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Dosimetric Evaluation and Patient-Specific Quality Assurance of Multi- Isocenter VMAT Plans for Pelvic Target Volumes on Halcyon 4.0

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Abstract

Background and purpose

Large pelvic targets may exceed the available field dimensions of ring-gantry linear accelerators, requiring multi-isocenter volumetric modulated arc therapy (VMAT). This study compared plan quality and measurement-based patient-specific quality assurance (PSQA) among different isocenter configurations for pelvic and extended pelvic-femoral targets treated on Halcyon 4.0.

Materials and methods

Twenty patients were retrospectively analyzed. For PTV-Pelvis, single-isocenter (1 ISO) and two-lateral-isocenter (2Lat ISO) plans were compared, whereas PTV-Extended was evaluated using 2Lat ISO and two-longitudinal-isocenter (2Long ISO) plans. All plans prescribed 30 Gy in 10 fractions and were calculated in Eclipse using Acuros XB. Plan quality was assessed using dosimetric indices and monitor units. PSQA was performed with ArcCHECK using 3%/3 mm global gamma analysis with a 10% dose threshold.

Results

For PTV-Pelvis, 2Lat ISO improved HI (0.318 vs. 0.348), COVI (0.982 vs. 0.975), and Dmax (109.94% vs. 111.53%) compared with 1 ISO (adjusted $p < 0.05$). For PTV-Extended, 2Lat ISO improved HI (0.321 vs. 0.375), COVI (0.971 vs. 0.935), D95% (96.43% vs. 94.82%), D98% (95.09% vs. 93.44%), and EI (4.18% vs. 11.28%) compared with 2Long ISO, with all differences remaining significant after correction. Gamma passing rates were 98.65–99.16%.

Conclusion

Lateral multi-isocenter VMAT improved target coverage and dose homogeneity, particularly for extended pelvic-femoral targets, while maintaining high PSQA passing rates.

Introduction

Large or anatomically complex targets can exceed the field size of a linear accelerator, requiring multiple isocenters and overlapping fields to achieve adequate coverage. Multi-isocenter volumetric modulated arc therapy (VMAT) has been applied to extended targets, including the craniospinal axis and total marrow, while seeking to maintain target coverage and spare normal tissues [1–5]. Helical tomotherapy can also treat long targets by translating the couch during delivery, but requires a dedicated platform [6, 7]. For centers using conventional C-arm or ring-gantry accelerators, reliable multi-isocenter VMAT remains an important practical option.

In multi-isocenter VMAT, maintaining dose continuity across the overlap regions between adjacent fields remains an important planning and delivery challenge. Positional uncertainties or errors in the relative alignment of adjacent fields can disturb the planned dose gradients and produce localized hot or cold spots at the junctions [8–10]. The magnitude of these dosimetric effects depends on the overlap width, the dose gradient across the junction, and the direction and extent of the positional error [8, 9]. Therefore, careful overlap optimization and reproducible patient positioning are essential. These measures should be complemented by measurement-based patient-specific quality assurance (PSQA) to verify agreement between the calculated and delivered dose distributions.

Although multi-isocenter techniques have mainly been described for targets extending in the cranio-caudal direction, large targets may also approach or exceed the available lateral field width. Previous studies by our group reported dosimetric advantages of lateral isocenter arrangements for large pelvic targets and of combined lateral and longitudinal configurations for extended pelvic–lumbar volumes [11, 12]. Lateral multi-isocenter approaches have also been investigated for synchronous bilateral breast irradiation, including their robustness against positioning errors and their dosimetric and radiobiological performance [13–15]. More recently, Zhou et al. included measurement-based PSQA in their evaluation of single- and dual-isocenter techniques for synchronous bilateral breast cancer [16]. However, the delivery accuracy of different multi-isocenter VMAT configurations for large pelvic targets remains insufficiently investigated.

VMAT shapes the dose distribution through coordinated changes in multileaf collimator positions, dose rate, and gantry speed [17]. However, increased modulation may increase delivery complexity and the potential for disagreement between planned and measured doses [17, 18]. Measurement-based PSQA evaluates the agreement between planned and delivered dose distributions. AAPM Task Group 218 provides standardized recommendations regarding measurement methods, gamma analysis, and tolerance and action limits [19]. For multi-isocenter VMAT, such verification is particularly relevant because several treatment components must be delivered accurately and reproducibly. In parallel, accurate geometric alignment between adjacent fields is required to maintain dose continuity across the junction [8, 10, 20].

This study compared VMAT isocenter configurations on the Halcyon platform for two pelvic target volumes. Single-isocenter and two-lateral-isocenter plans were compared for the initial volume; two-longitudinal-isocenter and two-lateral-isocenter plans were compared for the extended volume. We assessed target coverage, homogeneity, conformity, external dose spillage, and ArcCHECK-based PSQA for each plan. The work is motivated by the need for a practical treatment strategy when large pelvic targets exceed the standard field width. Its advantage is the combined assessment of plan quality and measured delivery accuracy, which tests whether the dosimetric benefits of lateral isocenter placement can be achieved with acceptable PSQA results.

Materials and methods

Linear accelerator

In the present study, all VMAT treatment plans were generated using a Halcyon 4.0 linear accelerator (Varian Medical Systems, Palo Alto, CA, USA). The system is a ring-gantry linear accelerator equipped with a 6-MV flattening-filter-free (FFF) photon beam and a dual-layer, stacked and staggered multileaf collimator (MLC), with a maximum gantry rotation speed of 4 RPM. The maximum field size is 28 × 28 cm^2 for a single isocenter, while treatment fields can be extended in the longitudinal direction up to 38.5 cm using two isocenters.

ArcCHECK

The ArcCHECK system (Sun Nuclear Corporation, Melbourne, FL, USA) is a cylindrical PMMA phantom designed to approximate patient geometry for dosimetric measurements. It contains a helical array of 1,386 SunPoint® diode detectors, each with an active volume of 0.019 mm^3, positioned at a physical depth of 2.9 cm and spaced 10 mm apart. This arrangement provides consistent beam's-eye-view (BEV) sampling at all gantry angles and enables measurement of both entrance and exit doses. Detector readings are acquired every 50 ms. The detector array has a diameter and length of 21 cm, while the central cavity has a diameter of 15 cm and accommodates interchangeable inserts [21], as illustrated in Fig. 1. In this study, the CavityPlug™ accessory (P/N 1220000-1Z), containing a solid PMMA insert, was placed in the central cavity to provide uniform density throughout the ArcCHECK phantom.

Phantom setup

Patient-specific quality assurance (PSQA) using ArcCHECK was performed for all investigated target volumes and VMAT isocenter configurations, including single-isocenter, two-lateral-isocenter, and two-longitudinal-isocenter plans. The assembled ArcCHECK cradle was placed on the treatment couch, and the phantom was securely positioned within the cradle supports, with the cavity panel facing the gantry and the electronics panel oriented toward the control room. The phantom was centered by aligning the coronal and sagittal room lasers with the corresponding reference lines on its surface. It was then connected to the Power Data Interface (PDI) 3.0 using the supplied power-and-data cable. The PDI was in the control room and connected to the acquisition computer via a USB cable and to the mains power supply. Before irradiation, all connections were checked to ensure proper communication among the ArcCHECK device, the PDI, and the acquisition software.

Patient characteristics and prescription

A total of 20 patients were included and divided into two groups according to the longitudinal extent of the PTV. The initial-PTV group comprised 10 patients, while the extended-PTV group included 10 patients whose PTV encompassed a larger portion of the femur in the longitudinal direction. All patients underwent CT simulation in the head-first supine position using a SOMATOM Sensation Open CT

scanner (Siemens Healthineers, Erlangen, Germany), with a slice thickness of 2 mm. A total dose of 30 Gy was prescribed in 10 fractions of 3 Gy each.

Treatment planning

Treatment plans were generated using the Eclipse treatment planning system, version 18.1.0 (Varian Medical Systems, Palo Alto, CA, USA), for delivery with a 6-MV flattening-filter-free photon beam at a maximum dose rate of 600 MU/min. Dose distributions were calculated using the Acuros XB algorithm with heterogeneity correction enabled and a calculation grid resolution of 0.25 cm.

For pelvic irradiation, the lateral extent of the planning target volume (PTV) may approach or exceed the maximum field width available on the Halcyon system, as previously investigated by Erraoudi et al. [11]. In such cases, two laterally separated isocenters may be required to achieve complete target coverage. Similarly, the longitudinal extent of the PTV may approach the maximum field-length limit, introducing additional planning and coverage challenges. Therefore, two target-volume configurations were investigated to determine the most appropriate VMAT technique according to target extent and to compare lateral and longitudinal junction arrangements.

The first configuration, designated PTV-Pelvis, consisted of a pelvic target (Fig. 2(a)). Two VMAT plans were generated for this volume: a single-isocenter plan (1 ISO) and a dual-lateral-isocenter plan (2Lat ISO) (Fig. 3). The second configuration, designated PTV-Extended, included the pelvis and an additional inferior portion of the femurs (Fig. 2(b)). For this longitudinally extended pelvic–femoral target, two multi-isocenter VMAT plans were generated: one using two longitudinally separated isocenters (2Long ISO) and the other using two laterally separated isocenters (2Lat ISO) (Fig. 4).

For PTV-Pelvis, the 1 ISO technique consisted of four full VMAT arcs delivered around a single isocenter, whereas the 2Lat ISO technique used two full arcs at each of two laterally separated isocenters. For PTV-Extended, the 2Long ISO technique used two full arcs at each of two longitudinally separated isocenters, while the 2Lat ISO technique used two full arcs at each of two laterally separated isocenters. Thus, all planning configurations comprised four full arcs in total.

For ArcCHECK-based PSQA, each clinical VMAT plan was transferred to the ArcCHECK phantom dataset in Eclipse to generate a corresponding verification plan while retaining the treatment parameters of the original plan. The expected dose distribution was subsequently recalculated on the phantom using the Acuros XB algorithm with a calculation grid resolution of 0.25 cm. The corresponding DICOM RT Dose (RD) and RT Plan (RP) files were exported from Eclipse and imported into SNC Patient™ software. The RT Dose file contains the TPS calculated dose distribution used for comparison with the ArcCHECK measurements, whereas the RT Plan file provides the isocenter and delivery information required for dose alignment and the application of angle dependent corrections. Agreement between the calculated and measured dose distributions was evaluated using gamma-index analysis with global normalization, a 10% dose threshold, and a 3%/3 mm dose-difference/distance-to-agreement criterion

Planning objectives

All treatment plans were generated using identical planning objectives to enable an objective dosimetric comparison among the investigated isocenter configurations. For PTV optimization, the objectives were established to ensure adequate target coverage while maintaining dose homogeneity and limiting high-dose regions. At least 95% of the PTV was required to receive 95% or more of the prescribed dose, corresponding to $D_{95\%} \geq 95\%$. In addition, the near-maximum dose was constrained to $D_{2\%} < 107\%$of the prescribed dose. For patient-specific quality assurance using ArcCHECK, a plan was considered acceptable when the gamma passing rate (%GP) exceeded the established action level of 95%.

Plan evaluation indicators

The dosimetric quality of the VMAT plans was evaluated using three complementary indecators: the homogeneity index (HI), conformity index (CI), and The **coverage index (COVI)** .

The HI was used to evaluate dose uniformity within the planning target volume (PTV) and was calculated as follows:

$$HI = \frac{D_{2\%} - D_{98\%}}{D_P}$$

Where $D_{2\%}$ and $D_{98\%}$ represent the doses received by 2% and 98% of the PTV, and D_P is the prescribed dose to the PTV [22, 23].An HI value approaching zero indicates greater dose homogeneity within the PTV, reflecting a smaller difference between the near-maximum and near minimum.

The Conformity of the prescribed dose distribution to the PTV was assessed using the conformity index (CI) (RTOG, USA), calculated as :

$$CI = \frac{V_{RI}}{V_{PTV}}$$

Where V_{RI} is the volume receiving 95% of the prescribed dose is, and V_{PTV} is the total volume of the PTV. A CI value approaching 1 indicates optimal conformity, corresponding to complete coverage of the target by the prescription isodose.

The **coverage index (COVI)** quantifies the proportion of the target volume encompassed by at least 95% of the prescribed dose. It is calculated as:

$$COVI = \frac{TV_{RI}}{TV}$$

where TV_{RI} is the target volume covered by the reference isodose, TV is the total target volume [24]. A value of 1 indicates complete target coverage.

In addition, the External Volume Index (EI) was calculated to provide more comprehensive assessment for irradiation of heathy tissues.

$$EI = \frac{NTV_{\geq RI}}{TV}$$

Where, NTV_{RI} is normal Tissue Volume receiving that receives a dose equal to or greater than the reference dose [25]

Beyond the dosimetric indices used to evaluate plan quality, the gamma index was employed to assess agreement between the dose distributions calculated by the treatment planning system and measured during patient-specific quality assurance. Gamma-index analysis combines the dose difference (DD) and distance-to-agreement (DTA) criteria into a single quantitative metric, accounting for both dosimetric and spatial discrepancies. The DTA represents the distance between a measured data point and the nearest point in the calculated dose distribution with an equivalent dose value [26]. A point was considered to pass when its gamma value was ≤ 1, indicating that both specified criteria were satisfied, whereas a gamma value > 1 indicated failure.

Normality of the paired differences was evaluated using the Shapiro–Wilk test. Normally distributed differences were analyzed using the paired-samples t-test, whereas non-normally distributed differences were evaluated using the Wilcoxon signed-rank test. Two-sided unadjusted p-values are reported, and the Benjamini–Hochberg procedure was applied to control the false discovery rate arising from multiple comparisons. An adjusted p-value below 0.05 was considered statistically significant.

Results

Following Benjamini–Hochberg correction, the 2Lat ISO configuration demonstrated better dose homogeneity than 1ISO, as indicated by a lower HI (adjusted p = 0.031). Regarding target coverage, 2Lat ISO produced a slight increase in the coverage index (0.982 vs 0.975) and D98% (95.31% vs 94.86%). The mean maximum dose was also reduced from 111.53% with 1ISO to 109.94% with 2Lat ISO (adjusted p = 0.031). Conversely, no statistically significant differences were found for CI, EI, D2%, D95%, Dmean, or MUs.

For the PTV-extended, the dosimetric differences between the two configurations were more pronounced. 2Lat ISO provided significantly better homogeneity than 2Long ISO, with mean HI values of 0.321 and 0.375, respectively and improved better target coverage, as demonstrated by a higher coverage index (0.971 vs 0.935). Moreover, the mean D95% reached 96.43% with 2Lat ISO, thereby satisfying the predefined coverage objective, whereas it was 94.82% with 2Long ISO. Similarly, D98% was significantly higher with 2Lat ISO (95.09% vs 93.44%). All four differences remained statistically

significant with an adjusted p < 0.001. EI was substantially lower with 2Lat ISO (4.18% vs 11.28%; adjusted p = 0.002), indicating markedly reduced dose spillage outside the target. In contrast, no significant differences were observed for CI, D2%, or Dmax. However, 2Lat ISO required more MUs than 2Long ISO (1290.62 vs 1210.83; adjusted p = 0.041). Overall, 2Lat ISO provided superior target coverage, dose homogeneity, and external dose control for the extended PTV, at the cost of a modest increase in treatment output.

Table 1
Dosimetric and delivery parameters for PTV-pelvis plans.

PTV-pelvis				
Parameter	**2Lat ISO**	**1 ISOP**	**P value**	**BH-adjusted p-value**
CI	**1.050 ± 0.032**	**1.041 ± 0.029**	**0.144**	**0.185**
HI	**0.318 ± 0.025**	**0.348 ± 0.019**	**0.005**	**0.028**
COVI	**0.982 ± 0.009**	**0.975 ± 0.010**	**0.013**	**0.029**
EI (%)	**4.74 ± 2.38**	**4.68 ± 1.86**	**0.883**	**0.883**
$D_{2\%}$ (%)	**104.85 ± 0.57**	**105.29 ± 0.32**	**0.045**	**0.067**
$\varvec{D_{95\varvec{\%}}}$ (%)	**96.65 ± 0.53**	**96.31 ± 0.65**	**0.032**	**0.058**
$D_{98\%}$ (%)	**95.31 ± 0.59**	**94.86 ± 0.68**	**0.010**	**0.029**
D_{max} (%)	**109.94 ± 1.13**	**111.53 ± 0.89**	**0.006**	**0.028**
MU	**1126.46 ± 99.76**	**1108.06 ± 97.30**	**0.500**	**0.562**

Table 2

ArcCHECK–based patient–specific quality assurance results for the investigated target volumes and isocenter configurations·

PTV-extended				
Parameter	**2Lat ISO**	**2Long ISO**	**P value**	**BH-adjusted p-value**
CI	**1.046 ± 0.037**	**1.069 ± 0.081**	**0.258**	**0.332**
HI	**0.321 ± 0.041**	**0.375 ± 0.030**	**< 0.001**	**< 0.001**
COVI	**0.971 ± 0.018**	**0.935 ± 0.024**	**< 0.001**	**< 0.001**
EI (%)	**4.18 ± 2.10**	**11.28 ± 6.35**	**< 0.001**	**0.002**
$D_{2\%}$ (%)	**104.73 ± 0.47**	**104.70 ± 0.42**	**0.864**	**0.864**
$\varvec{D}_{95\varvec{\%}}$ ($\varvec{\%}$)	**96.43 ± 0.72**	**94.82 ± 0.62**	**< 0.001**	**< 0.001**
$D_{98\%}$ (%)	**95.09 ± 0.82**	**93.44 ± 0.73**	**< 0.001**	**< 0.001**
D_{max} (%)	**111.07 ± 0.91**	**110.97 ± 1.16**	**0.802**	**0.864**
MU	**1290.62 ± 147.37**	**1210.83 ± 130.20**	**0.027**	**0.041**

Patient-specific quality assurance demonstrated satisfactory agreement between the calculated and measured dose distributions for all investigated configurations. Gamma passing rates ranged from 98.65% to 99.16%, remaining well above the predefined 95% acceptance criterion for both PTV-Pelvis and PTV-Extended. Mean gamma indices were consistently low, ranging from 0.323 to 0.339, while CAX dose differences remained close to zero (− 0.26% to 0.46%). A representative comparison of the ArcCHECK-measured and TPS calculated dose distributions for a 2Lat ISO PTV Extended plan is presented in Fig. 5. Although the maximum gamma index exceeded unity in some measurements, the high passing rates indicate that these deviations were limited to a small number of localized points and did not affect overall plan acceptability. Thus, the 1 ISO, 2Lat ISO, and 2Long ISO configurations demonstrated satisfactory delivery agreement.

Table 3

ArcCHECK patient–specific quality assurance results for the investigated isocenter configurations in the pelvic and extended PTV groups·

Parameters	PTV-pelvis		PTV-extended	
	2Lat ISO	1 ISO	2Lat ISO	2Long ISO
Gamma passing rate (%)	**98.96 ± 0.88**	**98.65 ± 1.09**	**99.00 ± 0.79**	**99.16 ± 0.73**
Maximum gamma index	**1.28 ± 0.20**	**1.34 ± 0.13**	**1.38 ± 0.22**	**1.21 ± 0.15**
Mean gamma index	**0.339 ± 0.024**	**0.325 ± 0.034**	**0.323 ± 0.038**	**0.338 ± 0.042**
CAX dose difference (%)	**0.26 ± 0.64**	**0.46 ± 0.57**	**−0.26 ± 1.07**	**0.25 ± 1.00**

Discussion

This study compared the dosimetric performance and delivery accuracy of VMAT isocenter configurations for pelvic and extended pelvic–femoral targets on the Halcyon platform. Earlier work from our group reported improved planning results with lateral isocenters for large pelvic targets and with a three-isocenter lateral–longitudinal arrangement for pelvic–lumbar volumes [11, 12]. Here, we assessed the value of two lateral isocenters relative to single- and two-longitudinal-isocenter plans and evaluated their delivery using ArcCHECK-based PSQA.

For the initial pelvic target, two lateral isocenters (2Lat ISO) improved dose homogeneity and slightly increased peripheral coverage relative to one isocenter (1ISO), while conformity, external dose spillage, and monitor units remained comparable (Fig. 6). Lateral field displacement may offer additional modulation space for a target approaching the Halcyon field-width limit. Because the differences were modest, 1ISO remains a reasonable choice when it provides adequate target coverage within the available field.

The benefit of lateral displacement was greater for the extended pelvic–femoral target. Compared with two longitudinal isocenters (2Long ISO), 2Lat ISO met the predefined coverage objective, improved homogeneity, and reduced external dose spillage without a significant increase in the high-dose indices (Fig. 6). Although this target was extended inferiorly, some femoral target regions also exceeded the lateral extent of a single 28-cm field. Longitudinal displacement increases the treatable superior–inferior length but does not address this lateral constraint. The complementary lateral fields may therefore explain the improved coverage and dose distribution observed with 2Lat ISO.

Island blocking may also contribute to the difference in external dose spillage. At some beam angles, separated pelvic femoral target regions can project onto the same multileaf collimator leaf pairs, preventing the leaves from irradiating both regions while shielding the intervening normal tissue [27, 28]. This mechanism could partly explain the greater spillage with 2Long ISO and might affect the optimizer's balance between target coverage and normal-tissue dose. However, the cited studies primarily concern

discrete targets, and we did not analyze control-point apertures; island blocking is therefore a hypothesis, not a demonstrated mechanism in these plans. The improved dose shaping with 2Lat ISO required more monitor units. Its planning benefit should be weighed against this additional treatment output.

ArcCHECK is established for routine IMRT and VMAT delivery QA through comparison of calculated and measured dose distributions [29, 30] and was therefore used in the present study to verify each plan.For multi-isocenter plans, the measurement incorporated the dose contributions from both isocenters and their overlapping fields after application of the planned couch shifts. Zhou et al. combined ArcCHECK and radiochromic film to evaluate longitudinal multi-isocenter VMAT junctions [10], whereas Misa et al. stitched calculated and measured portal-dosimetry fluence maps from different isocenters for craniospinal VMAT on Halcyon [31]. In contrast, our procedure accumulated the complete delivery in one ArcCHECK measurement without computational fluence stitching. The 4-cm isocenter separation allowed this approach to be applied to both lateral and longitudinal configurations, providing a practical method for cumulative PSQA of closely spaced multi-isocenter plans. This cumulative approach assessed the overall delivery of each multi-isocenter plan, including the junction region, rather than evaluating the junction independently.

All plans exceeded the institutional 95% gamma passing criterion at 3%/3 mm, with global normalization and a 10% dose threshold (Fig. 7). Passing rates were similar across target groups and configurations, including the more complex extended-target plans. Central-axis dose differences remained close to zero and within the predefined ± 3% limits, providing an additional check of dose agreement. Previous ArcCHECK studies have also reported high passing rates at 3%/3 mm and close agreement between calculated and measured central doses [32, 33]. These results support the deliverability of 2Lat ISO under the nominal conditions tested and extend our earlier planning studies with measurement-based PSQA.

These findings should be interpreted in light of the limitations of cumulative gamma analysis. Although the evaluation included dose contributions from the overlap region, it did not assess the junction independently. Moreover, conventional gamma-passing rates do not necessarily predict clinically relevant dose discrepancies within specific anatomical structures [34]. Dose–volume histogram-based verification could complement gamma analysis and point-dose measurements by relating detected discrepancies to targets and organs at risk [35]. Future studies incorporating junction-specific measurements and deliberate setup-error tests would be valuable for evaluating the robustness of lateral multi-isocenter delivery to positioning uncertainties.

Conclusion

Measurement-based PSQA supported the deliverability of the investigated VMAT configurations and enabled cumulative verification of dose contributions from both isocenters and their overlapping fields. The findings highlight the importance of considering target extent when selecting an isocenter arrangement and support lateral multi-isocenter VMAT as a practical option for large pelvic targets.

Further junction-specific measurements and setup-error testing are warranted to evaluate robustness to positioning uncertainties.

Declarations

Author Contribution

Kaoutar.El Bouochti: performed the experimental measurements, collected the data, and contributed to manuscript writing.Morad.Erraoudi: conceived the study, developed the research methodology, and contributed to manuscript writing.Fadwa.Fathi: performed the statistical analysis and interpreted the results.Mohammed.El.Ghalmi: supervised the experimental measurements.Oussama.Nhila: supervised the manuscript preparation and critically reviewed its scientific content. Mohammed.Talbi: reviewed and edited the manuscript for language and clarity.Chakir.El.Mahjoub: provided overall scientific supervision and critically revised the manuscript. All authors reviewed and approved the final manuscript.

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Figures

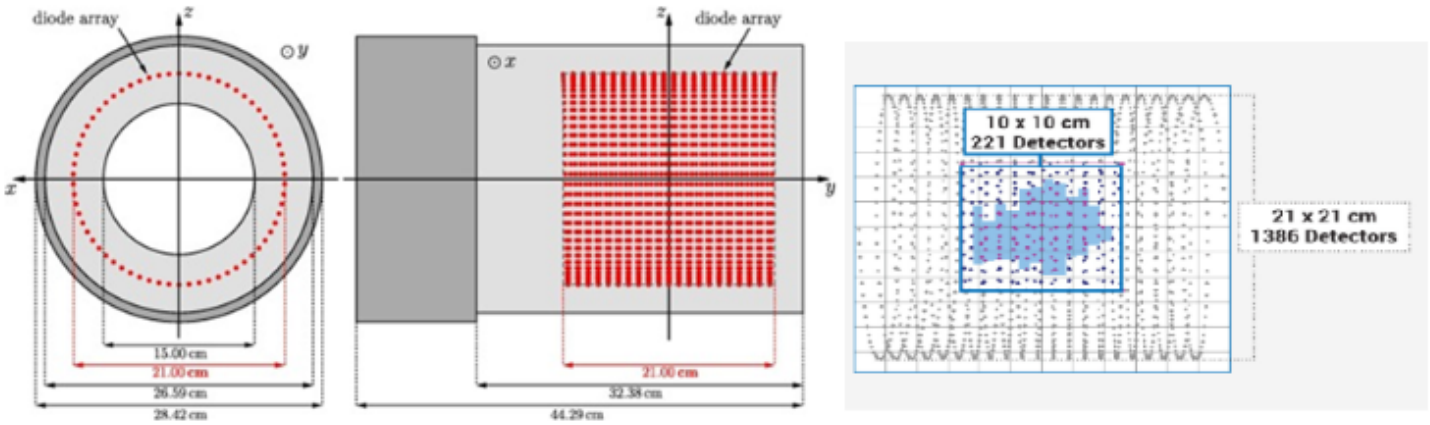


Figure 1

The geometry of the ArcCHECK (Sun Nuclear Corporation, 2023)

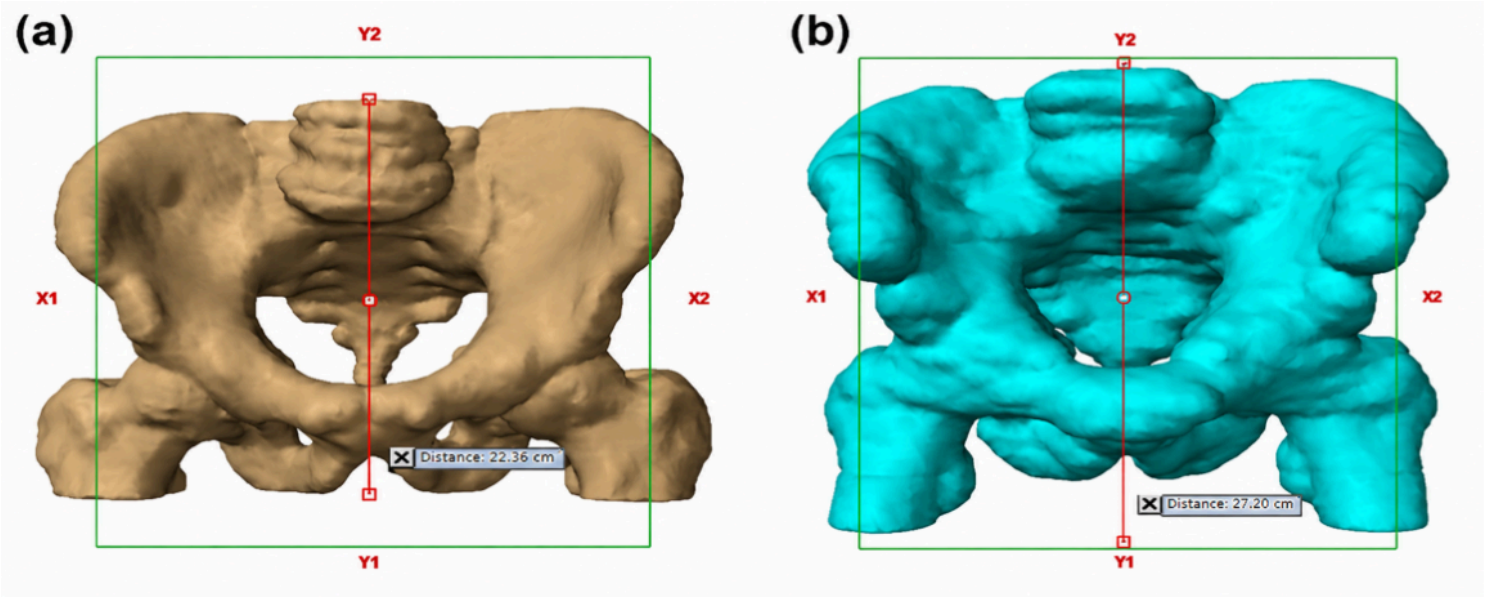


Figure 2

Three-dimensional representations of the target volumes and their longitudinal extents: (a) PTV-Pelvis (22.36 cm) and (b) PTV-Extended (27.20 cm).

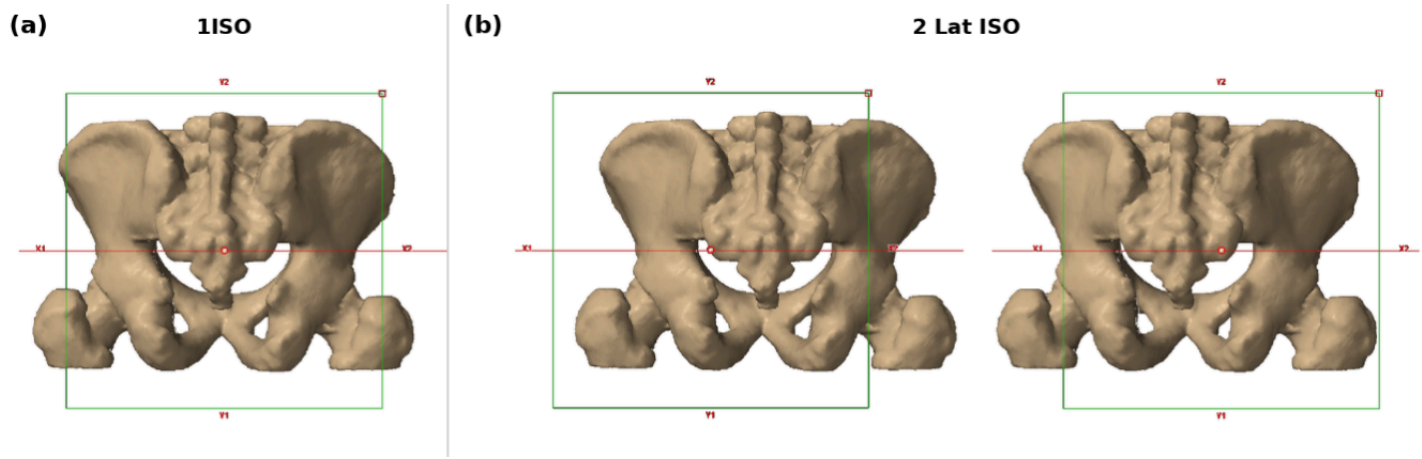


Figure 3

Illustration of the VMAT isocenter configurations used for the PTV-Pelvis: (a) single-isocenter configuration (1 ISO) and (b) dual-lateral-isocenter configuration (2Lat ISO). The green rectangles represent the treatment fields associated with each isocenter.

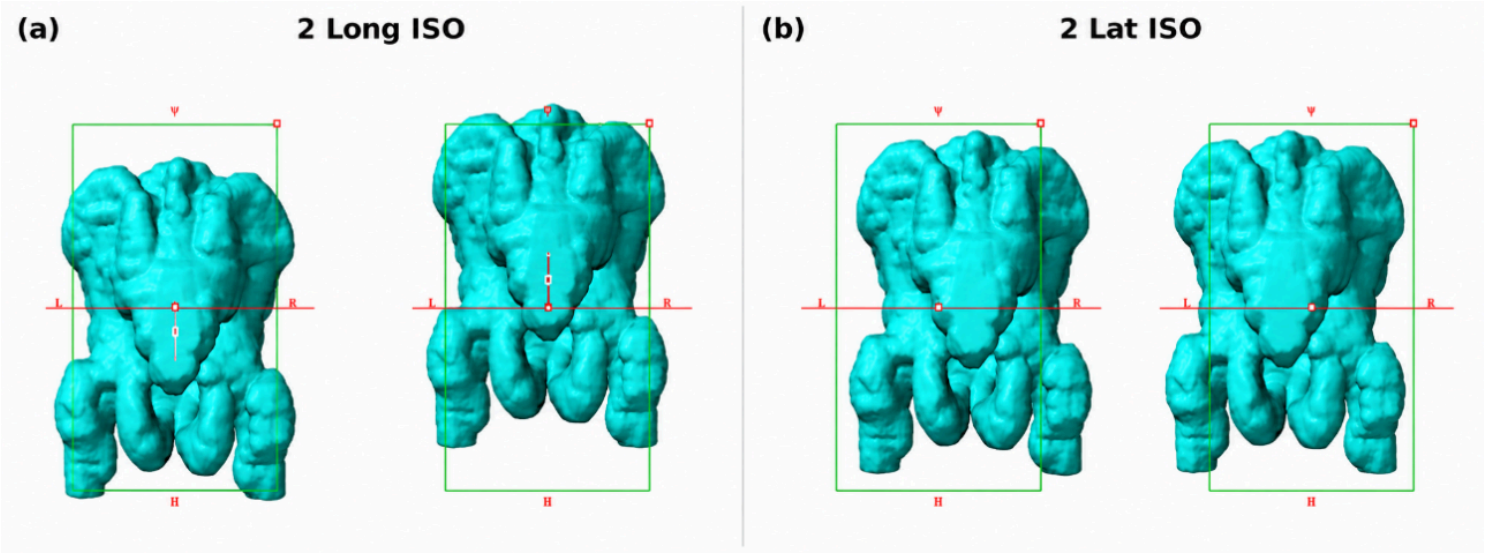


Figure 4

Illustration of the two multi-isocenter VMAT configurations used for the PTV-Extended: (a) two longitudinally separated isocenters (2Long ISO) and (b) two laterally separated isocenters (2Lat ISO). The green rectangles represent the treatment fields associated with each isocenter.

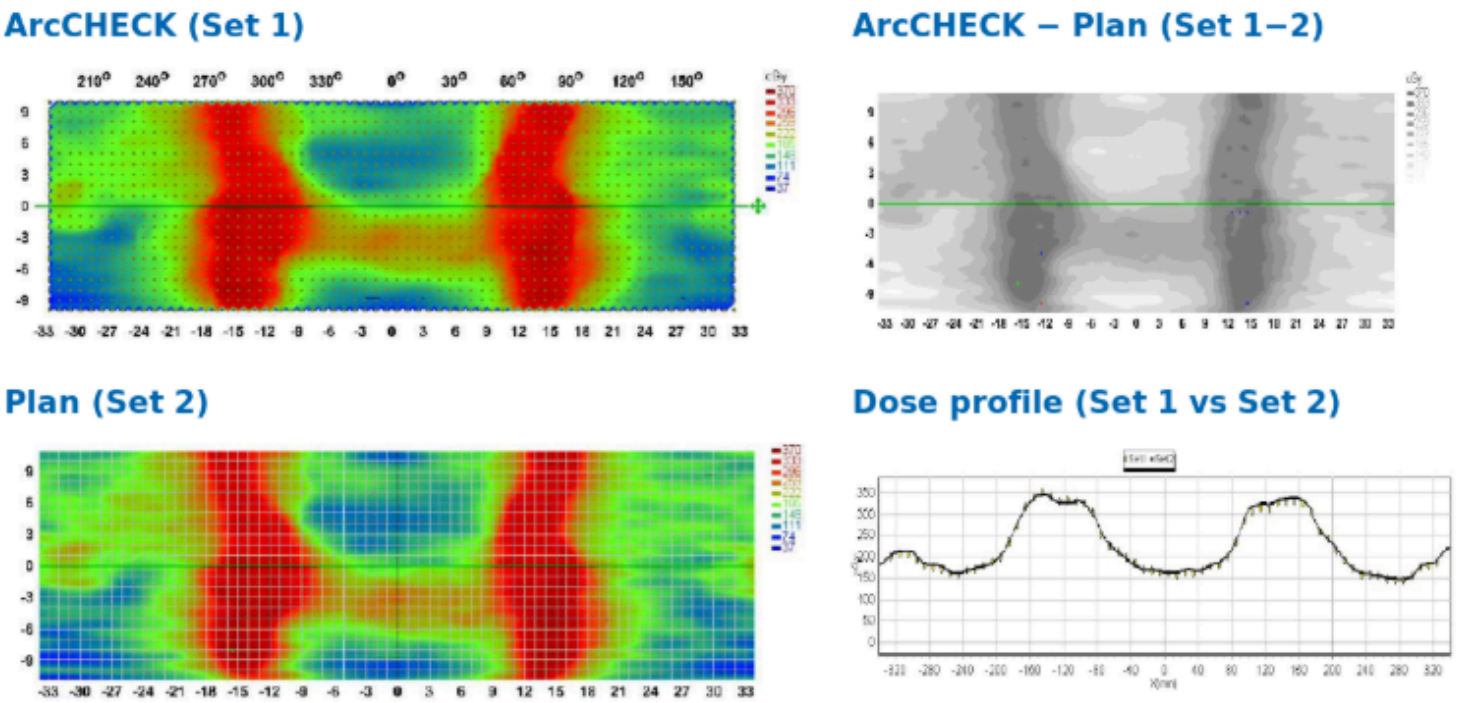


Figure 5

Representative patient-specific quality assurance (PSQA) analysis for a PTV-Extended plan using the two-lateral-isocenter (2Lat ISO) VMAT technique. ArcCHECK-measured (Set 1) and TPS-calculated (Set 2) dose distributions are presented together with the corresponding dose-difference map (Set 1–Set 2)

and dose-profile comparison, illustrating the agreement between measured and calculated dose distributions.

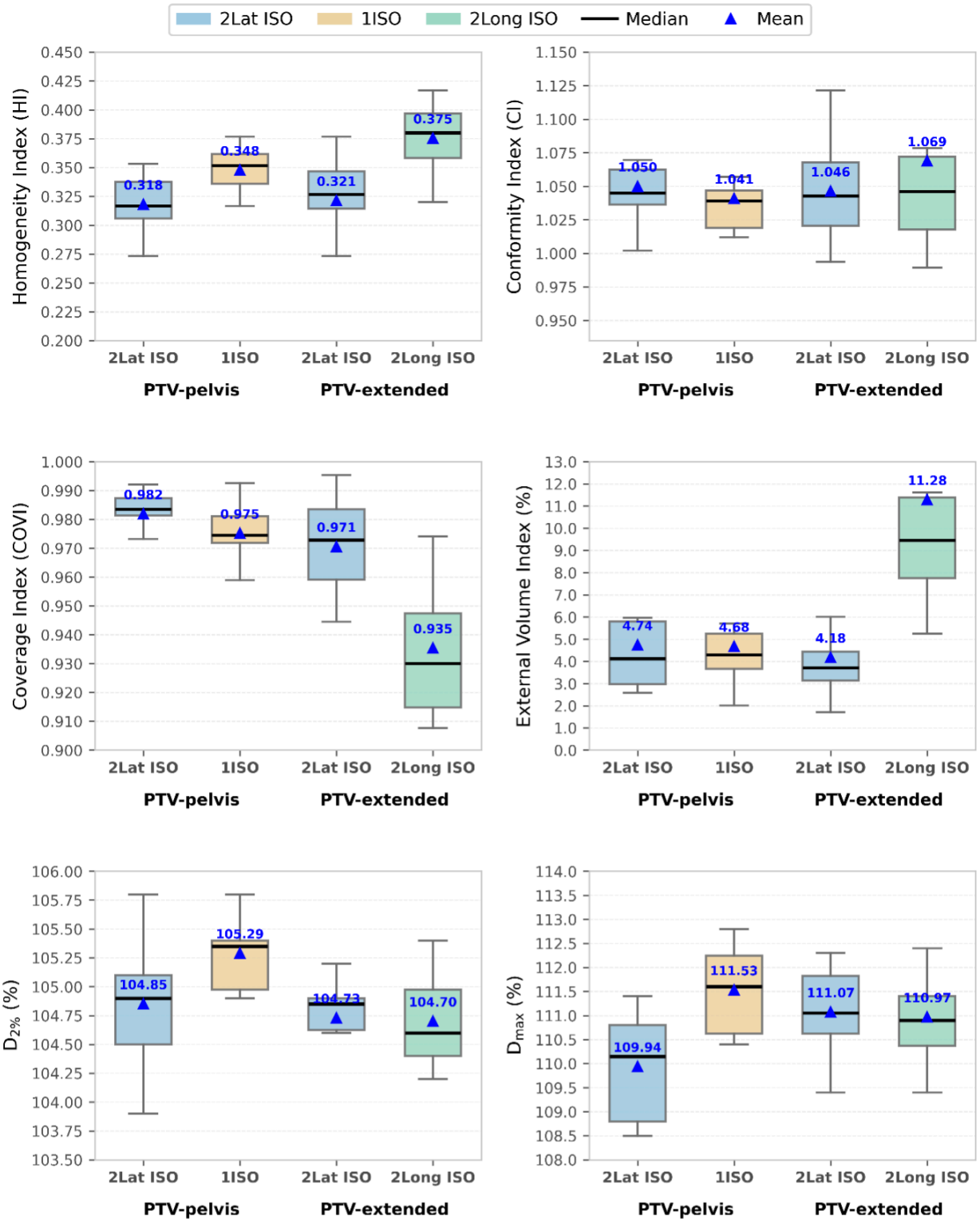


Figure 6

Comparison of HI, CI, COVI, EI, D_2%, and Dmax across VMAT isocenter configurations for PTV-Pelvis and PTV-Extended. Boxplots show the median, interquartile range, and data range; blue triangles and

labels indicate mean values.

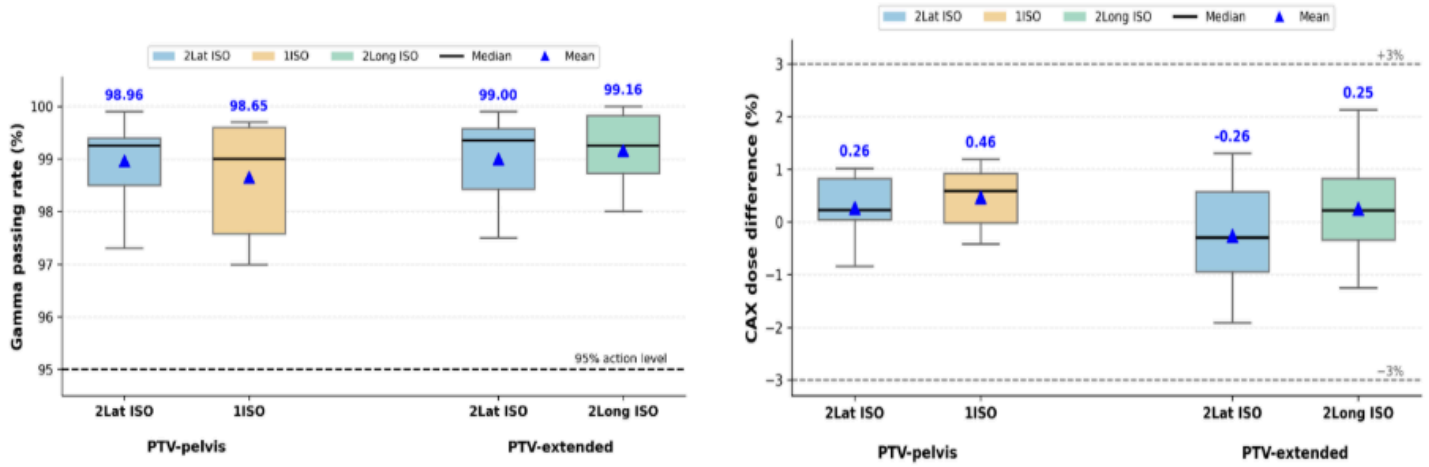


Figure 7

ArcCHECK-based PSQA results showing gamma passing rates and central-axis (CAX) dose differences across VMAT isocenter configurations for PTV-Pelvis and PTV-Extended. Blue triangles and labels indicate mean values; dashed lines represent the 95% gamma passing rate and ±3% CAX dose-difference limits.