Beam complexity and monitor unit efficiency comparison in two different volumetric modulated arc therapy delivery using automated planning

Chengqiang Li
  Shandong Cancer Hospital and Institute, Shandong First Medical University and Shandong Academy of Medical Sciences   https://orcid.org/0000-0002-8549-2416

Cheng Tao
  Shandong Cancer Hospital and Institute

Tong Bai
  Shandong Cancer Hospital and Insitute

Zhenjiang Li
  Shandong Cancer Hospital and Institute

Ying Tong
  Shandong Cancer Hospital and Institute

Jian Zhu
  Shandong Cancer Hospital and Institute

Yong Yin (✉ yinyongsd@126.com)
  yongyinsd@163.com

Jie Lu
  https://orcid.org/0000-0002-8789-8129

Research article

Abstract

Background: To investigate the beam complexity and monitor unit（MU）efficiency issues for two different volumetric modulated arc therapy (VMAT) delivery technologies for patients with left-sided breast cancer (BC) and nasopharyngeal carcinoma (NPC).

Methods: Twelve left-sided BC and seven NPC cases were enrolled in this study. Each delivered treatment plan was optimized in Pinnacle 3 treatment planning system with Auto-Planning module for Trilogy and Synergy systems. Similar planning dose objectives and beam configuration were used for each site in two different delivery systems to produce clinically acceptable plans. Beam complexity was evaluated in terms of segment area(SA), segment width(SW), leaf sequence variability(LSV), aperture area variability(AAV), modulation complexity score(MCS) based on MLC sequence and MU.

Results: With similar plan quality, the average SAs for Trilogy plans were smaller than those for Synergy plans: 55.5 ± 21.3 cm 2 vs. 66.3 ± 17.9 cm 2 (p<0.05) for the NPC cases, and 100.7 ± 49.2 cm 2 vs. 108.5 ± 42.7 cm 2 (p<0.05) for BC cases, respectively. The SW was statistically significant for two delivery systems (NPC: 6.87±1.95cm vs.6.72±2.71cm, p < 0.05; BC: 8.84±2.56cm vs.8.09±2.63cm, p < 0.05). LSV was statistically significant smaller for Trilogy (NPC: 0.84±0.033 vs.0.86±0.033, p < 0.05; BC: 0.89±0.026 vs.0.90±0.26, p < 0.05). The mean AAV was statistically significant larger for Trilogy than Synergy (NPC: 0.18±0.064 vs.0.14±0.037, p < 0.05; BC: 0.46±0.15 vs.0.33±0.13, p < 0.05). The MCS values for the Trilogy were higher than those for the Synergy: 0.14 ± 0.016vs. 0.12 ± 0.017 (p<0.05) for the NPC cases, and 0.42 ± 0.106 vs. 0.30 ± 0.087(p<0.05) for the BC cases. Compared with Synergy plans, the average MU for Trilogy plans were larger: 828.6±74.1MU and 782.9±85.2MU (p>0.05) for the NPC cases, and 444.8±61.3MU and 393.8±75.3MU (p>0.05) for the BC cases.

Conclusions: The pinnacle 3 Auto planning system can optimize BC and NPC plans to obtain the same plan quality using Trilogy and Synergy systems. We found that this two systems resulted in different SA, SW, LSV, AAV and MCS. As a result, we suggested that beam complexity should be considered in providing further methodologies while optimizing VMAT auto planning.

Background

Currently, volumetric modulated arc therapy (VMAT) is one of the most advanced delivery techniques in radiotherapy, which simultaneously integrates multi-leaf collimator (MLC) field shape modulation with gantry speed and dose rate variations. With more degrees of freedom during treatment, advanced arc plans provide a larger flexibility in shaping dose distributions and delivery the plan more efficiently than other static beams plans [1, 2]. VMAT technique has become clinically and commercially available by using Trilogy (Varian Medical Systems, Palo Alto, CA, USA) and Synergy (Elekta AB, Stockholm, Sweden) linear accelerators. However, there are many differences between the two machines, such as the method of dose rate control [3], MLC leaf width [4]and the jaw tracking technique [5]. Several investigations have been performed in order to show dosimetric effect on these system differences.

Studies have suggested that VMAT may be useful in a variety of treatment sites, such as BC [6–8] and NPC [9–12]. As well all known that high quality treatment plan relies on the skills and experience of the dosimetrist, which can vary greatly. Recently, some automatic planning solutions have been developed, such as atlas-based planning, ideal dose distribution estimation and template-based optimization [13].

The template-based Auto-Planning module has recently become clinically available in Pinnacle[3] radiation therapy treatment planning system (TPS). Several comprehensive studies have been performed to evaluate the benefit of this new auto-planning system [13–16]. The results showed that the Auto-Planning VMAT technique achieved adequate target dose coverage while maintaining low doses to organs-at-risk, and therefore reduced the potential for induction of second malignancy and side effects. Another conclusion from existing research results was that the auto-planning module could generate plans with consistent quality.

Due to the highly choreographed nature of VMAT delivery, many potential sources of error arise, necessitating patient specific quality assurance (QA) and dosimetric verification technique [17]. The treatment plan of VMAT requires compromise between dose conformity (complexity) and deliverability. The creation of modulation complexity score (MCS) [18] based on plan parameters allows for a quantitative assessment of plan complexity and can provide more information related to dose delivery than simple beam parameters such as monitor units (MU). Excessive complexity in VMAT plans increases the dose uncertainty, prolongs the treatment time, and increases the susceptibility to changes in patient or target geometry. McNiven et al. [19] performed a study to evaluate the utility of MCS to evaluate the relationship of the metric with deliverability in IMRT and reported that different clinical treatment sites have an inherent difference in the level of complexity, the average MCS of IMRT plans for head and neck as well as breast is 0.165 and 0.909, respectively.

However, the use of MCS for auto VMAT plan for different treatment sites is still rare. The purpose of this study was to evaluate beam complexity of two delivery systems optimized by the Auto-Planning.

Methods

Patients

A retrospective analysis was performed on 12 patients with left-sided BC and 7 patients with NPC who were randomly selected from our institution. The prescription dose was 50.0 Gy in 25 fractions for BC. There were three different dose levels in NPC patients included 54 Gy, 60 Gy, and 66 Gy in 30 treatment fractions with a simultaneous integrated boost technique.

For BC, plan objectives were: D100% >100% for CTV, D100% >90% for PTV, mean dose for heart and contralateral breast. V_{XGy} to ipsilateral lung and body were minimized to keep the dose to the organ at risks (OARs) as low as possible by setting higher priority upon avoidance of the contralateral breast,

lungs and heart, without compromising the PTV dose coverage and maximum hotspots should not exceed 110%.

For NPC, the treatment goals were that 95% of PTV should receive more than 95% of the prescribed dose and the maximum dose should below 110% of prescription dose. Regarding to the OARs, the maximum doses to the brain stem and the spinal cord were set to 54 Gy and 45 Gy, respectively. In addition, at least one side of the parotid glands should receive a mean dose less than 26 Gy, or the volume receiving 30 Gy radiation should be < 50%. The dose to other normal tissues was minimized within a reasonable range without affecting the target coverage.

Treatment optimization

The treatment planning was performed with Pinnacle[3] (V9.10, Philips Radiation Oncology Systems, Fitchburg, WI) treatment planning system. Each of the 19 treatment plans was optimized with Pinnacle Auto-Planning module for a Varian Trilogy (Varian Medical Systems, Palo Alto, CA) linear accelerator, equipped with a 120 leaf Millennium MLC and an Elekta Synergy (Elekta Ltd, Crawley, UK) linear accelerator, equipped with a 40 leaf MLCi using 6 MV photons, respectively. Varian Trilogy system can delivery VMAT plan using continuously variable dose rate while Elekta Synergy using binned variable dose rate. Trilogy system was equipped with a 120 Millennium MLC, the Millennium 120 multi-leaf collimators (MLCs) consists of two banks of 60 MLC leaves, with the outer 20 and inner 40 on each side having widths of 10 mm and 5 mm, respectively. Synergy system was equipped with MLCs comprising 40 leaf pairs projected leaf width of 10 mm at the isocenter. In addition, Synergy provides jaw tracking technique, Trilogy doesn't have jaw tracking capability.

The NPC VMAT plans in this study used two full arcs with gantry angles 181°−179° for a CW rotation and 179°−181° for a CCW rotation, collimator angles were set to be 15°and 345° to avoid possible overlapping tongue and groove effect. The BC VMAT plans consisted of two short partial arcs, each arc consisted of a 40° gantry rotation, irradiating between gantry angles 296°−336°and 104°−144° for a CW rotation with collimator angles of 5°−10°for decreasing the larger volume of low dose spread to healthy tissue based on our experience. The dose calculations were performed using Pinnacle's collapsed cone convolution superposition algorithm with the gantry spacing resolution 2°and the dose voxel size of 0.3 × 0.3 × 0.3 cm^3.

The Auto-Planning module requires the user to define a template with prioritized optimization goals for PTV coverage and dose limits for OARs. These prioritized optimization goals are used by the Auto-planning engine to formulate optimization objectives. Multiple optimization loops iteratively reformulate and adjust the optimization objectives to meet the criteria defined in the template. During the optimization process, the optimization of target coverage has higher priority over dose reduction to OARs. After the auto-optimization, the treatment plans were fine-tuned by an expert planner to adapt the PTV coverage and OARs protection as same as possible by the two delivery systems.

Complexity scores

To optimize arc delivery treatment plans, the treatment planning system uses multiple control points (CP) to represent the arc plan. The CP refers to the instantaneous configuration at a point in time and 'segment' refers to the duration between CPs, although the two may be used synonymously. Once treatment plan is completed for a patient, the plans were extracted from the treatment planning system as RTPlan files. RTPlan files contain the information of gantry angle, MLC configuration, Jaw position, and MU for each CP. As main part of our work, the beam complexity scores and dose-volumetric parameters were calculated by an in-house software developed in Matlab (Version 2010b, MathWorks, Natick, MA).

The complexity scores include MU, segment width (SW), segment area(SA), leaf sequence variability(LSV), aperture area variability(AAV) and modulation complexity score(MCS). The SW and SA for a given segment at a certain gantry angle is as described by Eqs. (1) and (2), respectively, where pos is the coordinate of the leaf position and N is the number of in-field moving leaves inside the jaw position. N is the total number of leaf pairs, n is the index number of leaf pairs. LeafWidth_n is the width of the nth leaf pair. $\text{SW}_{\text{segment\_i}}$ can be roughly understood as the area of a beam segment. The leaves that remained closed during treatment were not considered.

$$\text{SW}_{\text{segment}_i} = \max\left(\text{pos}_{n \in N \, \text{left bank}} - \text{pos}_{n \in N \, \text{right bank}}\right) \quad , \tag{1}$$

$$\text{SA}_{\text{segment}_i} = \sum_{n=1}^{N}\left(\langle\text{pos}_n\rangle_{\text{left bank}} - \langle\text{pos}_n\rangle_{\text{right bank}}\right) \times \text{LeafWidth}_n, \tag{2}$$

MCS and its parameters for each VMAT plans were determined by following formulae:

$$\text{pos}_{\max}(\text{segment}_i) = \langle\max(\text{pos}_{n \in N}) - \min(\text{pos}_{n \in N})\rangle_{\text{MLC bank}}, \tag{3}$$

$$\text{LSV}_{\text{segment}_i} = \langle\frac{\sum_{n=1}^{N-1}(\text{pos}_{\max} - |(\text{pos}_n - \text{pos}_{n+1})|)}{(N-1) \times \text{pos}_{\max}}\rangle_{\text{left bank}} \times \langle\frac{\sum_{n=1}^{N-1}(\text{pos}_{\max} - |(\text{pos}_n - \text{pos}_{n+1})|)}{(N-1) \times \text{pos}_{\max}}\rangle_{\text{right bank}}, \tag{4}$$

$$\text{AAV}_{\text{segment}_i} = \frac{\sum_{n=1}^{N}(\langle\text{pos}_n\rangle_{\text{left bank}} - \langle\text{pos}_n\rangle_{\text{right bank}}) \times \text{LeafWidth}_n}{\sum_{n=1}^{N}(\langle\text{pos}_n\rangle_{\text{left bank} \in \text{arc}} - \langle\text{pos}_n\rangle_{\text{right bank} \in \text{arc}}) \times \text{LeafWidth}_n}, \tag{5}$$

The parameter leaf sequence variability (LSV) was used to characterize the variation in segment shape and parameter aperture variability (AAV) was used to characterize the variation in segment area relative to the maximum aperture defined by all the segments.

To summarize the influence of LSV, AAV and MU, the MCS for a given arc is calculated based on the scores above, as Eq. (6) describes:

$$\text{MCS}_{\text{arc}} = \sum_{i=1}^{I-1}\left[\frac{\text{LSV}_{\text{segment}_i} + \text{LSV}_{\text{segment}_{i+1}}}{2} \times \frac{\text{AAV}_{\text{segment}_i} + \text{AAV}_{\text{segment}_{i+1}}}{2} \times \text{weight}_i\right]. \tag{6}$$

The MCS calculation based on three parameters: segment shape, area and weight, as in the original definition, has the value range from 0 to1. MCS = 1 means no modulation and these interpretations suggest that the average MCS score for a treatment site always decreases with increased inherent complexity.

Evaluation

The collected data represented as mean ± standard deviation was analyzed with SPSS software (version 13.0, Chicago, USA). The difference of Trilogy and Synergy plans were evaluated by the two-sided Wilcoxon matched-pair signed-rank test. The threshold for statistical significance was set at $p < 0.05$.

Results

PTVs coverage and OARs sparing

Average DVHs for the target volumes and the various OARs comparison between Trilogy and Synergy plans for NPC and BC were shown in Fig. 1. All plans sufficiently respected the planning objectives and could be clinically accepted. After post-optimization sequenced by Auto-Planning, there were no drastic variation in the dose-volume between PTVs and OARs.

MU efficiency

In Table 1, the average volume of PTV and number of MUs are summarized. The average MU among BC patients was 444.8 ± 61.3 for Trilogy and 393.8 ± 75.3 for Synergy. The average MU among NPC patients was 828.6 ± 74.1 for Trilogy and 782.9 ± 85.2 for Synergy.

Table 1
Statistical summary of the differences in MU efficiency

Site	Volume	MU		P value
		Trilogy	Synergy	(Trilogy vs. Synergy)
NPC	833.4 ± 174.8	828.6 ± 74.1	782.9 ± 85.2	0.128
BC	833.3 ± 198.9	444.8 ± 61.3	393.8 ± 75.3	0.203
P value (BC vs. NPC)		0.018	0.017	

Complexity scores comparison

MCS and its dependent parameters such as SA, LSV and AAV are summarized in Table 2. Significant changes were observed between the Trilogy and Synergy plans in terms of beam complexity scores for both NPC and BC plans ($p < 0.05$ for all). The detailed SA and AAV comparisons of the Trilogy and the Synergy plans for each control point are given in Figs. 2 and 3.

Table 2
Statistical summary of the differences in complexity scores

Site	Delivery System	Complexity scores				
		SW(cm)	SA (cm ^{2})	LSV	AAV	MCS
NPC	Trilogy	6.87 ± 1.95	55.5 ± 21.3	0.84 ± 0.033	0.18 ± 0.064	0.14 ± 0.016
	Synergy	6.72 ± 2.71	66.3 ± 17.9	0.85 ± 0.039	0.14 ± 0.037	0.12 ± 0.017
	P value	0.000	0.000	0.000	0.000	0.002
Breast	Trilogy	8.84 ± 2.56	100.7 ± 49.2	0.89 ± 0.026	0.46 ± 0.15	0.42 ± 0.106
	Synergy	8.09 ± 2.63	108.5 ± 42.7	0.90 ± 0.026	0.33 ± 0.13	0.30 ± 0.087
	P value	0.000	0.000	0.031	0.000	0.001

Discussion

This work demonstrated that the Pinnacle[3] Auto-Planning system was able to produce comparable quality VMAT plans by different delivery systems, and was therefore able to successfully handle the geometric and dosimetric variations between NPC and BC sites. The significant differences in modulation complexity of VMAT plans between Trilogy and Synergy were found.

The dosimetric studies of auto plan showed excellent target volume coverage and OARs sparing to various target paradigms [13–16]. Hazell et al. [14] compared auto plans with manual head and neck cancer IMRT treatment plans, they found that target coverages in the auto plans were similar to manual plans, but automatically generated plans had less irradiation of healthy tissue. In contrast to other studies, the primary goal in this study was to generate "same" plans.

There were several major differences between Varian Trilogy and Elekta Synergy systems used for delivering VMAT plans. To reduce the variability in the quality of treatment plans, dose objectives in Auto-Planning can be automatically generated to drive the optimization of the new plan. What is noteworthy is that it required further user intervention to manually set optimization objectives at the end of the auto optimization process. Allowing for a manual post optimization, the coverage for PTVs and dose constrains for OARs were as same as possible.

In summary, as shown in Fig. 1, the Pinnacle Auto-Planning was able to produce VMAT comparable plans using Trilogy and Synergy delivery systems for more complex cases (breast and NPC tumor regions). The only differences occurred about brainstem and spinal cord because the concern was mostly focused to constraint the max dose of these two organs during optimization. However, the values were still within the

tolerance range. Both delivery techniques, if considered from a clinical perspective appear to be equivalent.

Regarding the treatment MU, the corresponding data listed in Table 1 suggested that although the tumor volumes were similar for NPC and BC, the BC plans had lower MUs than NPC plans by applying approximately tangential arcs. The Synergy required less MU to treat the same volume tumor, even there was not drastic variation in the MU value among the two systems for either site. This difference of MU was largely attributed to the fact that large area segments were more often in Synergy plans than in Trilogy plans. Similar study in terms of IMRT plans was reported by Qi et al. [20]. As observed from their published study, high MU efficiency was observed in direct aperture optimization (DAO) plans than direct machine parameter optimization (DMPO) plans because large area segments were used often in DAO plans.

Both Synergy and Trilogy plans had clinically acceptable plan quality, but we observed that the SA was different. The breast plans used larger SA than NPC plans. Synergy used larger SA than Trilogy for the same site. The Synergy plans were manifested in the larger segment area and lower MU relative to the Trilogy plans. Furthermore, VMAT auto plans were more sensitive to MLC errors [22].

To assess the beam complexity, as stated in the results, we found significant differences. In this study, the MCS of NPC and BC plans were 0.14 and 0.42 for Trilogy, 0.12 and 0.3 for Synergy. Dhanabalan et al. [21] reported that average MCS for the head and neck VMAT plans were 0.2224. The MCS for auto plans were smaller than manual plans, which suggested the beams were more complex. The autoplans were more modulated as illustrated by Hansen et al. [13], which might cause the slightly lower pass rate of 97.7% in the ArcCHECK measurements. The question of the relationship of plan complexity and gamma index analysis of delivery accuracy was not included in this study.

However, much effort has been devoted to analysis that correlation using different patient-specific QA phantom. Crowe et al. [23] found that the 'small aperture score' provided threshold values which successfully distinguished deliverable treatment plans from plans that did not pass QA using MapCheck2 diode array. Li et al. [24] found that the planning parameters such as the average leaf travel and average field indicating a correlation between the plan complexity and the passing rate using ArcCHECK diode array. Dhanabalan et al. [21] studied the correlation results between the MCS and gamma analysis results indicate that MCS of a plan has a weak correlation with the planar as well as volumetric gamma analysis passing rates using Octavius4D phantom. Knowledge of this relationship will be further accumulated using our MatrixX and ArcCHECK phantom. This study demonstrates that treatment techniques differ in terms of treatment MU and MCS. Mcgarry et al. [25] suggested MCS was most suitable for inclusion within the cost function to limit complexity in IMRT optimization. VMAT plans, which are less complex, also have higher probabilities of yielding accurate dosimetric results.

Conclusions

In conclusion, all VMAT plans using Trilogy or Synergy implemented in the Pinnacle Auto-Planning module were clinically acceptable and comparable in terms of PTV coverage and OAR sparing for NPC and BC. The differences in SA, SW, LSV, AAV and MCS which should be considered in auto-plan designing were observed. In reality, this can be implemented as a function in TPS in the future.

Abbreviations

VMAT:Volumetric modulated arc therapy; MU:Monitor unit; BC:Breast cancer; NPC:Nasopharyngeal carcinoma; SA:Segment area; SW:segment width; LSV:Leaf sequence variability; AAV:Aperture area variability; MCS:Modulation complexity score; MLC:Multi-leaf collimator; TPS:Treatment planning system; QA:Quality assurance; DMPO:Machine parameter optimization; DAO:Direct aperture optimization; OARs:organ at risks;

Declarations

References

1. Otto K. Volumetric modulated arc therapy: IMRT in a single gantry arc. Med Phys. 2008;35:310–7.

2. Bedford JL. Treatment planning for volumetric modulated arc therapy. Med Phys. 2009;36:5128–38.

3. Wu Y, Dogan N, Liang X. Assessment of volumetric arc therapy plans for constant and variable dose rates. Med Phys. 2010;37:3350–1.

4. Kim JI, Park JM, Park SY, Choi CH, Wu HG, Ye SJ. Assessment of potential jaw-tracking advantage using control point sequences of VMAT planning. J Appl Clin Med Phys. 2014;15:4625–8.

5. Serna A, Puchades V, Mata F, Ramos D, Alcaraz M. Influence of multi-leaf collimator leaf width in radiosurgery via volumetric modulated arc therapy and 3D dynamic conformal arc therapy. Phys Med. 2015;33:293–6.

6. Jeulink M, Dahele M, Meijnen P, Slotman BJ, Verbakel W-FAR. Is there a preferred IMRT technique for left-breast irradiation? J Appl Clin Med Phys. 2015;16:5266–74.

7. Tsai PF, Lin SM, Lee SH, Yeh CY, Huang YT, Lee CC, et al. The feasibility study of using multiple partial volumetric-modulated arcs therapy in early stage left-sided breast cancer patients. J Appl Clin Med Phys. 2012;13:3806–17.

8. Popescu CC, Olivotto IA, Beckham WA, Ansbacher W, Zavgorodni S, Shaffer R, et al. Volumetric modulated arc therapy improves dosimetry and reduces treatment time compared to conventional intensity-modulated radiotherapy for locoregional radiotherapy of left-sided breast cancer and internal mammary nodes. Int J of Radiat Oncol Biol Phys. 2010;76:287–95.

9. Lu SH, Cheng JCH, Kuo SH, Lee J-JS, Chen LH, Wu JK, et al. Volumetric modulated arc therapy for nasopharyngeal carcinoma: a dosimetric comparison with TomoTherapy and step-and-shoot IMRT. Radiother Oncol. 2012;104(3):324–30.

10. Bertelsen A, Hansen CR, Johansen J, Brink C. Single arc volumetric modulated arc therapy of head and neck cancer. Radiother Oncol. 2010;95:142–8.

11. Ning ZH, Mu JM, Jin JX, Li XD, Li QL, Gu WD, et al. Single arc volumetric-modulated arc therapy is sufficient for nasopharyngeal carcinoma: a dosimetric comparison with dual arc VMAT and dynamic MLC and step-and-shoot intensity-modulated radiotherapy. Radiat Oncol. 2013;8:237–45.

12. Holt A, Van Gestel D, Arends MP, Korevaar EK, Schuring D, Kunze-Busch MC, et al. Multi-institutional comparison of volumetric modulated arc therapy vs. intensity-modulated radiation therapy for head-and-neck cancer: a planning study. Radiat Oncol. 2013;8:26–35.

13. Hansen CR, Bertelsen A, Hazell I, Zukauskaite R, Gyldenkerne N, Johansen J, et al. Automatic treatment planning improves the clinical quality of head and neck cancer treatment plans. Clin Transl Radiat Oncol. 2016;1:2–8.

14. Hazell I, Bzdusek K, Kumar P, Hansen CR, Bertelsen A, Eriksen JG, et al. Automatic planning of head and neck treatment plans. J Appl Clin Med Phys. 2016;17:272–82.

15. Sharfo AW, Voet PW, Breedveld S, Mens JW, Hoogeman MS, Heijmen BJ. Comparison of VMAT and IMRT strategies for cervical cancer patients using automated planning. Radiother Oncol.

2015;114:395−401.

16. Mitchell RA, Wai P, Colgan R, Kieby AM, Donovan EM. Improving the efficiency of breast radiotherapy treatment planning using a semi-automated approach. J Appl Clin Med Phys. 2017;18:18−24.

17. Tyagi N, Yang K, Gersten D, Yan D. A real time dose monitoring and dose reconstruction tool for patient specific VMAT QA and delivery. Med Phys. 2012;39:7194−204.

18. Webb S. Use of a quantitative index of beam modulation to characterize dose conformality: illustration by a comparison of full beamlet IMRT, few-segment IMRT (fsIMRT) and conformal unmodulated radiotherapy. Phys Med Biol. 2003;48:2051−62.

19. Mcniven AL, Sharpe MB, Purdie TG. A new metric for assessing IMRT modulation complexity and plan deliverability. Med Phys. 2010;37:505−15.

20. Qi P, Xia P. Relationship of segment area and monitor unit efficiency in aperture-based IMRT optimization. J Appl Clin Med Phys. 2013;14:232−43.

21. Dhanabalan R, Prakash J, Prabakar S, Ranganathan A, Johnjothi S, Nagarajan V. A study on the correlation between plan complexity and gamma index analysis in patient specific quality assurance of volumetric modulated arc therapy. Rep Pract Oncol Radiother. 2015;20:57−65.

22. Pogson EM, Aruguman S, Hansen CR, Currie M, Oborn BM, Blake SJ, et al. Multi-institutional comparison of simulated treatment delivery errors in ssIMRT, manually planned VMAT and autoplan-VMAT plans for nasopharyngeal radiotherapy. Phys Med. 2017;42:55−66.

23. Crowe SB, Kairn T, Kenny J, Knight RT, Hill B, Langton CM, et al. Treatment plan complexity metrics for predicting IMRT pre-treatment quality assurance results. Australas Phys Eng Sci Med. 2014;37:475−82.

24. Li G, Wu K, Peng G, Zhang Y, Bai S. A retrospective analysis for patient-specific quality assurance of volumetric-modulated arc therapy plans. Med Dosi. 2015;39:309−13.

25. Mcgarry CK, Chinneck CD, O'Toole MM, O'Sullivan JM, Prise KM, Hounsell AR. Assessing software upgrades, plan properties and patient geometry using intensity modulated radiation therapy (IMRT) complexity metrics. Med Phys. 2011;38:2027−34.
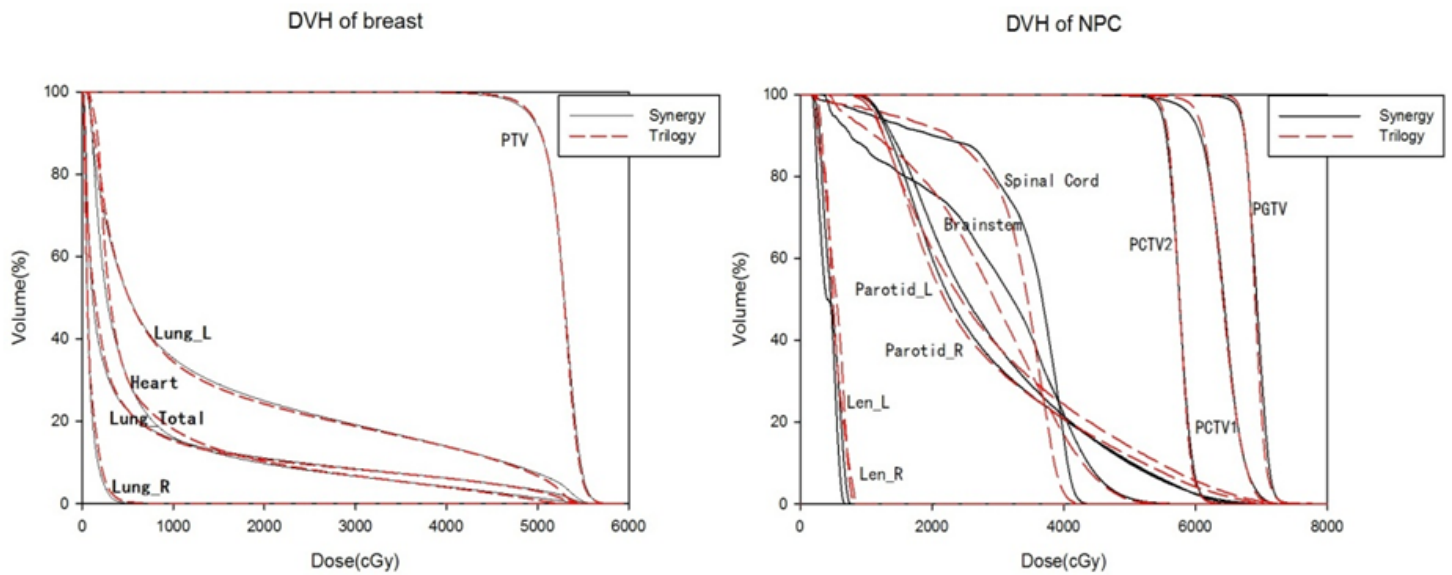
Figures

Figure 1

Mean DVHs comparison between Trilogy and Synergy plans for BC(left) and NPC(right). Solid line: Synergy; dashed line: Trilogy.
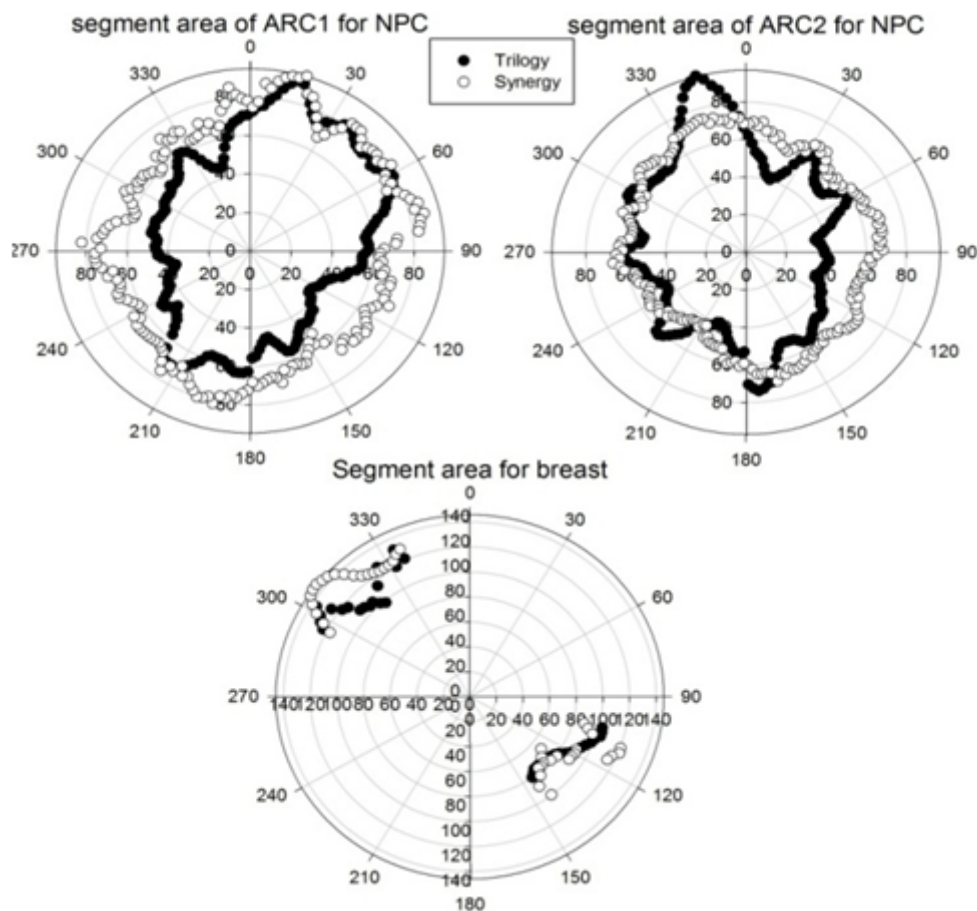

Figure 2

Average SA comparison between Trilogy and Synergy plans for NPC and BC. White circle: Synergy; black circle: Trilogy.
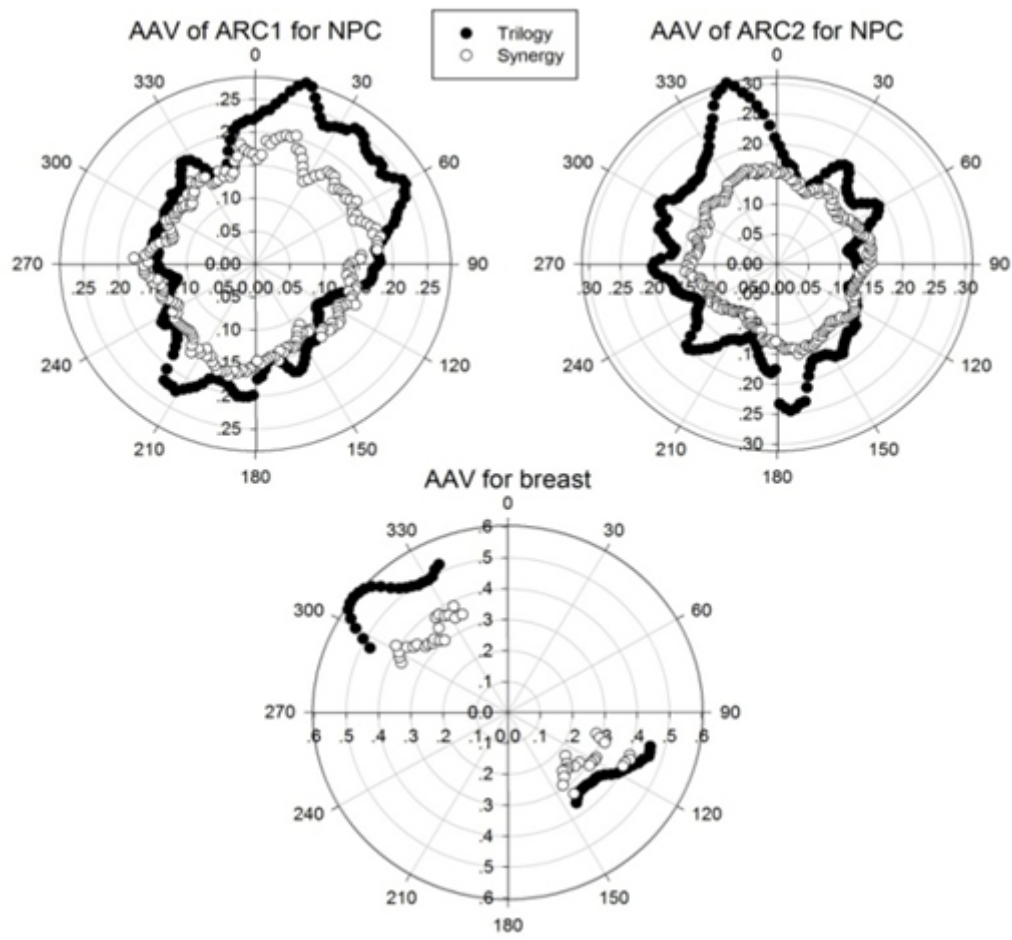

Figure 3

Average AAV comparison between Trilogy and Synergy plans for NPC and BC. White circle: Synergy; black circle: Trilogy.