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Scientific Article

Planning Automation for Treatment Techniques Comparison and Robustness Analysis: Tangential Intensity Modulated Radiation Therapy and Volumetric Modulated Arc Therapy for Whole Breast Irradiation

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Purpose: This study evaluates the use of the mCycle automated planning system integrated into the Monaco Treatment Planning System for step-and-shoot intensity modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) in whole breast irradiation (WBI). The aim was to assess whether automation can standardize plan quality across a diverse patient cohort and compare dosimetric outcomes and robustness of the 2 techniques against setup errors and anatomical variations.

Methods and Materials: A total of 65 patients with breast cancer who underwent postoperative WBI were selected for the study. Treatment plans were generated using mCycle, which employs multicriteria optimization with no manual intervention. Two automated planning techniques—IMRT and VMAT—were implemented and evaluated based on dosimetric outcomes, physician review, planning time, and plan robustness. The plan deliverability was verified through γ index and point dose measurements.

Results: The mCycle system produced clinically acceptable plans for both IMRT and VMAT across all patient cohorts. VMAT showed superior target coverage (V95% = 97.9%) and better sparing of ipsilateral organs at risks (OARs), whereas IMRT demonstrated enhanced sparing of contralateral OARs and greater robustness to anatomical changes such as breast swelling. Planning times were reduced with VMAT because of complete automation. Plan deliverability was confirmed with high γ passing rates and acceptable point dose deviations.

Conclusions: The use of mCycle in WBI planning successfully standardized plan quality and improved workflow efficiency. VMAT provided superior target coverage and ipsilateral OAR sparing but was more sensitive to anatomical changes. IMRT showed better contralateral OAR sparing and robustness. Both techniques are viable, with advantages depending on clinical scenarios.

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Introduction

Breast cancer is the most prevalent cancer among women and a leading cause of female mortality worldwide.[1] Radiation therapy (RT) plays a crucial role in breast cancer treatment, representing about 25% of our Radiation Oncology Department's annual workload. Recent technological advancements in RT, including fixed- and rotational-field intensity modulated RT (IMRT) and image guided RT (IGRT), have led to more complex and conformal dose distributions. These innovations demand higher levels of control and integration, making the RT workflow more complex and time-consuming. Despite extensive computerization, such as inverse planning, effective and high-quality treatment planning still requires considerable human and time resources.

Automated planning (AP) has long been sought to streamline the planning process, optimize the RT workflow, and reduce intra- and interplanner variability that can affect plan quality. Numerous studies have focused on implementing and commissioning automated tools for RT planning, reflecting growing interest in the field. Market solutions for AP fall into 3 main categories: knowledge-based planning, template-based algorithms, and multicriteria optimization (MCO).[2] Automation is anticipated to significantly impact planning workload, particularly for breast cancer.

AP in RT is also vital for objectively comparing different treatment techniques, minimizing operator-related biases. By adhering to standardized protocols and algorithms, AP reduces variations that may arise from different planners' expertise. This standardization is crucial for fair comparison of techniques such as IMRT and volumetric modulated arc therapy (VMAT). Automated systems can quickly generate multiple treatment plans, facilitating a thorough evaluation of various techniques within a shorter timeframe. This efficiency is advantageous for studies comparing different delivery methods, where planning complexity can be a limiting factor. Additionally, automated plans are reproducible, which is essential for retrospective studies and quality assurance.

Our study investigates an MCO AP system, mCycle, integrated into the research version of Monaco Treatment Planning System (TPS) v5.59 (Elekta AB), now available as Elekta ONE Autoplanning.

Breast applications of mCycle have been investigated by Marrazzo et al.[3] Other studies have explored prostate cancer, prostate stereotactic body RT (SBRT), bilateral head and neck cancer and rectal cancer treated at an MR-Linac,[4] prostate SBRT,[5] cervical cancer applications,[6] and head and neck cancer treatment.[7]

The primary goal of our study was to implement 2 fully AP techniques using mCycle for both IMRT and VMAT in whole breast irradiation (WBI). We aimed to assess whether mCycle standardizes plan quality across a diverse patient cohort with varying anatomical features typical of the breast region, ensuring clinical acceptability. Additionally, we seek to compare IMRT and VMAT for WBI in terms of plan quality and robustness against setup errors and breast swelling.

Methods and Materials

Patients and clinical protocols

A total of 65 patients with breast cancer who underwent postoperative WBI were randomly selected for this study: 20 left-sided patients treated in free breathing (left-FB), 25 left-sided patients treated in deep inspiration breath hold (left-DIBH), and 20 right-sided patients treated in free breathing (right-FB). All patients received a total dose of 40.05 Gy delivered in 15 fractions (2.67 Gy per fraction), followed by a boost dose of 13.35 Gy in 5 fractions to the postoperative bed, administered using an electron beam.

Patients were scanned using a Philips Big Bore scanner (3-mm slice thickness), positioned supine with their arms raised above their heads, using either a WingSTEP (Elekta AB) or a Wing Board (CIVCO Inc). The C-RAD Sentinel laser scanning system (C-RAD AB) was used to reconstruct a breathing signal and guide the DIBH CT acquisitions. DIBH CT scans were performed when the respiratory signal fell within a patient-specific gating window.

Clinical target volumes (CTVs) were delineated according to the European SocieTy of Radiation Oncology (ESTRO) contouring guidelines[8] and organs at risks (OARs) encompassing heart, lungs, and contralateral breast were manually contoured by an experienced physician. The planning target volume (PTV) was obtained by a 5-mm isotropic expansion of the CTV and then cropped 5 mm from the skin surface.

All the patients enrolled in this study were planned at a VersaHD Elekta linac (Elekta AB), equipped with an Agility multileaf collimator. Planning goals are the same as defined in the internal clinical protocol used in our center for WBI and reported in Table 1.

AP system

Plans were generated using a novel system for fully AP, mCycle, provided within Monaco Research TPS (Elekta AB) and described in literature.[4]

The mCycle AP system is based on a lexicographic a priori MCO, which can generate a single Pareto-optimal and derivable plan, with no manual intervention by the operator. Input for the plan optimization is a technique and tumor-site specific protocol, called wish-list (WL), containing treatment objectives and hard planning constraints with assigned priorities and goal values. The WL

Table 1 Planning goals used in the internal clinical protocol used in our center for WBI

OAR	Dose constraints
PTV	V95% > 95%
	V105% < 5%
	D0.1cc < 110%
Heart	V10Gy < 5%
	V2Gy < 30 %
	Dmean < 2.5 Gy
Ipsilateral lung	V18Gy < 15%
Contralateral lung	V2.5Gy < 15%
Contralateral breast	Dmean ≤ 1.5Gy

Abbreviations: D0.1cc = dose received by 0.1 cm^3 of the considered structure; Dmean = mean dose; OAR = organ at risk; PTV = planning target volume; VX% = volume of the selected structure receiving X% of the prescription dose; VXGy = volume of the selected structure receiving XGy; WBI = whole breast irradiation..

is defined by translating the institution's clinical protocol into 1 or more cost functions. The optimization process consists of 2 steps: first, the fluence map is obtained through an iterative optimization process that mimics the typical planner's trial-and-error approach. In this process, the achieved objectives are turned into hard constraints, and efforts are made to progressively enhance the plan, while preserving the accomplishments made thus far. Objectives' goals are pushed beyond the specified requests if feasible or until a defined "sufficient value" is reached. A "sufficient value" is the minimum acceptable goal required for that constraint or objective function so that once achieved its weight will not be raised further. It prevents unnecessary dose optimization, which could affect target coverage or cause OARs limits to be exceeded. Second, the fluence segmentation and segments weight and shape optimization are performed using the new Pseudo-Gradient Descent Segment Shape Optimizer. Both steps are driven by the WL.

For this study, 2 WLs were implemented based on our clinical planning goals (Table 1), 1 for the step-and-shoot IMRT technique and 1 for the VMAT technique.

To ensure a robust WL that serves different anatomies, its definition requires initial tweaking using a subset of patients. Ten left-FB patients, not included in the 65 patients of the validation data set, were used to fine-tune the WL. We specifically selected left-FB patients for fine-tuning because they represent the most challenging scenario, primarily because of the heart's proximity.

Treatment techniques

Two 6-MV tangential fields with patient-specific angles have been adopted in the step-and-shoot IMRT technique: beam entrance (gantry angle) has been manually chosen to avoid the contralateral breast, and both gantry and collimator angle are defined, so as to reduce dose to ipsilateral lung and heart, the latter especially in the left breast case. The choice of beam angles was the only manual step required.

Two 6-MV partial arcs, 60° wide each, with fixed start and stop gantry angles, have been chosen for the VMAT technique (left breast: 290°-350° and 160°-100°; right breast: 70°-10° and 200°-260°). This arcs configuration, often called "bow-tie" configuration, allows a better low doses conformation to target reducing the dose received by nearby OARs.[9,10] No manual intervention was required in this technique.

Fluence and Sequencing optimization parameters have been evaluated and set on the basis of the clinical experience, taking into account the results of the pretreatment verification conducted in our center. These parameters include: beamlet width, which defines the accuracy of the fluence profile discretization in the direction of the leaf motion; the degree of fluence smoothing, which increases or decreases the complexity of fluence peaks to be segmented, also implying an increase or decrease in plan complexity; plan quality-calculation speed balance; the minimum segment area allowed; minimum segments width; minimum number of MU per segment; and maximum number of segments per plan. For the VMAT technique only: the maximum number of arcs allowed and the maximum number of control points per arc.

In all plans, a skin flash margin of 2.5 cm was added outside the body surface to allow robustness against breathing motion and deformations, using the Monaco functionality.

Dosimetric and clinical plan evaluation

Plans were evaluated based on their dosimetric results considering the achievement of plan's clinical goals for PTV and OARs. The following plan parameters were considered: PTV: dose received by 0.1 cm^3 of the considered structure (D0.1cc), V95%, V105%; heart: mean dose (Dmean), V2Gy, V10Gy; contralateral breast: Dmean; ipsilateral lung: V18Gy; contralateral lung: V2.5Gy.

For each plan, the dose distribution was independently assessed by an experienced radiation oncologist who was asked to rank the automated generated plans into 3 categories: clinically acceptable, ie, the dose distribution satisfies all the clinical requests; conditionally acceptable, ie, a constraint is slightly exceeded because of anatomical limits; and not clinically acceptable, ie, 1 or more constraints are exceeded.

Planning time was also evaluated and compared with a manual planning approach. It was defined as the effective working time required by the user. The optimization time was not included in the planning time, because it depends

heavily on hardware characteristics and does not involve user intervention. Nonetheless, we provided an estimate of the optimization time for reference.

Plan deliverability and delivery times

In order to investigate the deliverability of the automated generated plans, dosimetric verification measurements were performed and evaluated in terms of γ passing rate (global approach; 3%; 2 mm) and point dose measurements for a subset of 18 randomly selected plans (6 per each subset of patients). Plans were transferred to the ArcCheck (Sun Nuclear Corporation) 3-dimensional array, using the quality assurance feature of Monaco TPS, and considered clinically deliverable when the γ index exceeded 90%.

Point dose measurement was carried out with an Exradin A1SL ionization chamber (Standard Imaging) ionization chamber placed in the middle of the ArcCheck inner plug. The acceptance criterion for the point dose measurement was point dose deviation $< 5\%$.

Plan delivery times were measured during dosimetric verification.

Statistical analyses

Statistical significance of differences between IMRT and VMAT techniques for the dosimetric plan parameters of interest was evaluated using the paired-sample Wilcoxon signed-rank test with a significance level of 0.05. Statistical analysis was performed with OriginPro (version 9.0.0, OriginLab Corporation).

Plan robustness

A plans robustness evaluation for both IMRT and VMAT plans was carried out on the entire set of 65 patients, by implementing 3 classes of errors: random error, systematic error, and anatomical variation.

The random error was simulated by a rigid and random displacement of the isocenter along the antero-posterior, latero-lateral, and cranio-caudal directions within a 0.5-cm radius, which is the residual intrafraction shift found in literature.[11-13] At each treatment fraction a specific random displacement was applied, and the cumulative dose was obtained by summing up the 15 treatment fractions. This was accomplished through a Monaco script developed in C# to pass the isocenter shifts via a CSV file and allowing Monaco to automatically apply the shifts, recalculate the plans, save them, and export them in Dicom RT for dose accumulation.

The introduced displacement varies randomly between fractions, but the same set of shifts has been used when comparing the 2 techniques (IMRT and VMAT) for each patient.

A rigid displacement of ± 0.3 cm with respect to the isocenter was introduced to simulate the systematic error. The larger plan deterioration was found with a composite shift of the isocenter along the caudal, posterior, and outward lateral direction (left in the left cases and right in the right cases).[14] This isocenter variation can be representative of a systematic setup error.

Breast swelling was simulated by adding a 0.5-cm and a 0.3-cm thickness bolus to the patient and by expanding the CTV and PTV of 0.5 cm or 0.3 cm, respectively, in the anterior and outward lateral directions (again, left in the left cases and right in the right cases).

Differences from the original plan in target (PTV and CTV) coverage (V95%), homogeneity (V105%) and maximum dose, as well as OARs doses, were calculated and examined.

Results

Automatic treatment techniques

The 2 implemented WLs, containing objective functions and OARs constraints with their priorities, are reported in Table E1 and E2. No changes were made to the wish-list functions or the priorities among the 3 different patient cohorts, and no manual fine-tuning was applied to individual patients after the automatic optimization, except for a potential rescaling of the normalization point, which was only performed if the adjustment was $< 1\%$. The only adjustment made was adding a sufficient goal value of 0.5 on heart's Quadratic Overdose functions in the right-FB case. A sufficient value has been required in the right-FB case to limit the dose reduction on the heart, which generally is not a critical organ in the right treatments, yet it was the cause of target undercoverage for many patients.

The start and stop gantry angles for the VMAT technique were specifically chosen to spare the contralateral breast and reduce the radiation dose to the ipsilateral lung, while maintaining close tangency to the internal thoracic wall. In the left case, the angles are 290° to 350° and 160° to 100°, whereas in the right case, they are 70° to 10° and 200° to 260°. The collimator angles for the 2 arcs were set to 5° and 355°, respectively, specifically to prevent interleaf leakage from affecting the same slice during rotation.

The Fluence and Sequencing optimization parameters have been chosen to maximize the likelihood of achieving a high-quality plan while maintaining modulation degree at a level that allows for successful plan delivery and consistent quality assurance. A summary of the parameters for each technique is provided in Table E3.

Table 2 Dosimetric results for IMRT and VMAT plans

			Mean ± 1 SD			Range			*P* value (<.05)			Out range		
			Right-FB	Left-FB	Left-DIBH	Right-FB	Left-FB	Left-DIBH	Right-FB	Left-FB	Left-DIBH	Right-FB	Left-FB	Left-DIBH
PTV	**D0.1cc [Gy]**	**IMRT**	43.5 ± 0.3	43.5 ± 0.3	43.5 ± 0.2	42.8-43.8	42.6-44.0	43.1-43.9	**.002***	**<.001***	**.005***	0/20	0/20	0/25
		VMAT	43.1 ± 0.4	43.3 ± 0.4	43.3 ± 0.3	41.9-43.9	42.5-43.9	42.4-43.7				0/20	0/20	0/25
	V105% [%]	**IMRT**	3.5±1.4	4.5 ± 2.0	4.5 ± 1.9	1.2-6.4	1.1-7.2	1.4-8.9	.985	**.022***	.808	0/20	0/20	0/25
		VMAT	3.7 ± 3.6	4.3 ± 2.5	6.0 ± 2.5	0.0-9.9	0.4-9.7	0.1-9.4				0/20	0/20	0/25
	V95% [%]	**IMRT**	96.3±1.0	96.4 ± 1.1	96.1 ± 0.8	95.0-98.2	95.1-98.4	95.1-98.0	**.020***	**.004***	**.009***	0/20	0/20	0/25
		VMAT	97.3 ± 1.2	97.6 ± 1.6	98.6 ± 1.2	95.3-99.0	95.4-99.8	95.4-99.6				0/20	0/20	0/25
Heart	**Dmean [Gy]**	**IMRT**	0.9 ± 0.1	2.1 ± 0.8	1.5 ± 0.6	0.7-1.2	1.1-3.7	0.9-3.4	.104	.294	.101	0/20	**5/20***	**2/25***
		VMAT	1.1 ± 0.2	1.7±0.3	1.4 ± 0.3	0.8-1.3	1.1-2.2	0.9-2.3				0/20	0/20	0/25
	V10Gy [%]	**IMRT**	0.0 ± 0.0	2.7 ± 2.5	1.1 ± 1.8	0.0-0.0	0.0-7.4	0.0-7.3	**.009***	.282	**<.001***	0/20	**5/20***	**2/25***
		VMAT	0.0 ± 0.0	0.3 ± 0.6	0.1 ± 0.5	0.0-0.0	0.0-2.2	0.0-2.3				0/20	0/20	0/25
	V2Gy [%]	**IMRT**	2.5 ± 3.2	23.3 ± 9.3	12.9 ± 6.4	0.0-11.4	4.2-41.5	3.6-28.6	**<.001***	**<.001***	1.000	0/20	**5/20***	0/25
		VMAT	1.2 ± 1.4	22.0 ± 8.0	12.1 ± 8.7	0.0-4.7	3.2-37.1	2.1-35.1				0/20	**3/20***	**2/25***
Contralateral breast	**Dmean [Gy]**	**IMRT**	0.7 ± 0.2	0.7 ± 0.2	0.7 ± 0.3	0.4-1.1	0.4-1.3	0.3-1.6	.185	.236	**.003***	0/20	0/20	0/25
		VMAT	1.0 ± 0.2	1.1 ± 0.3	1.1 ± 0.4	0.7-1.5	0.5-1.6	0.4-2.5				0/20	**1/20***	**4/25***
Ipsilateral lung	**V18Gy [%]**	**IMRT**	12.0 ± 3.1	11.3 ± 3.9	12.4 ± 3.1	7.6-14.4	7.8-22.1	6.9-19.3	**<.001***	**<.001***	**<.001***	0/20	**2/20***	**5/25***
		VMAT	7.6 ± 2.3	6.3 ± 3.1	8.9 ± 2.8	4.5-13.6	0.7-12.1	2.9-15.6				0/20	0/20	**1/25***
Contralateral lung	**V2.5Gy [%]**	**IMRT**	0.0 ± 0.1	0.0 ± 0.1	0.1 ± 0.1	0.0-0.3	0.0-0.6	0.0-0.4	.126	.187	.591	0/20	0/20	**1/25***
		VMAT	0.0 ± 0.0	0.1 ± 0.2	0.1 ± 0.1	0.0-0.1	0.0-0.7	0.0-0.5				0/20	0/20	0/25
External	**D0.1cc [Gy]**	**IMRT**	43.2 ± 0.7	42.8 ± 1.2	43.2 ± 0.9	41.4-43.9	38.7-43.8	40.9-44.0	**<.001***	**<.001***	**<.001***	0/20	0/20	0/25
		VMAT	43.0 ± 0.7	43.4 ± 0.4	43.4 ± 0.3	41.2-43.9	42.5-43.9	42.4-43.7				0/20	0/20	0/25

Abbreviations: D0.1cc = dose received by 0.1 cm^3 of the considered structure; DIBH = deep inspiration breath hold; Dmean = mean dose; FB = free breathing; IMRT = intensity modulated radiation therapy; PTV = planning target volume; VMAT = volumetric modulated arc therapy.
*Statistically significant differences.

Dosimetric plan evaluation and comparison

Dosimetric results for IMRT and VMAT plans are summarized in Table 2. All the automated generated plans with the 2 techniques, among the 3 cohorts of patients, achieved the required objectives for PTV. The VMAT technique generally provides better PTV coverage with a mean V95% of 97.9% ± 1.4%, compared with 96.2% ± 1.0% of the step-and-shoot IMRT. Both techniques show good control of high doses within the PTV and in the total patient body, where the near maximum dose (D0.1cc) constraint is never exceeded. In the right-FB case, we obtained the bests results in terms of OARs sparing, because none of our constraint was exceeded, whereas the left-FB case presented the most challenging scenario for the heart's constraints with 5 plans out of 20 failing to achieve all our heart's goals with the IMRT technique, and 3 plans out of 20 not encompassing the V2Gy heart constraint with the VMAT technique. In the left-DIBH subgroup, we observe a slight increase in plans that exceed our established limits for the contralateral breast with the VMAT technique and for the ipsilateral lung with the IMRT technique.

In Figure 1, the histograms illustrate the differences between the results obtained with the IMRT and VMAT techniques for all the main objectives of clinical interest. Notably, VMAT demonstrates clear superiority in complying with heart and ipsilateral lung constraints, whereas IMRT outperforms significantly in terms of the contralateral breast constraints. For the contralateral lung, although VMAT shows a higher count of better outcomes, it also exhibits a wider range of values, resulting in IMRT having a lower mean dose in this scenario. Overall, VMAT demonstrates superior performance in sparing the ipsilateral OARs in all 3 groups because of its enhanced dose conformation to the target. However, it exhibits slightly inferior results compared with IMRT in terms of contralateral OARs sparing, primarily because of the wider low dose distribution characteristic of VMAT techniques.

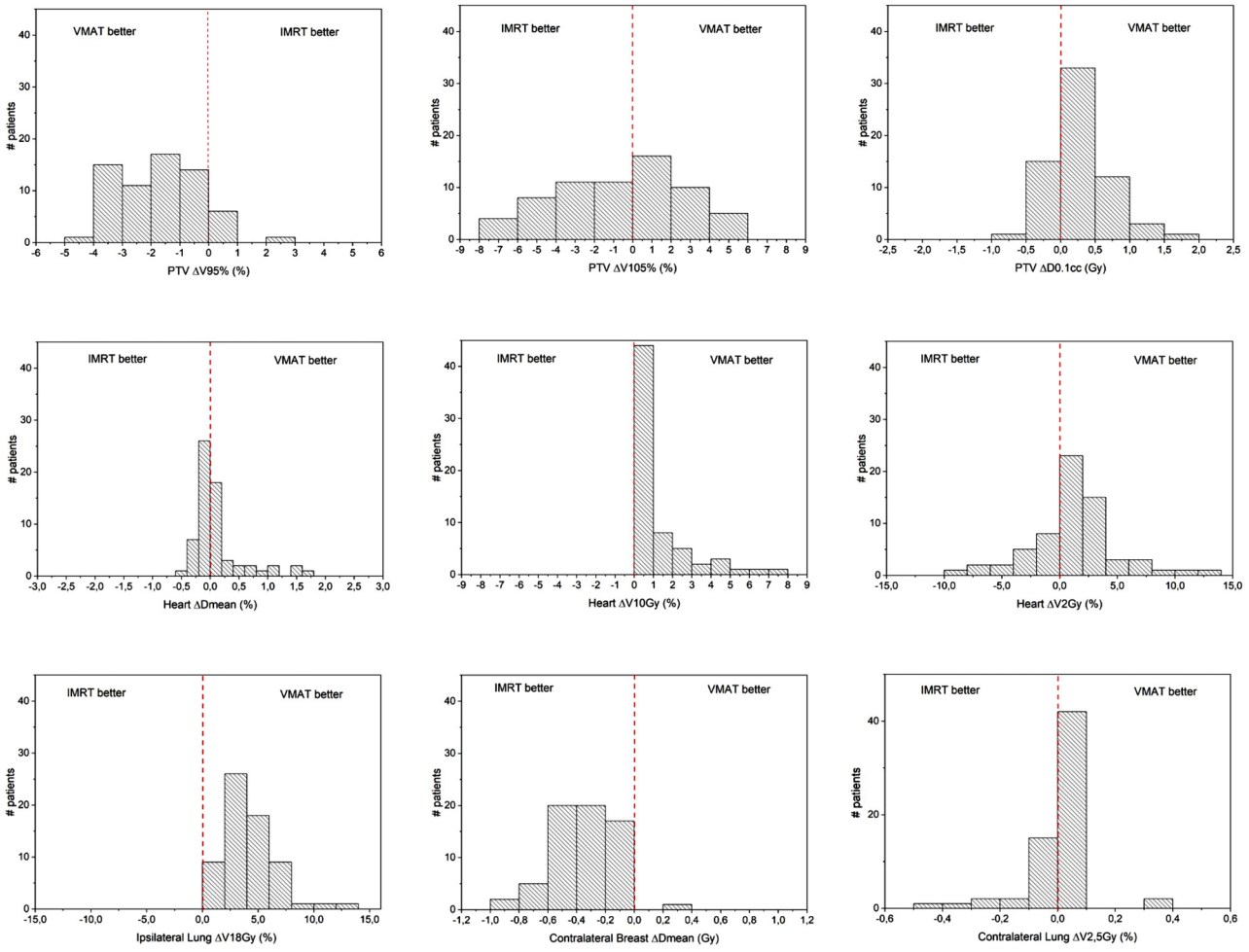

Figure 1 Histograms illustrating the differences between the results obtained with the IMRT and VMAT techniques for all the main clinical parameters. *Abbreviations:* IMRT = intensity-modulated radiation therapy; VMAT = volumetric modulated arc therapy.

Table 3 Results of the physician evaluation

	IMRT			VMAT		
	Clinically acceptable	Conditionally acceptable	Not acceptable	Clinically acceptable	Conditionally acceptable	Not acceptable
right-FB	16/20 (80%)	3/20 (15%)	1/20 (5%)	20/20 (100%)	0/20 (0%)	0/20 (0%)
left-FB	12/20 (60%)	2/20 (10%)	6/20 (30%)	16/20 (80%)	4/20 (20%)	0/20 (0%)
left-DIBH	23/25 (92%)	0/25 (0%)	2/20 (8%)	23/25 (92%)	1/25 (4%)	1/25 (4%)
Total	51/65 (78%)	5/65 (8%)	9/25 (14%)	59/65 (91%)	5/65 (8%)	1/65 (1%)

Abbreviations: DIBH = deep inspiration breath hold; FB = free breathing; IMRT = intensity modulated radiation therapy; VMAT = volumetric modulated arc therapy.

Concerning planning time, about 5 minutes were necessary for the IMRT plans (excluding calculation time) where the operator has to manually choose the gantry and collimator angles, and only 1 minute for VMAT plans that were fully automated. To give an idea of the optimization times involved, with the hardware available to us, the average optimization time was between 10 and 25 minutes (average 15) for IMRT and between 20 and 45 (average 30) for VMAT. The manual planning time ranges from 30 minutes to 1 hour, depending on the complexity of the plan.

Physician plans evaluation

Table 3 summarizes the results of the physician evaluation. VMAT plans generally received more favorable assessment, with 59 out of 65 plans considered clinically acceptable, compared with 51 plans in IMRT. Among the 3 patient cohorts, left-DIBH patients expressed the best results, with >90% of their plans deemed clinically acceptable. Both techniques performed well for right-FB patients, with all automated plans considered clinically acceptable in VMAT, whereas only 1 plan in IMRT was deemed unacceptable. The left-FB group with IMRT exhibited the poorest results, with 6 out of 20 plans considered unacceptable. Considering the total number of acceptable plans (clinically and conditionally), a clinical approval rate of >90% was consistently achieved, except for the left-FB group in the IMRT case.

Plan deliverability and delivery times

The γ passing rates showed no significant difference between IMRT and VMAT, with 95.6% $\pm$ 1.6% for the former and 95.0% $\pm$ 3.1% for the latter. However, there was a notable difference in point dose between the 2 techniques, with a point dose deviation of 0.4% $\pm$ 0.3% for IMRT and 3.4% $\pm$ 1.7% for VMAT. No differences were observed among the 3 patient groups. The mean delivery time measured was 172 $\pm$ 45 seconds for IMRT and 248 $\pm$ 24 seconds for VMAT.

Plan robustness

Table 4 presents the average PTV V95%, V105%, D0.1cc, and CTV V95% for IMRT and VMAT plans across the 4 types of induced errors. It also shows the number of plans that fail to meet clinical requirements. Figure 2 illustrates the number of IMRT and VMAT plans that violate clinical constraints (for both targets and OARs) for the different types of induced errors.

Although residual random errors do not significantly degrade plan quality in terms of PTV coverage and OAR sparing, a noticeable deterioration is observed in cases of

Table 4 Average PTV V95%, V105%, D0.1cc, and CTV V95% for IMRT and VMAT plans for the 4 types of induced errors. The number of plans not satisfying the clinical requirements is also reported

		IMRT					VMAT				
		Mean	SD	min	max	out (65)	Mean	SD	min	max	out (65)
Original	PTV V95%	96.2	1.1	94.0	98.4	7	97.8	1.4	95.3	99.8	0
	PTV V105%	4.8	3.3	1.1	23.9	3	5.0	3.6	0.0	16.0	5
	PTV D0.1cc	43.7	0.4	42.8	44.9	7	43.3	0.4	41.9	44.1	1
	CTV V95%	98.5	0.8	96.4	99.8	0	99.0	0.9	96.1	100.0	0
Random error	PTV V95%	96.0	1.1	94.1	98.5	11	96.4	1.9	90.2	99.6	15
	PTV V105%	1.7	1.3	0.0	4.9	0	2.1	2.0	0.0	8.1	0
	PTV D0.1cc	42.8	0.3	41.9	43.5	0	42.6	0.5	41.0	43.2	0
	CTV V95%	98.8	0.9	95.5	99.9	0	98.7	1.0	95.2	100.0	0
Systematic error	PTV V95%	96.3	2.6	83.6	99.7	15	96.3	2.6	90.3	99.7	22
	PTV V105%	5.1	3.0	0.2	12.4	4	4.5	3.2	0.1	12.4	3
	PTV D0.1cc	43.9	0.6	42.5	45.5	28	43.7	0.7	42.4	45.6	15
	CTV V95%	97.8	2.4	83.6	100.0	3	97.5	1.9	91.3	100.0	6
Bolus 3 mm	PTV V95%	90.8	4.2	73.9	96.9	60	90.6	7.7	43.1	98.7	46
	PTV V105%	2.1	1.0	0.5	5.3	0	1.4	1.4	0.0	7.0	0
	PTV D0.1cc	43.6	0.3	42.9	44.8	0	43.2	0.7	41.7	44.6	0
	CTV V95%	95.6	3.2	84.9	99.7	23	93.4	6.5	51.4	99.9	35
Bolus 5 mm	PTV V95%	86.4	5.1	74.3	95.3	62	84.6	7.5	67.9	97.6	61
	PTV V105%	1.6	0.9	0.3	5.0	0	1.3	1.4	0.0	7.9	0
	PTV D0.1cc	43.7	0.4	42.9	44.7	11	43.5	0.9	41.7	46.1	16
	CTV V95%	91.3	5.7	72.9	99.7	40	87.3	7.1	70.3	99.2	55

Abbreviations: D0.1cc = dose received by 0.1 cm^3 of the considered structure; IMRT = intensity modulated radiation therapy; max = maximum; min = minimum; PTV = planning target volume; VMAT = volumetric modulated arc therapy.

systematic errors, primarily related to hot spots within the PTV and the maximum PTV dose. For the majority of plans, CTV coverage remains adequate, with only 3 out of 65 IMRT plans and 6 VMAT plans showing a CTV V95% of < 95%.

Notably, despite the application of a skin flash, breast swelling leads to a significant reduction in PTV and CTV coverage, with IMRT proving to be more robust than VMAT (23 out of 65 IMRT plans with CTV V95% < 95%, compared with 35 VMAT plans for 3-mm bolus and

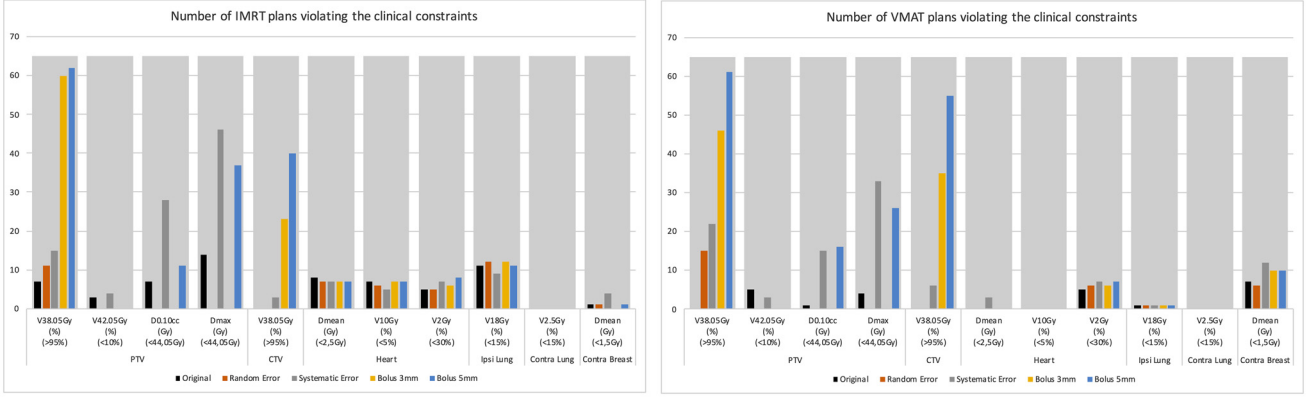

Figure 2 Number of IMRT and VMAT plans violating clinical constraints (for both targets and OARs) for the different types of induced errors. *Abbreviations:* IMRT = intensity-modulated radiation therapy; VMAT = volumetric modulated arc therapy.

40 out of 65 IMRT plans with CTV V95% < 95%, compared with 55 VMAT plans for 5-mm bolus).

Discussion

In this study, we evaluated the feasibility and effectiveness of using a novel AP system, mCycle, integrated into the Monaco TPS for the generation of step-and-shoot IMRT and VMAT plans in the context of WBI. The goal was to determine whether AP can standardize plan quality across a diverse patient cohort while ensuring clinical acceptability. Additionally, we aimed to compare the dosimetric outcomes and robustness toward setup errors and breast swelling of IMRT and VMAT plans generated by mCycle.

The results demonstrate that the mCycle system is capable of generating clinically acceptable plans for both IMRT and VMAT techniques across all patient cohorts, with a notable consistency in plan quality. VMAT plans, in particular, showed a higher rate of clinical acceptability compared with IMRT, with 59 out of 65 VMAT plans deemed clinically acceptable versus 51 out of 65 for IMRT. This finding aligns with the growing body of literature suggesting that VMAT offers superior dosimetric outcomes in terms of target coverage and OAR sparing because of its ability to modulate dose delivery more precisely.[10,15]

The dosimetric analysis revealed that VMAT generally provides better PTV coverage than IMRT, with a mean V95% of 97.9% compared with 96.2% for IMRT. This improved target coverage with VMAT is consistent with previous studies that highlight the technique's ability to provide superior PTV coverage and dose homogeneity.[16-20]

In the present study, in contrast to large part of the literature comparing IMRT and VMAT for breast cancer treatment and using manual planning,[16,19,20] VMAT also offers advantages on ipsilateral OARs sparing. This is in agreement with what has been previously found by Redapi et al,[10] also using AP on a large sample size.

However, IMRT demonstrated superior sparing of contralateral OARs, particularly the contralateral breast, likely because of its more localized dose delivery, which reduces the spread of low doses across nontarget areas. These findings corroborate earlier studies that reported similar trade-offs between IMRT and VMAT, with VMAT excelling in dose conformity and IMRT providing better protection to distant OARs.[10,15]

Concerning plan deliverability, both IMRT and VMAT plans generated by mCycle exhibited high deliverability, with γ passing rates exceeding 95% for both techniques. However, VMAT plans showed a larger point dose deviation during verification, which may be attributed to the greater complexity and modulation of VMAT plans. Despite this, the overall deliverability of the plans was within clinically acceptable limits, confirming the reliability of mCycle-generated plans for routine clinical use.

Robustness evaluation is crucial in RT, because setup errors and anatomical changes can significantly impact treatment outcomes. Our analysis showed that, although both techniques maintained adequate target coverage under random error conditions, systematic errors led to a noticeable degradation in plan quality, particularly in terms of PTV dose homogeneity and maximum dose. These findings are in line with previous research indicating that systematic setup errors can lead to hot spots within the target volume, increasing the risk of treatment-related toxicity.[14]

Breast swelling presented a significant challenge, particularly for VMAT plans, which showed a higher rate of failure to maintain adequate CTV coverage compared with IMRT. This result suggests that although VMAT offers superior initial dosimetric performance, its sensitivity to anatomical changes may necessitate more frequent plan adaptations during the course of treatment. The higher robustness of IMRT to breast swelling observed in this study aligns with earlier reports that emphasize the importance of considering anatomical variability in treatment planning, particularly for patients with breast cancer.[21] To our knowledge, this is the first study to evaluate the dosimetric effect of both random and systematic setup errors, as well as breast swelling, in a large patient cohort.

Conclusions

In conclusion, the use of the mCycle AP system in WBI demonstrates significant potential for improving the efficiency and consistency of RT planning. VMAT, while offering superior target coverage and ipsilateral OAR sparing, may require closer monitoring and adaptation in cases of anatomical changes such as breast swelling. IMRT, on the other hand, provides better protection to contralateral OARs and exhibits greater robustness to certain errors, making it a valuable alternative in specific clinical scenarios.

Disclosures

Roberto Pellegrini and Peter Voet reports a relationship with Elekta AB, Stockholm, Sweden that includes: employment. Livia Marrazzo reports a relationship with Elekta AB, Stockholm, Sweden that includes: travel reimbursement. Stefania Pallotta and Cinzia Talamonti reports a relationship with Elekta AB, Stockholm, Sweden that includes: travel reimbursement. Deborah Chilà reports a relationship with Elekta AB, Stockholm, Sweden that includes: funding grants. The other authors declare that they have no known competing financial interests or

personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.adro.2025.101719.

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