (6.5 ± 1.9 minutes vs 8.8 ± 2.0 minutes, $P < .0001$) and total MU (386.3 ± 109.4 MU vs 406.3 ± 107.9 MU, $P < .05$). This simplified sIMRT method can meet the requirements of thoracic tumors radiotherapy planning, and has higher time effectiveness. In the future, it needs to be further explored in clinical practice.

Abbreviations: 3D-CRT = 3-dimensional conformal radiotherapy, D_{max} = maximum dose, HI = homogeneity index, MU = monitor units, OARs = organs at risk, PTV = planning target volume, sIMRT/IMRT = (simplified) intensity-modulated radiation therapy, *Vx* = the percentage of the organs volume of receiving dose ≥ *x* Gy.

Keywords: dosimetry, monitor unit (MU), number of segments, segment area, simplified intensity-modulated radiation therapy (sIMRT), thoracic neoplasms

1. Introduction

Radiotherapy is one of the main treatment methods for malignant tumors, and about 70% of patients need to receive radiotherapy during the treatment. Three-dimensional conformal radiotherapy (3D-CRT) significantly improved the tumor target conformality and reduced the irradiated dose to the surrounding normal tissues compared with the 2-dimensional (2D) radiotherapy era. Intensity-modulated radiation therapy (IMRT) further improved the dose and conformality of the tumor target and reduced the organs at risk (OARs) compared with 3D-CRT, which effectively decreased the local recurrence rate and the normal tissue complications.[1,2]

However, the IMRT technique also has some shortcomings: first, when the number of segments is high, the segment area/monitor units (MU) is low, the results of treatment delivery may deviate from those calculated by the treatment planning system (lateral electronic equilibrium).[3,4] Second, the excessive number of segments results in a longer treatment time, and the patients' declining ability to maintain their position as well as organ movements may contribute to off-target irradiation or dose overlap.[3,5] Third, the small number of the segment MU, which increased the dose uncertainty due to the unstable radiation quality and output of the linear accelerator at the beginning of each beam-field. Moreover, it is a challenge to the machine's ability to start and stop

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All data generated or analyzed during this study are included in this published article [and its supplementary information files].

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instantaneously and may result in damage.[3,6] Fourth, the multi-leaf collimator tongue-and-groove effects can generate leakage rays, which are significantly correlated with the number of segments and the total MU.[3,7] Fifth, the health care institutions must also deploy more resources in terms of manpower, and time.

At present, there are several simplified IMRT (sIMRT) studies, and the proposed methods including the direct aperture optimization technique, limiting the maximum number of segments per beam-field, the minimum segment area, and the minimum number of MU, etc, which had achieved positive results.[8–11] On this basis, Zhou[3] proposed a combined sIMRT method by limiting the parameters such as the number of segments, segment area, and segment monitor units. It has been validated in brain metastases, non-small cell lung cancer, liver cancer, and pelvic tumors, while its application to thoracic tumors still needs further exploration.[12–15]

2. Materials and methods

We retrospectively analyzed patients with thoracic tumors who underwent IMRT at our institution. Inclusion criteria were as follows: pathologically diagnosed thoracic tumors patients (including lung cancer, esophageal cancer, or malignant thymoma, etc); Karnofsky Performance Status ≥ 70, 25 < age < 75 years old, and no contraindications to chemoradiotherapy; no distant metastasis or combined with other organs tumors simultaneously; not received radiation therapy previously.

2.1. Position immobilization and computed tomography (CT) scanning

All patients were immobilized in the supine position by a thermoplastic mold, and enhanced CT was performed by Siemens large-aperture CT simulator. To obtain optimal scanning images, there were some differences in scanning parameters between different patients and tumors. The scanning range was from the fourth cervical vertebra (C4) to the fourth lumbar vertebra (L4), with a slice thickness of 5 mm. The images were transmitted to the Prowess Panther 5.10 treatment planning systems through a local area network.

2.2. Target delineation and radiotherapy planning

The tumor target and OARs were delineated by the experienced radiation oncologist of our hospital according to the Radiation Therapy Oncology Groups countering guidelines, and the reviewed by a senior radiation oncologist. Conventional IMRT and sIMRT plans were designed by the same medical physicist on Eclipse for the included patients, both based on the direct aperture optimization technique. Meeting the optimal dose distribution of the tumor target area while minimizing the radiation dose of the surrounding normal tissues. Additional constraints added to the sIMRT: average number of segments per beam-field ≤ 5, segment area ≥ 10 cm^2, segment monitor units ≥ 10 MU.[3] The dose limitations and optimization conditions for the tumor target and OARs are the same as the conventional IMRT planning. The prescription dose was 50 to 70 Gy per 25 to 30 fractions, and the prescription dose line contains at least 95% of the tumor target. The OARs dose-limitations are as follows: lungs: V_5 (Vx: the percentage of the organs volume of receiving dose ≥ x Gy) < 60%, V_{20} < 28%, V_{30} < 20%; heart: V_{30} < 40%, V_{40} < 30%; esophageal: V_{50} < 50%; spinal-cord: D_{max} (maximum dose) < 40 Gy. The linear accelerator energy was 6 MV, once daily, 5 times a week.

2.3. Planning evaluation

Dose-volume histograms were used to evaluate the IMRT and sIMRT plans. The tumor target dosimetric parameters include: $D_{98\%}$, $D_{2\%}$, and D_{mean} (represent the dose received by 98%, 2% of the tumor target volume, and mean dose); $V_{100\%}$ and $V_{110\%}$ (represent the volume contained in 100% and 110% prescription dose as a percentage of the target area volume, respectively); homogeneity index (HI) was used to evaluate the uniformity of prescription dose distribution in the tumor target and was calculated by the following equation[16]:

$$HI = \frac{D_{5\%}}{D_{95\%}}$$

$D_{5\%}$, $D_{95\%}$ represented the dose received by 5%, 95% volume of the planning target volume (PTV), respectively. The closer the HI to 1, the better homogeneity of the PTV. Mean lung dose, $V_{5–40}$ were evaluated for the lungs, left/right lung, $V_{25–45}$ for the heart, D_{mean} and V_{50} for the esophageal, D_{max} and D_{mean} for the spinal-cord. We also compared the total MU and actual delivery time of the 2 groups planning.

2.4. Statistical analysis

The measurements were described by mean ± standard deviation, and the paired t-test was conducted to compare the dose-volume parameters of the tumor target and OARs difference between different groups. Statistical analysis was performed with SPSS 25.0 (IBM SPSS Statistics, Chicago), and $P < .05$ was considered statistically significant.

3. Results

A total of 34 patients were included in this study, 26 men and 8 women, with a mean age of 58.3 ± 8.7 years old. There were 23 patients with lung cancer, 7 patients with esophageal cancer, and 4 patients with thymoma, respectively.

Finally, sIMRT planning significantly reduced the number of beam-fields (4.41 ± 1.08 vs 4.94 ± 0.95), the number of segments per beam-field (6.94 ± 0.89 vs 9.06 ± 0.24), and significantly increased the SMA (6.50 ± 1.86 cm^2 vs 3.56 ± 0.86 cm^2) and minimum MU (5.82 ± 1.78 MU vs 3.47 ± 0.71 MU) when compared with IMRT planning ($P < .05$).

Compared with IMRT planning, sIMRT planning significantly increased the mean dose of expanded gross tumor volume (PGTV)-D_{mean} (0.6 Gy), $D_{2\%}$ (1.2 Gy), V_{110} (3.1%), PTV-D_{mean} (0.8 Gy), V_{110} (7%), respectively, while the HI (1.24 ± 0.25 vs 1.26 ± 1.12, $P > .05$) was similar between 2 groups ($P > .05$). The detailed information is presented in the Table 1.

Compared with IMRT planning, sIMRT planning significantly reduced the mean dose of left-lung V_5 (51.0 ± 16.3% vs 53.5 ± 16.6%), right-lung V_5 (50.8 ± 19.6% vs 53.9 ± 18.8%), V_{10} (40.0 ± 19.7% vs 41.8 ± 19.3%), lungs-V_5 (49.2 ± 10.0% vs 52.4 ± 12.1%), V_{10} (38.2 ± 7.5% vs 39.7 ± 9.3%), significantly increased the mean dose of left-lung V_{20} (25.7 ± 16.4% vs 23.3 ± 15.7%), V_{25} (21.2 ± 15.7% vs 19.7 ± 14.9%), V_{30} (17.3 ± 14.6% vs 16.3 ± 13.4%), V_{40} (10.7 ± 11.5% vs 9.7 ± 10.1%), heart-V_{40} (11.0 ± 9.9% vs 10.3 ± 9.3%), V_{45} (7.5 ± 7.8% vs 6.2 ± 6.5%), lungs-V_{20} (24.8 ± 5.2% vs 24.0 ± 4.6%), V_{25} (20.4 ± 4.5% vs 19.7 ± 4.3%), and esophagus-D_{mean} (30.2 ± 7.4 Gy vs 29.2 ± 7.6 Gy), respectively ($P < .05$). The spinal-cord-D_{max}, D_{mean}, and esophagus-D_{max} were similar between the 2 groups ($P > .05$). The dosimetric parameters for the OARs are presented in Table 2, and the typical planning and dose-volume histogram are shown in Figure 1.

Meanwhile, the 2 groups planning delivery demonstrated that the sIMRT significantly decreased the treatment time (6.5 ± 1.9 vs 8.8 ± 2.0 minutes, $P < .0001$), and total MU (386.3 ± 109.4

Table 1

Dosimetric comparison in tumor target between sIMRT planning and conventional IMRT planning.

	IMRT	sIMRT	*t*	*P*
PGTV (n = 30)				
D_{mean} (Gy)	61.8 ± 10.4	62.4 ± 10.5	–5.157	<0.001*
$D_{98\%}$ (Gy)	57.6 ± 9.0	57.4 ± 9.0	0.899	0.376
$D_{2\%}$ (Gy)	64.5 ± 11.1	65.7 ± 11.2	–5.917	<0.001*
V_{100} (%)	94.7 ± 1.7	94.7 ± 2.8	–0.095	0.925
V_{110} (%)	1.4 ± 3.2	4.5 ± 5.4	–3.297	0.003*
PTV (n = 33)				
D_{mean} (Gy)	55.4 ± 8.8	56.2 ± 8.9	–7.003	<0.001*
D_{98} (Gy)	46.0 ± 6.8	46.1 ± 6.8	–0.679	0.502
D_{2} (Gy)	62.3 ± 10.7	61.4 ± 14.3	0.446	0.659
V_{100} (%)	95.3 ± 1.4	95.5 ± 1.5	–1.023	0.314
V_{110} (%)	50.6 ± 28.3	57.6 ± 25.1	–5.775	<0.001*
HI	1.26 ± 0.12	1.24 ± 0.25	0.551	0.586

$D_{98\%}/D_{2\%}$ = represent the dose received by 98/2% of the tumor target volume, D_{mean} = mean dose, HI = homogeneity index, IMRT = intensity-modulated radiation therapy, PGTV = expanded gross tumor volume, sIMRT = simplified intensity-modulated radiation therapy, V_{100}/V_{110} = represent the volume contained in 100/110% prescription dose as a percentage of the target area volume.
*Represents significant statistical difference.

Table 2

Dosimetric comparison in OARs between sIMRT planning and conventional IMRT planning.

OARs	IMRT	sIMRT	*t*	*P* value
Left-lung (n = 34)				
D_{mean} (Gy)	13.2 ± 6.5	13.5 ± 7.2	–1.503	.142
V_{5} (%)	53.5 ± 16.6	51.0 ± 16.3	2.140	.040*
V_{10} (%)	40.8 ± 17.2	40.0 ± 17.2	0.650	.520
V_{15} (%)	31.0 ± 16.0	31.9 ± 17.0	–1.484	.147
V_{20} (%)	23.3 ± 15.7	25.7 ± 16.4	–2.617	.013*
V_{25} (%)	19.7 ± 14.9	21.2 ± 15.7	–3.272	.003*
V_{30} (%)	16.3 ± 13.4	17.3 ± 14.6	–2.180	.036*
V_{35} (%)	12.9 ± 11.6	13.9 ± 13.3	–1.773	.085
V_{40} (%)	9.7 ± 10.1	10.7 ± 11.5	–2.329	.026*
Right-lung (n = 34)				
D_{mean} (Gy)	14.5 ± 7.9	14.4 ± 8.3	0.989	.330
V_{5} (%)	53.9 ± 18.8	50.8 ± 19.6	2.500	.018*
V_{10} (%)	41.8 ± 19.3	40.0 ± 19.7	2.897	.007*
V_{15} (%)	33.6 ± 18.3	32.9 ± 18.7	1.420	.165
V_{20} (%)	28.0 ± 16.5	27.5 ± 17.3	0.500	.620
V_{25} (%)	22.3 ± 15.2	23.1 ± 15.7	–1.384	.176
V_{30} (%)	19.0 ± 14.2	19.1 ± 14.4	–0.541	.592
V_{35} (%)	15.4 ± 13.1	15.3 ± 13.2	0.110	.913
V_{40} (%)	11.9 ± 12.0	12.0 ± 12.1	–0.074	.942
Lungs (n = 34)				
D_{mean} (Gy)	13.2 ± 2.8	13.1 ± 2.8	0.543	.591
V_{5} (%)	52.4 ± 12.1	49.2 ± 10.0	3.195	.003*
V_{10} (%)	39.7 ± 9.3	38.2 ± 7.5	2.268	.030*
V_{15} (%)	30.6 ± 6.1	30.5 ± 6.1	0.466	.644
V_{20} (%)	24.0 ± 4.6	24.8 ± 5.2	–3.042	.005*
V_{25} (%)	19.7 ± 4.3	20.4 ± 4.5	–3.274	.002*
V_{30} (%)	16.2 ± 4.1	16.7 ± 4.2	–1.970	.057
V_{35} (%)	12.9 ± 4.1	13.2 ± 4.1	–0.934	.357
V_{40} (%)	9.8 ± 4.2	10.1 ± 4.2	–1.255	.218
Heart (n = 34)				
V_{25} (%)	21.3 ± 16.4	21.8 ± 16.6	–1.466	.152
V_{30} (%)	17.4 ± 13.6	17.8 ± 13.7	–1.239	.224
V_{35} (%)	13.8 ± 11.2	14.3 ± 11.6	–1.584	.123
V_{40} (%)	10.3 ± 9.3	11.0 ± 9.9	–2.401	.022*
V_{45} (%)	6.2 ± 6.5	7.5 ± 7.8	–2.882	.007*
Esophageal (n = 15)				
D_{mean} (Gy)	29.2 ± 7.6	30.2 ± 7.4	–2.972	.010*
V_{50} (%)	19.7 ± 21.2	20.9 ± 21.7	–1.795	.094
Spinal-cord (n = 34)				
D_{max} (Gy)	37.7 ± 2.3	38.1 ± 3.5	–1.012	.319
D_{mean} (Gy)	13.8 ± 5.8	13.7 ± 5.8	0.808	.425

D_{max} = maximum dose, D_{mean} = mean dose, IMRT = intensity-modulated radiation therapy, sIMRT = simplified intensity-modulated radiation therapy, OAR = organs at risk, *Vx* = the percentage of the organs volume of receiving dose ≥ *x* Gy.
*Represents significant statistical difference.

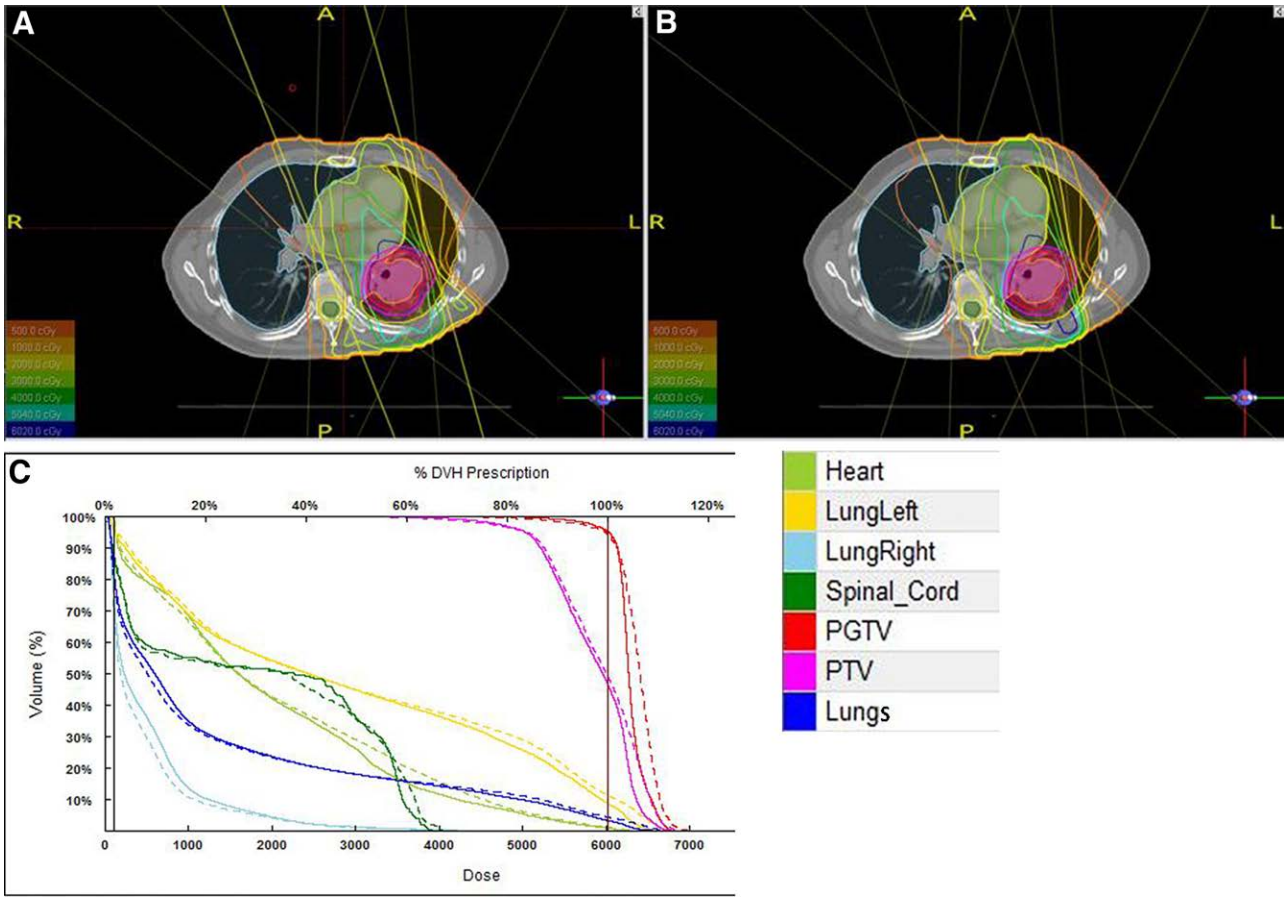

Figure 1. Comparison of the dose between conventional IMRT (A) and sIMRT (B) planning distribution and the corresponding dose–volume histograms (C). IMRT = intensity-modulated radiation therapy, PGTV = expanded gross tumor volume, PTV = planning target volume, sIMRT = simplified intensity-modulated radiation therapy.

vs 406.3 ± 107.9, $P < .05$) when compared with IMRT (Table S1, Supplemental Digital Content, http://links.lww.com/MD/O465).

4. Discussion

According to the results of malignant tumor prevalence statistics in China (2022), lung cancer ranked first in the number of new cases and deaths.[17] Radiotherapy plays an important role in the treatment of thoracic tumors (e.g., lung cancer, esophageal cancer), and IMRT is the widely used radiation therapy technique. However, it has its shortcomings such as a long time of treatment/planning validation, small segment MU increase dose uncertainly, and more resource consumption. There have been some studies on simplified IMRT techniques, based on these, this study evaluates the value of a multi-parameter combined simplified IMRT technique.

The results showed that the sIMRT significantly increased the tumor target irradiation dose, but HI was similar when compared with IMRT. And sIMRT significantly increased the high dose-volume parameters of the lungs, heart, and esophagus. Although this would increase the possibility of radiation-associated injury in OARs to some extent, while meeting the clinical dose-restriction requirements. Moreover, the planning delivery validation showed that the significantly reduced the treatment time and total MU. Ren et al[18] designed 4 plans, including 3D-CRT, 5 beam-fields sIMRT, 5 beam-fields IMRT, and 7 beam-fields IMRT for non-small cell lung cancer patients, and the results showed that the sIMRT can meet the clinical dose-limitations of OARs, and the number of segment MU was similar with 3D-CRT, but significantly lower than IMRT planning. Zhang et al[19] demonstrated that both sIMRT and IMRT plans can meet the esophageal cancer radiotherapy planning requirements. Although IMRT planning has superior tumor target dose distribution and superior spinal cord protection, there was no significant difference in the irradiated dose to the heart and lungs, and the number of segments and total MU were significantly reduced in sIMRT planning. Our study has a richer disease type and is more generalizable compared with theirs. In addition, this sIMRT method has been applied to other tumors and similar conclusions can be concluded: the overall quality of the sIMRT planning is slightly lower than the IMRT planning, but the preservation of some OARs is better than the IMRT planning, and the treatment time of the sIMRT planning is about half of the IMRT planning.[5,12,20] Studies have shown that long hospitalization time, high cost and low payment rate of medical insurance are the characteristics of lung cancer treatment, and patients and their families have to face an unaffordable financial burden.[21] Our studies have demonstrated that the sIMRT has a smaller number of segments compared with IMRT, which correlate with the decrease of patient radiotherapy costs, and shortened the time of hospitalization further reduced the overall costs.

Moreover, Xiang et al[22] evaluated the dosimetric difference between sIMRT and volumetric modulated arc therapy (VMAT) planning in hepatocellular carcinoma, and the results showed that both plans can meet the clinical dose requirements, but VMAT has superior conformity Index (CI)/HI. Cai et al.[23] compared the dosimetric difference between sIMRT and Tomotherapy planning in esophageal cancer, and the results showed that both plans were suitable for it, but

TOMO planning had better dose distribution and significantly reduced the lungs high dose-volume parameters compared with the sIMRT planning. Currently, it has also been used to clinical practice, Zhu et al[14] investigated the clinical value of sIMRT combined with transarterial chemoembolization (TACE) in the treatment of hepatocellular carcinoma. The results showed that compared with IMRT, the sIMRT can achieve similar efficacy and prognosis, without increasing toxic side effects, and even has the tendency to reduce the occurrence of radiation-induced liver injury, which can be used as an alternative to conventional IMRT. Some other studies have explored the value of sIMRT in combination with chemotherapy or targeted therapy, but there is still lacking the results of sIMRT and IMRT in randomized controlled trials.[15,24]

There are several limitations in this study. Firstly, the number of patients was limited (explored different thoracic tumors). Secondly, the number of beam-fields was not limited, and the differences between different numbers of beam-fields were not explored. Thirdly, due to the limitation of our treatment planning system, some cases do not reach the required parameter restrictions. Fourthly, this study was limited to dosimetric analysis, and the actual clinical practice value was not investigated at this time.

To summarize, this sIMRT is a radiation therapy technique that can be widely used, simple and feasible, cost-effective and time-effective. It can shorten the treatment time and reduce the machine damage, as well as the potential to reduce the patients' radiotherapy cost. It is also of great significance to the hospital that with a heavy workload of radiotherapy or lack of manpower and material resources. Compared with IMRT, it has similar dose distribution and planning quality.

5. Conclusion

The number of segments per beam-field, segment area, and number of monitor units based on multi-parameter combined limitation sIMRT planning can meet the clinical radiotherapy requirements and shorten the treatment time. In the future, its clinical benefit needs to be further investigated in clinical randomized controlled trials.

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