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Impact of Dose Rate Settings on Delivery Accuracy in Dynamic Swing Arc for Prostate SBRT

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ABSTRACT

Purpose:
Dynamic Swing Arc (DSA) irradiation with the OXRAY radiotherapy system integrates simultaneous gantry rotation and ring motion, enabling high-dose-rate delivery for prostate stereotactic body radiotherapy (SBRT). Although the system can deliver 6 MV flattening-filter-free (FFF) beams up to 1150 MU/min, large and rapid dose rate modulations may challenge the mechanical response and dosimetric accuracy. This study evaluated the impact of varying minimum dose rate settings on dosimetric accuracy, delivery efficiency, and organ-at-risk (OAR) sparing for DSA-based prostate SBRT.

Methods:
Three prostate cancer cases were planned using a 36.25 Gy/5 fx DSA technique prescribed to PTV D95. Four minimum dose rate settings were compared: 250, 450, 650, and 850 MU/min (all with a maximum of 1150 MU/min). The dosimetric quality was assessed using standard clinical metrics. Delivery accuracy was quantified using gamma analysis (2 mm/3 %, 10% threshold) with a high-resolution 2D detector array. Treatment log files were analyzed to compare the planned and delivered dose rate modulation and cumulative monitor units (MU).

Results:
Higher minimum dose rate conditions significantly reduced the beam-on time while maintaining comparable PTV coverage. However, the intermediate OAR doses increased moderately with higher minimum dose rates, particularly at 850 MU/min. Gamma pass rates improved with increased minimum dose rate: the lowest setting (250 MU/min) exhibited the lowest pass rate (mean ~63%), whereas 650 and 850 MU/min settings consistently exceeded 95% gamma passing rate. Log analysis revealed that lower minimum dose rates were associated with frequent rapid dose rate adjustments, which correlated with increased delivery deviation.

Conclusion:
For DSA-based prostate SBRT on the OXRAY platform, a minimum dose rate of 650 MU/min balances efficient delivery with high dosimetric fidelity and acceptable OAR sparing. Lower minimum dose rates may compromise delivery accuracy because of mechanical dose rate modulation limitations.

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INTRODUCTION

Dynamic Swing Arc (DSA) is a sophisticated beam delivery technique that facilitates non-coplanar volumetric-modulated arc therapy (VMAT). Unlike conventional non-coplanar VMAT delivered on C-arm linear accelerators, which necessitates time-consuming couch rotation and increases the risk of collision between the gantry and the patient or couch, DSA enables continuous gantry and O-ring rotation simultaneously around two axes without moving the treatment couch. This technique is primarily implemented in the second-generation O-ring-shaped radiotherapy system (OXRAY, Hitachi High-tech Corporation, Japan). By eliminating the need for couch movement, DSA not only shortens treatment duration but also minimizes intra-fractional errors related to patient repositioning and couch positioning accuracy. From a dosimetric perspective, the increased degrees of freedom in beam delivery provided by DSA have been shown to significantly enhance dose homogeneity and target conformity while sparing organs at risk (OARs) across various clinical sites, including the head and neck, prostate, pancreas, and brain. However, the impact of dose-rate setting, particularly the restriction of dose-rate variation during DSA optimization and delivery, has not been investigated. A systematic evaluation of this issue is necessary because dose-rate constraints may directly influence both the achievable plan quality and robustness of treatment delivery, especially for highly modulated plans requiring complex synchronization of multiple mechanical components. Therefore, this study aimed to evaluate the effect of dose rate settings on irradiation accuracy in DSA treatment planning.

METHODS AND MATERIALS

This study was approved by the Institutional Review Board at Fujita Health University, and all patients consented to participate (HM25-104). Treatment plans for stereotactic prostate radiation therapy using DSA were created for 3 prostate cancer patients who underwent radiation therapy at Fujita Health University Hospital. Planning was performed using RayStation version 2023B (RaySearc Laboratories, Sweden). All treatment plans employed a 6-MV FFF beam, and DSA plans were generated using a single gantry rotation (Figure 1). All treatment plans were prescribed at a prescription dose of 36.25 Gy in 5 fractions at the D95% isodose. The dose constraints for the treatment plan are shown in Table 1. Four scenarios of dose-rate variation settings were applied for all cases during DSA treatment planning: dose-rate variation of 250-1150 (Pattern A), 450-1150 (Pattern B), 650-1150 (Pattern C), and 850-1150 (Pattern D) MU/min. Pattern A was reference setting of DSA. The dose distributions, dose constraints, and irradiation times were compared for these settings. We compared the dose distributions, dose-volume histograms (DVHs), and dose indices for all four treatment plans. Patient specific quality assurance for all four dose-rate scenarios was performed using StereoPHAN in combination with SRS-MapCHECK (SunNuclear Corporation, USA).

RESULTS

All dose-rate settings maintained the prescribed target coverage, with PTV D95 remaining stable at 36.2–36.3 Gy across the four planning patterns. Most OAR dose indices were within the predefined constraints, indicating that changing the minimum dose rate did not substantially compromise plan acceptability. Dose-rate setting affected delivery efficiency and patient-specific QA results. The irradiation time decreased as the minimum dose rate increased, from 203.3 ± 55.7 s in Pattern A (250–1150 MU/min) to 152.0 ± 31.8 s in Pattern D (850–1150 MU/min), corresponding to an approximately 25% reduction in beam-on time. A clear difference was observed in dose verification accuracy. Pattern A showed markedly reduced gamma passing rates in two of the three cases (68.5% and 62.9%, 2 mm/3%, TH 10%), whereas Patterns B–D achieved consistently high passing rates of 99.8–100%. These results indicate that the widest dose-rate modulation range did not improve delivery accuracy; rather, it appeared to increase the probability of transient delivery deviations.

Although Pattern D provided the shortest irradiation time, it showed a tendency toward slightly higher intermediate rectal and bladder doses compared with lower dose-rate settings. Pattern C (650–1150 MU/min) maintained high gamma passing rates while preserving acceptable OAR sparing, suggesting a favorable balance between delivery efficiency and dosimetric robustness.

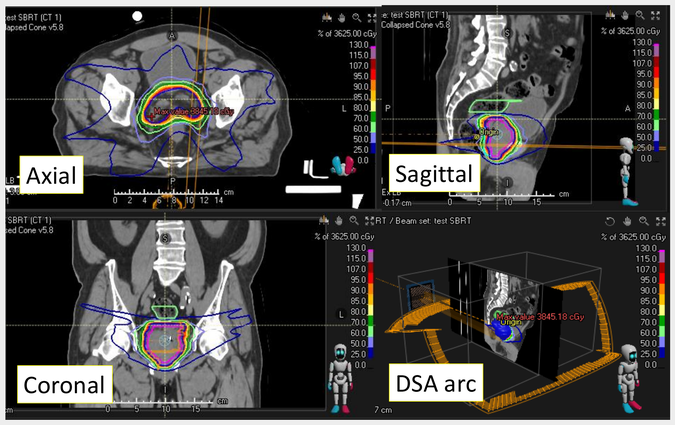

Figure 1. Demonstrative DSA plan by RayStation version 2023B

Table 1. The dose constraints, irradiation time, and the results of dose verification

Dose-rate setting		Pattern A	Pattern B	Pattern C	Pattern D
PTV	$D_{95\%}$ (Gy)	36.3±0.0	36.2±0.0	36.2±0.0	36.3±0.0
Rectum	$V_{18.1Gy}$ (%)	22.3±6.7	24.1±6.6	23.1±5.6	25.3±8.6
	V_{29Gy} (%)	5.1±2.9	6.2±3.4	5.8±3.2	6.2±3.7
	V_{36Gy} (cm^3)	0.1±0.2	0.1±0.1	0.1±0.1	0.1±0.2
Bladder	$V_{18.1Gy}$ (%)	29.6±16.8	31.3±16.1	31.0±15.7	31.3±16.0
	V_{37Gy} (cm^3)	3.3±1.1	5.0±2.8	5.0±2.6	4.3±1.5
F head L	$V_{14.5Gy}$ (%)	2.0±1.0	1.6±1.1	1.3±1.2	1.3±1.2
F head R	$V_{14.5Gy}$ (%)	1.7±1.8	1.2±1.3	1.3±1.8	0.9±1.2
Penile bulb	$V_{29.5Gy}$ (%)	4.6±6.5	4.7±6.7	2.9±4.2	3.4±4.8
Bowel	$V_{18.1Gy}$ (cm^3)	1.1±1.6	1.2±1.7	1.3±1.8	1.3±1.9
	V_{30Gy} (cm^3)	0.0±0.0	0.0±0.0	0.0±0.0	0.0±0.0
Irradiation time (Sec)		203.3±55.7	164±54.4	161.7±36.3	152.0±31.8
Passing Rate Criteria: 2 mm/3%, TH10%	Case 1	100	100	100	100
	Case 2	68.5	100	100	100
	Case 3	62.9	99.8	99.8	100

DISCUSSION

This study demonstrated that the minimum dose-rate setting is a clinically relevant planning parameter for DSA-based prostate SBRT. Although all plans achieved comparable PTV coverage and generally acceptable OAR doses, delivery accuracy differed substantially according to the dose-rate setting. In particular, the lowest minimum dose rate, which allowed the largest dose-rate modulation range, resulted in poor gamma passing rates in two cases.

This finding suggests that excessive dose-rate variability may challenge the synchronization of dose delivery with gantry rotation, O-ring rotation, and MLC motion. In DSA, these components change simultaneously along a non-coplanar trajectory; therefore, even when cumulative MU agreement is maintained, transient deviations in dose-rate tracking may translate into local dosimetric discrepancies. The present results are consistent with prior observations in dynamic VMAT delivery that variable dose rate and gantry-angle-dependent beam control can affect beam stability and should be verified under clinically relevant conditions.

Increasing the minimum dose rate improved gamma passing rates and shortened irradiation time. However, simply maximizing the minimum dose rate may not be optimal because a higher lower-bound dose rate can reduce fluence modulation flexibility and may increase intermediate OAR doses. In this study, Pattern D achieved the shortest delivery time but showed a tendency toward higher rectal and bladder dose indices, whereas Pattern C achieved excellent gamma passing rates with acceptable OAR sparing.

These results indicate that dose-rate settings should be optimized as part of the DSA planning process rather than selected only for delivery efficiency. A setting of 650–1150 MU/min may provide a practical balance between dosimetric accuracy, treatment time, and OAR sparing for prostate SBRT on the OXRAY platform. Further validation using a larger cohort, additional plan complexity metrics, and detailed log-file analysis is warranted.

CONCLUSIONS

The minimum dose-rate setting significantly affected DSA delivery accuracy for prostate SBRT.

A low minimum dose rate of 250 MU/min was associated with reduced gamma passing rates in patient-specific QA despite acceptable target coverage and OAR doses.

A setting of 650–1150 MU/min provided the most balanced performance, achieving high dosimetric accuracy, acceptable OAR sparing, and efficient delivery. Dose-rate settings should therefore be considered during DSA treatment planning.

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