



OPEN **Dosimetric evaluation of field parameters in VMAT for cervical cancer with inguinal lymphatic drainage extension**

Jing Zeng^{1,2}, Jinlong Hao^{1,2}, Jianguo Zhao¹✉ & Peisong Sun¹

For cervical cancer radiotherapy, patients requiring inguinal lymphatic drainage (ILD) extension fields pose challenges due to the large and complex target volume. To investigate the dosimetric effects of x-jaw width, jaw aperture position, and the number of arcs on volumetric modulated arc therapy (VMAT) plans for ILD extension fields, in order to optimize treatment planning. Thirty-nine patients were retrospectively included, and seven VMAT planning groups were created: OF (open field), $X=15/16/17/18$ (jaw widths of 15–18 cm), SP (split-field, four arcs), and $X=15$ M (jaw aperture moved toward the isocenter). Dosimetric parameters, including homogeneity index (HI), target coverage, and organs-at-risk (OARs) doses, were compared. The $X=15$ plan achieved significantly lower intestinal, bladder, and rectal doses compared to the $X=17$ and $X=18$ plans ($p<0.05$). The SP plan demonstrated superior HI and OARs sparing compared to the $X=15$ plan, but required longer treatment times. The $X=15$ M plan resulted in reduced edge doses but increased intestinal and bladder doses. For cervical cancer ILD extension fields, dual-arc VMAT plans with a 15 cm jaw width ($X=15$) are recommended for optimal balance between target coverage and OARs sparing. Split-field plans may be considered if extended treatment time is acceptable.

Keywords Cervical cancer, Volumetric modulated arc therapy, Inguinal lymphatic drainage extended field, Field parameters

Cervical cancer remains a leading cause of cancer-related mortality among women globally. For patients with advanced disease involving the lower third of the vagina, radiotherapy often necessitates the inclusion of inguinal lymphatic drainage (ILD) extension fields. These extended fields present unique challenges due to their large lateral dimensions and complex geometry, requiring careful balance between adequate target coverage and sparing of organs-at-risk (OARs)^{1–3}.

Volumetric modulated arc therapy (VMAT) has emerged as the preferred modality for cervical cancer radiotherapy, offering superior dose conformity and reduced treatment times compared to conventional techniques. However, the quality of VMAT plans is highly dependent on key field parameters, including x-jaw width, jaw aperture position, and the number of arcs. While prior studies have demonstrated that limiting jaw width can enhance OARs sparing, this approach may compromise target coverage in ILD fields, which demand broader lateral coverage^{4–6}.

This study systematically investigates the impact of varying field parameters on VMAT plan quality for cervical cancer ILD extension fields. By comparing configurations with different jaw widths, aperture positions, and arc numbers, we aim to identify optimal planning strategies that achieve a balance between target coverage and OARs sparing, thereby improving clinical outcomes.

Participants and methods

Patient characteristics

This retrospective study included 39 cervical cancer patients (age range: 30–78 years, mean: 58.47 years) treated at our institute between January 2019 and December 2023. Data were accessed for research purposes on January 1, 2024. According to the staging by the International Federation of Gynecology and Obstetrics (FIGO) in 2018, they were classified as stage IIIA (requiring radiotherapy for ILD areas), and the pathological diagnosis was

¹Department of Gynecologic Oncology, Tianjin Institute of Gynaecology Obstetrics, Tianjin Central Hospital of Gynaecology Obstetrics, Tianjin, China. ²Jing Zeng and Jinlong Hao contributed equally to this work. ✉email: zhaojianguozxfc@163.com

moderately to poorly differentiated squamous cell carcinoma. This study strictly adhered to ethical standards in medicine.

As a retrospective study, it was granted an exemption from obtaining informed consent from patients in the ethical review process, receiving approval from the hospital's ethics committee (Ethics Review No. 2023KY045). The ethics approval (2023KY045) explicitly covered the retrospective collection of data from 2019 to 2023. A waiver of informed consent was granted for the use of historical data, as stated in the approval. The informed consent was obtained from all subjects. The authors had access to information that could identify individual participants during or after data collection.

Simulation and target delineation

Patients were immobilized in supine position using thermoplastic masks with full bladder protocol. CT simulation was performed using Philips Brilliance CT Big Bore scanner. Images were transferred to Eclipse 13.6 treatment planning system (Varian Medical Systems). Clinical target volume (CTV) extended from L4 vertebra superiorly to 3.5–4.5 cm below ischial tuberosity inferiorly. Planning target volume (PTV) was generated by adding margins of 0.7 cm superior-inferior and 0.5 cm in other directions to CTV. The average PTV dimensions were 28.92 cm (range: 24.9–32.2 cm) crano-caudally and 23.60 cm (range: 21.5–26.4 cm) laterally.

Plan design

All plans were designed by the same physicist to ensure consistency. The prescribed dose for the PTV was 48.6 Gy (27 fractions of 1.8 Gy each), with a simultaneous boost to the Planning Gross Tumor Volume (PGTV) of 50 Gy. Plans were generated on a Varian iX linac using Eclipse 13.6 (Millennium 120 MLC, 15 cm leaf length). The isocenter positions, collimator angles, and optimization objective weight parameters were kept consistent across all groups. The isocenter position in the X and Z directions was automatically generated by the rotational geometry tool of the Eclipse system, while the Y direction was selected as the midpoint of the PTV in the head-to-foot direction. The collimator angles for the clockwise and counterclockwise fields were set at 10° and 350°, respectively.

Field configuration details

The plans primarily differed in the x-jaw positions and the number of fields, as detailed below:

1. Open Field Group (OF Group): Two arc fields were automatically generated using rotational geometry tools, ensuring that both sides of each field's jaws did not obstruct the PTV + margin (set at 5 mm in this study) during rotation. Such fields were referred to in the literature as open fields⁷ or fully opened fields⁸.
2. Fixed Width Double Arc VMAT Plans (X=15/16/17/18 Groups): Each field had one jaw position consistent with the OF Group. The other jaw position was adjusted to achieve field widths of 15, 16, 17, and 18 cm. These plans were referred to as X=15, X=16, X=17, and X=18 Groups, respectively. In these four groups, one jaw of each field remained in the open field position, ensuring no obstruction to the PTV + margin during rotation.
3. X=15 M Group: Based on the X=15 Group, both sides of each field's jaws were shifted 2 cm in the same direction, creating the X=15 M Group. Literature referred to the area between the jaws where radiation passed through as the field aperture (x-jaw aperture)⁸. The X=15 M Group shifted the center of the field aperture towards the isocenter, enhancing symmetry relative to the isocenter. In this plan, due to the movement of the field aperture, both fields partially obstructed the PTV + margin during rotation.
4. Split Field Group (SP Group): This group was derived by splitting the fields of the OF Group. Each open field was divided into two 15 cm fields, retaining one jaw position consistent with the OF Group, with overlap near the isocenter axis. The combined apertures of the split fields equaled the aperture of the open field. The SP Group comprised four fields, two clockwise and two counterclockwise.

This study first investigated the impact of increasing field width on treatment plans by comparing the OF Group, X=15 Group, X=16 Group, X=17 Group, and X=18 Group plans. Subsequently, it evaluated the effect of the field aperture's position relative to the isocenter axis by comparing the X=15 Group and the X=15 M Group. Finally, the study examined the effect of increasing the number of fields on treatment plans by comparing the X=15 Group and SP Group plans.

Dosimetric evaluation

The dosimetric parameters were compared after normalizing the plans. Due to the high overlap between the small intestine and the PTV in some selected cases of this study, it is clinically acceptable to allow a certain degree of dose reduction to the PTV to ensure that the dose to the small intestine does not exceed the limit. Consequently, the V48.6 Gy for the plans of each case in this study ranged from 85 to 95%, rather than being uniformly set to 95%. However, it was ensured that the V48.6 Gy values for each case across all groups remained the same.

For the PTV, this study calculated the Homogeneity Index (HI) of the plans. The definition of the Homogeneity Index is given by: $HI = (D2 - D98\%)/D50\%$, where D2%, D50%, D98% represent the doses received by 2%, 50%, and 98% of the PTV volume, respectively. The HI value ranges from 0 to 1, with values closer to 0 indicating better dose uniformity within the target area.

In this study, the PTV was segmented into three parts. The upper boundary was defined by the superior edge of the femoral head, creating two regions: PTVup (upper PTV) and PTVdown (lower PTV). Within PTVdown, the inner boundary was set by the inner edges of both femoral heads, resulting in PTVmid (middle PTV) for the inner side and PTVedge (edge PTV) for the outer side. Figure 1 illustrates this segmentation method: the

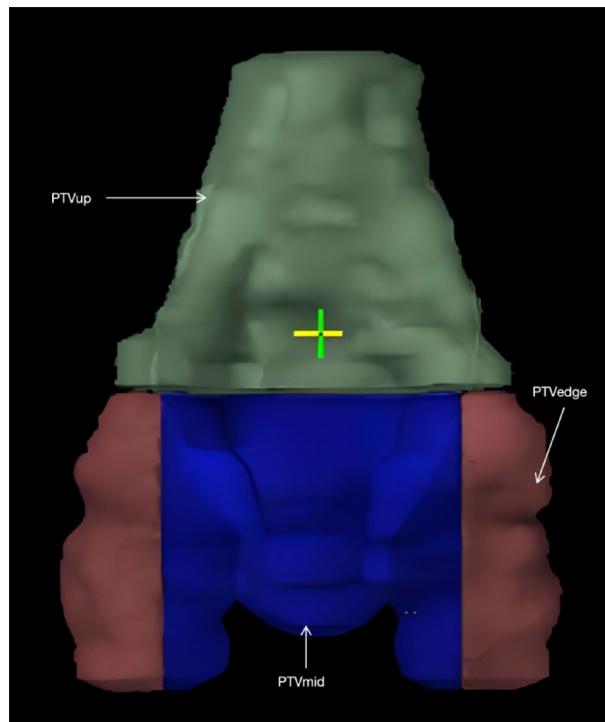


Fig. 1. Three-Part Segmentation of PTV (Eclipse treatment planning system, v13.6, <https://www.varian.com/z-h-hans/products/radiosurgery/treatment-planning>).

pink area represents PTVedge, the blue area represents PTVmid, and the light green area represents PTVup. This segmentation allows PTVedge to approximate the dose distribution at the edges of the inguinal extension fields. The volumes and D95% doses of PTVedge, PTVmid, and PTVup were statistically compared between the $X = 15$ and $X = 15\text{ M}$ groups.

Regarding the organs at risk, this study compared the mean doses Dmean of the small intestine, bladder, and rectum across the plans of each group. All relevant data are in the [supplementary files](#).

Statistical analysis

Statistical analysis was conducted using IBM SPSS Statistics 21. Analysis of Variance for Randomized Block Design (RBD ANOVA), SNK-q tests, and paired t-tests were applied as appropriate. A p value < 0.05 was considered significant.

Results

Comparison of target coverage

In the Eclipse Arc Geometry Tool, the colors representing the different parts of the PTV indicate the degree of coverage of the target area, referred to as "target coverage," as shown in Fig. 2. Generally, the closer the color is to yellow, the higher the target coverage, which is favorable for improving the quality of the plan; conversely, the closer the color is to blue, the worse the coverage.

Figure 3 provides an example of target coverage for three plans ($X = 15$, $X = 18$, and $X = 15\text{ M}$) for the same patient. All three Beam's Eye Views (BEVs) are shown from a clockwise perspective at an angle of 181° . As observed in the figure, the target coverage for the $X = 18$ group and the $X = 15\text{ M}$ group is superior to that of the $X = 15$ group. For instance, in the lower layers of the inguinal extension field, blue areas are present in the $X = 15$ group, while no such areas are observed in the other groups. Additionally, in the region near the inferior margin of the obturator, corresponding to the area near the lower margin of the cervical cancer PTV without extension fields, parts of the $X = 18$ and $X = 15\text{ M}$ groups are shown in yellow, while the $X = 15$ group is entirely green.

Effect of jaw width on plan quality

Table 1 compares the dosimetric parameters among the OF, $X = 15$, $X = 16$, $X = 17$, and $X = 18$ groups, including the HI and the mean doses to the small intestine, bladder, and rectum (Dmean_INT, Dmean_BLA, and Dmean_REC). The $X = 15$ group exhibited a Dmean_INT of 25.93 ± 1.65 Gy and a superior HI compared to the $X = 17$ and $X = 18$ groups ($p < 0.05$). In contrast, the OF group showed significantly higher HI and OARs doses compared to all other groups. Figure 4 provides the dose-volume histogram (DVH) curves of the plans for Group $X = 15$, Group $X = 18$, and Group OF as an example of a typical case.

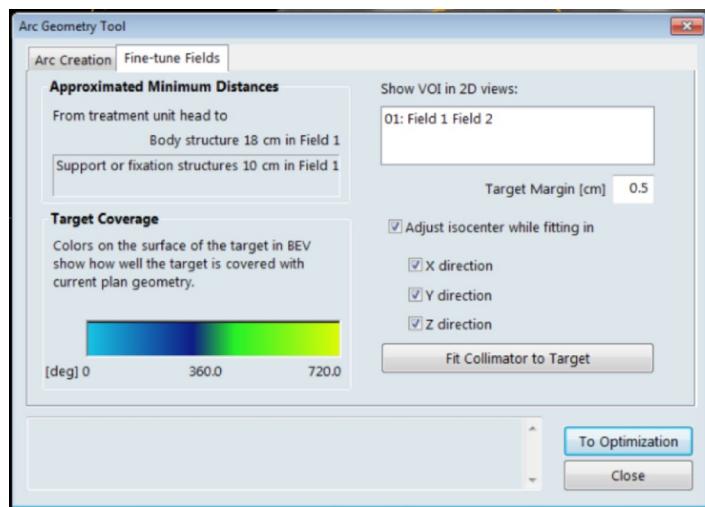


Fig. 2. Schematic Diagram of the Arc Geometry Tool.

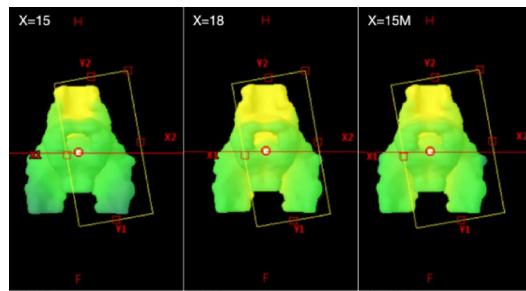


Fig. 3. BEV Examples for the Same Case (Eclipse treatment planning system, v13.6, <https://www.varian.com/z-h-hans/products/radiosurgery/treatment-planning>).

Group	HI	Dmean_INT (Gy)	Dmean_BLA (Gy)	Dmean_REC (Gy)
X=15	0.175 ± 0.113	25.93 ± 1.65	42.95 ± 2.16	42.48 ± 2.08
X=16	0.174 ± 0.112	25.99 ± 1.64	42.95 ± 2.15	42.38 ± 2.11
X=17	0.175 ± 0.113	26.06 ± 1.66	43.00 ± 2.12	42.44 ± 2.13
X=18	0.177 ± 0.113	26.17 ± 1.63	42.98 ± 2.13	42.50 ± 2.20
OF	0.193 ± 0.107	26.87 ± 1.78	44.75 ± 1.99	43.35 ± 1.89

Table 1. Dosimetric Comparison of Different Jaw Widths.

Effect of jaw aperture position

Table 2 presents a comparison of dosimetric parameters between the X=15 and X=15 M plans. The X=15 M group exhibited significantly higher HI and intestinal doses compared to the X=15 group ($p < 0.05$). Figure 5 provides the DVH curves of the plans for Group X=15 and Group X=15 M as an example of a typical case.

To further clarify the reasons for the differences in uniformity between the two plans, the PTV was divided into three parts, and the D95% doses for each part (as defined in Fig. 1) were statistically analyzed and compared. The results are presented in Table 3.

Effect of increasing arc number

Table 4 presents a comparison of dosimetric parameters between the X=15 group and the SP group, which has increased the number of arcs to four. The SP group achieved the lowest HI (0.166 ± 0.112 , $p < 0.05$) and reduced bladder and rectal doses compared to the X=15 group. Figure 6 provides the DVH curves of the plans for Group X=15 and Group SP as an example of a typical case. However, treatment time increased due to the additional arcs.

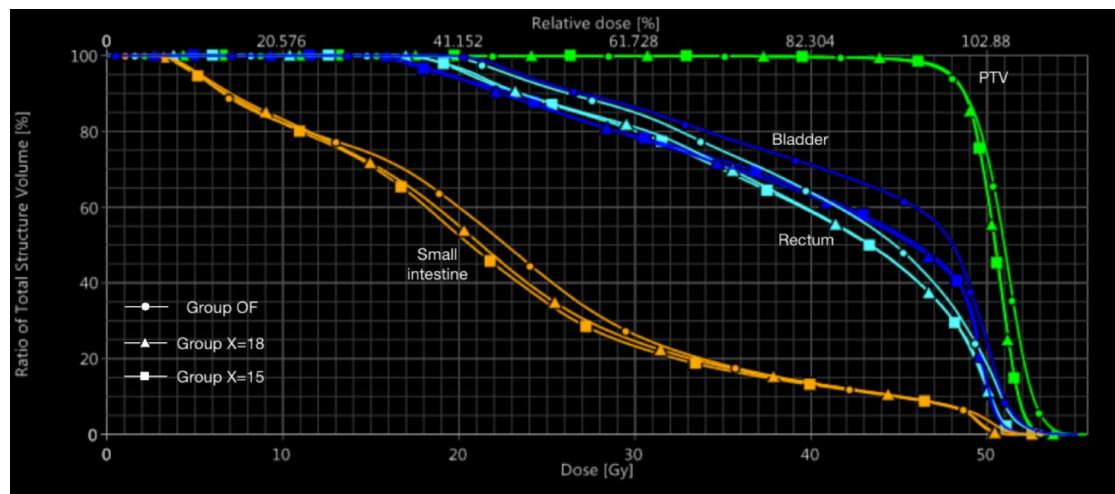


Fig. 4. DVH curves of the plans for Group X = 15, Group X = 18, and Group OF.

	HI	Dmean_INT	Dmean_BLA	Dmean_REC
X = 15	0.175 ± 0.11	25.93 ± 1.65	42.95 ± 2.16	42.48 ± 2.08
X = 15 M	0.178 ± 0.113	26.05 ± 1.64	43.04 ± 2.10	42.42 ± 2.09
P	0.006*	0*	0.047*	0.218

Table 2. Comparison of HI, Average Dose to Organs at Risk, and Intergroup Comparisons for X = 15 and X = 15 M Plans. A P value < 0.05 indicates a statistically significant difference, which is marked with an asterisk (*) in the table.

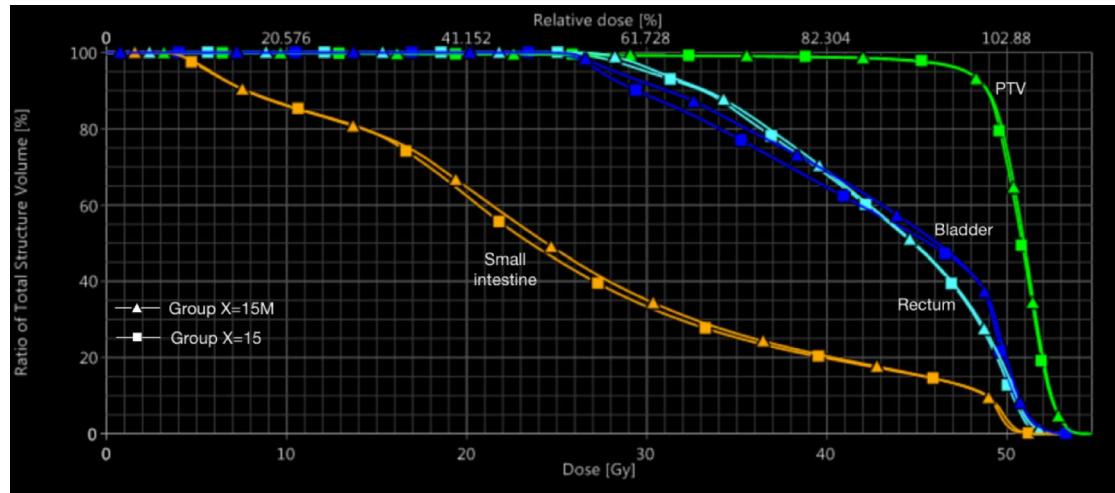


Fig. 5. DVH curves of the plans for Group X = 15 and Group X = 15 M.

Discussion

This study investigates the planning of cervical cancer treatments with ILD extension fields, which present unique challenges due to their large lateral width and complex geometry. The findings demonstrate that field parameter modifications, such as increasing beam width, shifting the jaw aperture, and increasing the number of arcs, can significantly influence target coverage and OARs sparing. The results provide insights into optimizing VMAT plans to achieve a balance between treatment efficacy and safety.

Our results show that limiting the jaw width to 15 cm (X = 15 group) offers superior dose uniformity and OARs sparing compared to wider jaw widths (X = 16–18 groups) or open field plans (OF group). This aligns with previous studies, such as Huang et al.⁹, who demonstrated that VMAT plans with restricted jaw widths resulted in lower doses to multiple OARs compared to open field plans in cervical cancer radiotherapy. Similarly,

	D95%_PTVed	D95%_PTVmi	D95%_PTVup
X = 15	47.38 ± 1.68	47.79 ± 0.53	47.48 ± 2.48
X = 15 M	46.98 ± 1.80	47.86 ± 0.55	47.48 ± 2.39
P	0*	0*	0.897

Table 3. Comparison of D95% for Each Part of PTV Between X = 15 and X = 15 M Plans. A P value < 0.05 indicates a statistically significant difference, which is marked with an asterisk (*) in the table.

	HI	Dmean_INT(Gy)	Dmean_BLA(Gy)	Dmean_REC(Gy)
X = 15	0.175 ± 0.113	25.93 ± 1.65	42.95 ± 2.16	42.48 ± 2.08
SP	0.166 ± 0.112	25.99 ± 1.65	42.59 ± 2.18	42.19 ± 2.16
P	0*	0.062	0*	0*

Table 4. Comparison of HI, Average Dose to Organs at Risk, and Intergroup Comparisons for X = 15 and SP Groups. A P value < 0.05 indicates a statistically significant difference, which is marked with an asterisk (*) in the table.

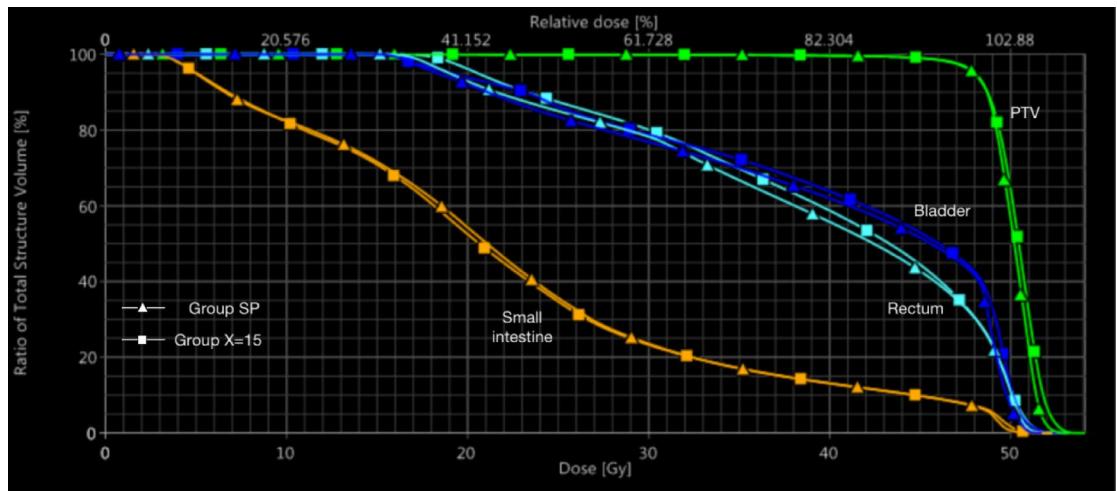


Fig. 6. DVH curves of the plans for Group X = 15 and Group SP.

Keil et al.⁷ found that restricting the x-jaw width improved dose modulation and reduced intestinal doses in endometrial cancer radiotherapy. These findings collectively highlight the importance of limiting jaw width in VMAT planning to optimize dosimetric outcomes. However, as shown in our study, increasing the jaw width to 17 or 18 cm improves target coverage at the expense of higher intestinal doses. This trade-off is consistent with findings by Rossi et al. who reported that wider fields enhanced target coverage but increased OARs doses in pelvic radiotherapy¹⁰. The primary reason for this phenomenon is that increasing the field width improves target coverage. However, when the field width exceeds 15 cm, the modulation capability of the MLC (multileaf collimator) leaves decreases, leading to a decline in plan quality. On the other hand, a narrower jaw opening limits the field size, requiring the MLC leaves to undergo relatively larger movements for modulation. This increased potential for modulation enhances the ability to spare OARs more effectively. The current study further quantifies this trade-off, demonstrating that the benefits of increased coverage are outweighed by the risks of higher intestinal exposure, especially in ILD extension fields with large lateral dimensions.

Based on Fig. 3, shifting the field aperture towards the isocenter improves target coverage in the plan. However, in the dosimetric comparison, the X = 15 M group performs worse than the X = 15 group. While several dosimetric differences between the X = 15 and X = 15 M groups reach statistical significance (e.g., differences in intestinal dose and HI), the absolute differences were relatively small. For instance, the mean intestinal dose difference is less than 1 Gy, and changes in HI are below 0.01. These differences, while measurable, may not necessarily translate into meaningful clinical benefits or reductions in toxicity. It is important to emphasize that such marginal dosimetric improvements should be interpreted cautiously, as their impact on clinical outcomes, such as reductions in gastrointestinal (GI) or genitourinary (GU) toxicity, remains uncertain without supporting clinical data. Shifting the jaw aperture toward the isocenter (X = 15 M group) improves target coverage at the edges but results in significantly higher HI values and increased doses to the small intestine and bladder. This finding is consistent with clinical observations that centralizing the beam aperture can compromise dose

modulation at the periphery of the target volume. Sarma et al. similarly noted that altering the jaw aperture position in prostate cancer plans improved target coverage but increased OARs doses due to reduced modulation capacity at the field edges¹¹. Our analysis of PTV segmentation (PTVedge, PTVmid, and PTVup) reveals that the X=15 M plan concentrates more dose in the central portion of the target (PTVmid) while underdosing the edges (PTVedge). This imbalance suggests that while jaw aperture adjustments may enhance coverage for centrally located targets, they are less effective for extended fields, such as those required in ILD plans. The potential reason for the observed effect is that the PTV left-right width in the ILD extension field plan is larger than in the non-extension field plan. In the X=15 M group, the field positions are more concentrated near the isocenter axis compared to the X=15 group, resulting in less direct beam coverage of the left and right edge regions. This insufficient coverage limits the optimization algorithm's ability to deposit doses effectively, manifesting as reduced modulation opportunities due to the limited angles for MLC leaves to extend fully to the edges, thereby compressing the MLC motion range. Additionally, secondary scattering is weakened, as the proportion of scattered photons received by the edge regions increases, but the low coverage reduces the contribution of scattered doses. Moreover, algorithm errors are amplified; the AAA model used in this study's optimization tends to overestimate the actual dose in low-coverage regions because it does not dynamically correct secondary electron imbalances at heterogeneous interfaces. In summary, the insufficient edge coverage in the X=15 M field and the reduced accuracy of the AAA algorithm in edge regions may both contribute to the relatively lower dose at the field edges in the X=15 M group. Future studies could explore advanced optimization techniques, such as adaptive planning or dynamic jaw tracking, to address this limitation.

The SP group, which utilized four arcs instead of two, demonstrates improved dose uniformity (lower HI) and reduced doses to the bladder and rectum compared to the X=15 group. These findings are consistent with reports by Keil et al.⁷ and Rossi et al.¹⁰ who showed that increasing the number of arcs improved plan quality and reduced OARs doses in pelvic and rectal cancer radiotherapy. Similarly, Jang et al.⁸ demonstrated that splitting wide open fields into multiple narrower fields reduced OARs doses in whole pelvic irradiation, further supporting the benefits of increasing arc numbers in VMAT planning. However, the use of additional arcs increases treatment time, which may introduce greater risks of patient movement and setup errors. This is particularly relevant in ILD plans, where the large target volume and extended treatment duration exacerbate the potential for intrafraction motion. Future research should investigate strategies to mitigate these risks, such as image-guided radiotherapy (IGRT) or real-time motion management.

The findings of this study align with and expand upon previous research in VMAT planning for pelvic cancers. Huang et al.⁹ demonstrated that restricting jaw width to 15 cm improved OARs sparing in cervical cancer VMAT plans, consistent with our findings in ILD extension fields. Keil et al.⁷ highlighted the benefits of splitting fields into multiple arcs for endometrial cancer, which parallels our results showing improved dosimetric outcomes in the SP group. And Rossi et al.¹⁰ emphasized the trade-offs between target coverage and OARs doses in rectal cancer plans, which is similarly observed in our study when comparing X=15 and X=18 groups. These studies collectively underscore the importance of tailoring VMAT field parameters to the specific geometry and dosimetric requirements of the target volume. Our study contributes to this body of knowledge by providing a detailed analysis of ILD extension fields, which are less commonly studied but present unique challenges due to their large lateral dimensions.

This study has several limitations that warrant further investigation. First, the sample size is relatively small, and the variability in target volume sizes may influence the results. The use of a non-uniform and case-specific normalization criterion, namely targeting a V48.6 Gy within a broad range, may introduce confounding variables. To address this, we employed the RBD ANOVA to compare plan quality across different groups. Unlike a completely randomized design, the RBD ANOVA not only accounts for variation between groups but also isolates the variation caused by block factors (e.g., the distribution of "low coverage" versus "high coverage" cases across groups). This approach minimized bias in inter-group comparisons and improved the reliability of the results. Second, the study focuses on a single type of linear accelerator and planning system, which may limit the generalizability of the findings to other platforms. Future research should explore the impact of different accelerators, such as those with dynamic jaw tracking capabilities, on dosimetric outcomes. Additionally, the increased treatment time associated with the SP group highlights the need for strategies to reduce intrafraction motion. Techniques such as IGRT, respiratory gating, or adaptive planning could be explored to address this challenge. Finally, this study is limited by its retrospective and purely dosimetric nature, with no direct clinical outcome data available for validation. However, anecdotal evidence and institutional experience suggest that improved dose homogeneity and reduced OARs doses, as observed in the X=15 group, could potentially lower the risk of acute and late toxicities, particularly in GI and GU systems. For example, previous studies have reported correlations between reduced small intestine doses and decreased rates of radiation-induced enteritis. Future research incorporating prospective clinical data is essential to confirm whether the observed dosimetric trends lead to tangible improvements in patient outcomes.

Conclusion

In cervical cancer ILD plans, increasing jaw width or shifting the jaw aperture toward the isocenter improves target coverage but increases OARs doses, particularly to the small intestine. Increasing the number of arcs enhances plan quality but prolongs treatment time, potentially increasing the risk of setup errors. Based on our findings, dual-arc VMAT plans with a 15 cm jaw width and off-center jaw aperture are recommended for routine clinical use. Future research should focus on advanced optimization techniques and clinical validation to further refine VMAT planning for ILD extension fields.

Data availability

Data is provided within the manuscript or supplementary information files.

Received: 27 February 2025; Accepted: 15 July 2025

Published online: 19 July 2025

References

- Yadav, G. et al. Dosimetric influence of photon beam energy and number of arcs on volumetric modulated arc therapy in carcinoma cervix: A planning study. *Rep. Pract. Oncol. Radiother.* **22**, 1–9. <https://doi.org/10.1016/j.rpor.2016.09.002> (2017).
- Batumalai, V. et al. Impact of dosimetric differences between CT and MRI derived target volumes for external beam cervical cancer radiotherapy. *Br. J. Radiol.* **93**, 1114. <https://doi.org/10.1259/bjr.20190564> (2020).
- Wu, Y. et al. A comparative dosimetric study of cervical cancer patients with para-aortic lymph node metastasis treated with volumetric modulated arc therapy vs. 9-field intensity-modulated radiation therapy. *Ann. Transl. Med.* **7**, 675. <https://doi.org/10.21037/atm.2019.10.53> (2019).
- Bhatla, N., Aoki, D., Sharma, D. N. & Sankaranarayanan, R. Cancer of the cervix uteri. *Int. J. Gynaecol. Obstet.* **164**, 1229–1230. <https://doi.org/10.1002/ijgo.15395> (2024).
- Zhang, G. et al. A novel risk factor for para-aortic lymph node recurrence after definite pelvic radiotherapy in stage IIIB cervical cancer. *Technol. Cancer Res. Treat.* **21**, 15330338221141540. <https://doi.org/10.1177/15330338221141541> (2022).
- Song, S. et al. The size of the metastatic lymph node is an independent prognostic factor for the patients with cervical cancer treated by definitive radiotherapy. *Radiother. Oncol.* **108**, 168–173. <https://doi.org/10.1016/j.radonc.2013.04.015> (2013).
- Keil, J. et al. A dosimetric study using split x-jaw planning technique for the treatment of endometrial carcinoma. *Med. Dosim.* **45**, 278–283. <https://doi.org/10.1016/j.meddos.2020.02.001> (2020).
- Jang, H. et al. Effective organs-at-risk dose sparing in volumetric modulated arc therapy using a half-beam technique in whole pelvic irradiation. *Front. Oncol.* **11**, 611469. <https://doi.org/10.3389/fonc.2021.611469> (2021).
- Huang, B., Fang, Z., Huang, Y., Lin, P. & Chen, Z. A dosimetric analysis of volumetric-modulated arc radiotherapy with jaw width restriction vs 7 field intensity-modulated radiotherapy for definitive treatment of cervical cancer. *Br. J. Radiol.* **87**, 20140183. <https://doi.org/10.1259/bjr.20140183> (2014).
- Rossi, M., Boman, E., Skyytä, T. & Kapanen, M. A novel arc geometry setting for pelvic radiotherapy with extensive nodal involvement. *J. Appl. Clin. Med. Phys.* **17**, 73–85. <https://doi.org/10.1120/jacmp.v17i4.6028> (2016).
- Sarma, G. et al. Impact of split X-jaw technique on target volume coverage and organ at risk sparing in prostate cancer: A comparative dosimetric study. *J. Radiother. Pract.* **22**, 41. <https://doi.org/10.1017/S1460396922000103> (2023).

Author contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

Funding

This study was funded by Tianjin Key Medical Discipline (Specialty) Construction.

Project (Obstetrics and gynecology). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-025-12224-y>.

Correspondence and requests for materials should be addressed to J.Z.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2025