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Retrospective evaluation of patient-specific intensity-modulated radiotherapy plan verification data in a single department

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Abstract

Objective: This study aims to retrospectively analyze and evaluate patient-specific quality assurance (QA) data from radiotherapy plans using Intensity-Modulated Radiotherapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT) techniques at Akdeniz University Department of Radiation Oncology between 2017 and 2023.

Methods: QA data from 1574 treatment plans for 1078 patients were reviewed. Treatment plans were generated using PRECISE TPS for static IMRT and MONACO TPS for dynamic IMRT/VMAT techniques. Gamma index analysis was performed using MatriXX with a 3%/3 mm acceptance criterion. Data was categorized based on disease location, treatment devices, and planning systems, then statistically analyzed using Google Sheets and Looker Studio.

Results: Throughout this survey, no QA data was available for the year 2021 due to equipment upgrades. The anatomical distribution of plans was head-neck (496), pelvis (492), thoracic (542), abdomen (31), vertebra (10), femur (2). Most frequently applied techniques included 9-field IMRT (31.9%), dual-arc VMAT (23.3%), and single-arc VMAT (19.4%). Mean ± SD Gamma pass rates were 97.29% ± 1.60 for IMRT (356 plans) and 99.13% ± 1.10 for VMAT (1012 plans).

Conclusion: Both treatment planning systems (TPSs) yielded high gamma pass rates, indicating a high level of treatment delivery accuracy and reliability. VMAT usage increased over time due to its compatibility with equipment and precise dose delivery.

Keywords: radiotherapy, IMRT, VMAT, quality assurance, gamma index, dosimetry

Abbreviations: OARs, organs-at-risk; IMRT, intensity-modulated radiotherapy; VMAT, volumetric modulated arc therapy; TPS, treatment planning system; LINAC, linear accelerator; CT, computed tomography

Introduction

Radiation therapy constitutes a cornerstone in the multidisciplinary management of cancer, offering high-precision, organ-preserving treatment options for a wide range of malignancies. Over recent decades, the field has undergone a paradigm shift with the introduction of advanced techniques such as Intensity-Modulated Radiotherapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT). These methods utilize sophisticated algorithms and multi-leaf collimator (MLC) dynamics to modulate the intensity of photon beams, allowing clinicians to conform dose distributions tightly to the target while sparing surrounding organs-at-risk (OARs).[1-3]

IMRT and VMAT have become widely adopted due to their demonstrated advantages in both dosimetric accuracy and clinical outcomes, especially in anatomically complex sites such as the head and neck, prostate, and thoracic regions.[2,4,5] However, the increased conformality and complexity of dose delivery introduces new challenges in quality assurance (QA), particularly in patient-specific plan verification. Ensuring the fidelity of these treatment plans is critical, as even minor deviations in dose or positioning can compromise tumor control or lead to unintended toxicity in normal tissues.[6,7,8]

To this end, robust QA frameworks have been developed and standardized through initiatives such as those outlined by the American Association of Physicists in Medicine (AAPM), including Task Group 119 and Task Group 218, which provide recommendations for tolerances and methodologies in measurement-based verification.[7,9,10] Among these, the gamma index analysis remains a widely accepted and practical tool for comparing measured and calculated dose distributions, integrating both spatial and dosimetric criteria.[11] Despite its routine application, variations in QA results may arise due to factors such as beam modulation complexity, machine characteristics, anatomical site, and even software versioning, necessitating ongoing institutional validation and evaluation.[12,13,14]

Furthermore, recent advancements in data science have begun to supplement traditional QA protocols. Emerging research into predictive modeling using machine learning algorithms, supporting vector classifiers, and complexity metrics suggests the potential for proactive QA, wherein plan verification outcomes can be anticipated and optimized before delivery.[15,16] Such innovations highlight the need for continuous retrospective analyses of QA outcomes to identify patterns, enhance plan robustness, and refine clinical workflows.

In this context, the present study conducts a retrospective evaluation of patient-specific IMRT and VMAT QA data collected over several years at Akdeniz University Hospital's Radiation Oncology Department. The analysis focuses on gamma index pass rates and investigates potential correlations across treatment planning systems (TPS), anatomical treatment sites, delivery machines, and techniques. By systematically assessing QA performance metrics in real-world settings, this study aims to contribute to the evidence base required for refining institutional QA protocols, identifying areas of improvement, and ensuring high standards of clinical safety and treatment efficacy.

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Materials and Methods

This study received ethics approval from the Clinical Research Ethics Committee of Akdeniz University Faculty of Medicine (Approval No: TBAEK-110, Date: 29 February 2024). In addition, permission for the use of patient radiotherapy data and related devices was obtained from Akdeniz University Hospital on 12 March 2024.

This retrospective study included quality assurance (QA) data from 1574 radiotherapy treatment plans administered to 1078 patients between the years 2017 and 2023 at the Department of Radiation Oncology, Akdeniz University. These patients were treated using advanced radiotherapy techniques, specifically Intensity-Modulated Radiotherapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT). Treatment plans were developed using two distinct Treatment Planning Systems (TPS): PRECISE was used for static IMRT techniques, while MONACO was employed for dynamic IMRT and VMAT planning. Both systems were integrated with Elekta linear accelerator (LINAC) machine - specifically the Synergy and Agility Head model - which delivered the therapeutic radiation to the patients.

To verify the accuracy of treatment delivery, patient-specific QA was conducted using the IBA I'mRT MatriXX system in conjunction with the PTW UNIDOS electrometer. Prior to treatment, QA plans were recalculated on computed tomography (CT) images of a water-equivalent phantom, simulating patient anatomy. These recalculated dose distributions were then compared to the actual measured distributions obtained from the MatriXX 2D ion chamber array. The comparison was quantified using the Gamma Index method with a 3% dose difference and 3 mm distance-to-agreement (DTA) acceptance criteria, consistent with clinical QA protocols. A QA worksheet was generated for each plan and subsequently approved by both the medical physics and radiation oncology teams. In this study, the archived QA worksheets were retrospectively assessed.

For comprehensive analysis, all QA data were systematically classified according to several parameters, including year of treatment, anatomical site of the tumor, radiotherapy technique employed (static IMRT, dynamic IMRT, single- or dual-arc VMAT), treatment energy, and planning system used. The disease site classification included categories such as head and neck, thoracic, pelvic, abdominal, vertebral, and femoral regions. All raw QA data were entered into Google Sheets, and advanced visualization and statistical summaries were generated using Google Looker Studio, allowing the team to detect trends, variations, and anomalies in treatment accuracy over the multi-year study period (Figure 1).

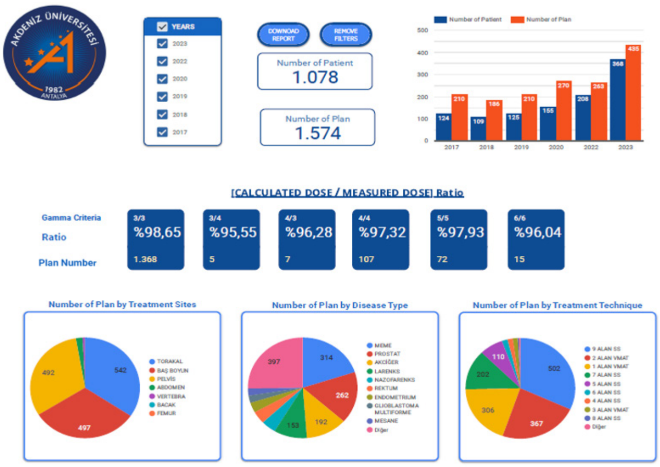

Figure 1 Distribution of treatment plans in the radiation oncology clinic between 2017-2023.

By compiling and analyzing these comprehensive datasets, this section provides a foundation for understanding the dosimetric integrity of patient-specific QA across different radiotherapy modalities and equipment configurations used at a single high-volume academic institution.

Results

A total of 1574 radiotherapy treatment plans corresponding to 1078 individual patients were analyzed for quality assurance based on Gamma index criteria. The distribution of these plans across treatment years revealed that no data was available in 2021 due to a major update and replacement of linear accelerator devices, which temporarily suspended QA measurements for IMRT and VMAT techniques. The remaining years showed consistent QA measurements and data collection, enabling comparative analysis.

When classifying plans by anatomical treatment sites, the highest number of cases were associated with the thoracic region (542 plans), followed by head and neck (496 plans), and pelvic regions (492 plans). Less frequent treatment sites included the abdomen (31 plans), vertebrae (10 plans), and femur (2 plans). This distribution highlights the clinical workload and disease spectrum addressed by the department (Table 1).

Table 1 Statistical results of treatment plan according to treatment sites, treatment technique, treatment planning system, treatment machine and energy criteria

Treatment sites	Total plan	Percentage
Abdomen	31	1.97%
Leg	1	0.06%
Head and neck	497	31.58%
Femur	1	0.06%
Pelvis	492	31.26%
Thoracic	542	34.43%
Vertebra	10	0.64%
TPS	**Total plan**	**Percentage**
Precise	550	34.94%
Monaco	1024	65.06%
Treatment technique	**Total plan**	**Percentage**
IMRT	876	55.65%
VMAT	698	44.35%
Treatment machine	**Total plan**	**Percentage**
Elekta synergy	876	55.65%
Elekta synergy agility	698	44.35%
Energy	**Total plan**	**Percentage**
6 MV	1531	97.28%
10 MV	42	2.66%
18 MV	1	0.06%

Regarding the radiotherapy techniques used, the 9-field static IMRT technique was the most commonly applied method, accounting for 31.9% of all plans. Dual-arc VMAT plans constituted 23.3% of cases, while single-arc VMAT was used in 19.4% of the plans. This indicates a notable clinical preference toward more advanced arc therapy over time.

The Gamma index analysis revealed highly favorable outcomes for both planning systems. For plans generated with the PRECISE TPS and delivered via static IMRT, the mean ± standard deviation (SD) Gamma pass rate was 97.29% ± 1.60 across 356 plans. Meanwhile, plans developed using the MONACO TPS for dynamic IMRT and

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VMAT demonstrated an even higher mean ± SD Gamma pass rate of 99.13% ± 1.10 over 1012 plans (Table 2 and 3). These findings support the dosimetric precision and robustness of both treatment planning systems, with slightly better results favoring the VMAT technique.

Table 2 The effect of treatment planning system on Gamma index data

TPS	Precise	Monaco
Gamma Index Criteria (%/mm)	(3/3)	(3/3)
Number of plan analysis	356	1012
Average of gamma passing rate (%)	%97.29	%99.13
Standard deviation	±1.60	±1.10

Table 3 The effect of treatment technique on Gamma index data

Treatment technique	IMRT	VMAT
Gamma Index Criteria (%/mm)	(3/3)	(3/3)
Number of plan analysis	676	692
Average of gamma passing rate (%)	%98.05	%99.24
Standard deviation	±1.69	±0.94

Discussion

The results of this retrospective analysis provide compelling evidence supporting the high dosimetric reliability of IMRT and VMAT treatment plans as implemented at Akdeniz University Department of Radiation Oncology. The observed Gamma index pass rates consistently exceeded clinical acceptance thresholds, demonstrating the effectiveness of both PRECISE and MONACO TPS platforms in producing clinically accurate and deliverable treatment plans. Particularly noteworthy is the superior performance of VMAT plans in terms of dosimetric accuracy, as reflected by their higher mean Gamma pass rates compared to IMRT plans.

The transition observed over time toward increased utilization of VMAT techniques is consistent with broader trends in radiotherapy practice, where VMAT is often favored for its reduced treatment time, enhanced dose conformity, and adaptability to complex anatomical targets. These advantages are especially significant in high-throughput clinical settings and for cases requiring precise dose modulation near organs at risk. The temporary data gap in 2021, due to LINAC upgrades, also underscores the importance of regular equipment modernization in maintaining and improving treatment quality.

This study's findings reinforce the essential role of patient-specific QA in maintaining treatment safety and serve as a validation of current clinical practices. The integration of robust QA tools such as the IBA MatriXX and the adoption of standard evaluation metrics like the 3%/3 mm Gamma index further enhance confidence in the accuracy of radiotherapy delivery. The institution's systematic approach to data logging and retrospective evaluation offers a valuable model for quality control and clinical audit in radiotherapy departments.

The findings of this retrospective study demonstrate high dosimetric accuracy for both IMRT and VMAT treatment plans, with VMAT yielding a mean Gamma pass rate of 99.13%, compared to 97.29% for IMRT. These results align with previously published studies emphasizing superior efficiency and accuracy of VMAT techniques. For example, Teoh et al.[1] reported VMAT's enhanced conformity and reduced treatment delivery times across multiple tumor sites, making it particularly advantageous in high-volume clinics.

In a meta-analysis by Ren et al.,[4] VMAT was found to outperform IMRT in terms of target coverage and organ-at-risk sparing in prostate cancer patients, a finding consistent with our observed preference for VMAT in pelvic and thoracic cases. Similarly, Rao et al.[5] compared Elekta VMAT with helical tomotherapy and fixed-field IMRT, concluding that VMAT provided better dose conformity and delivery efficiency in head and neck cancer cases. These parallels with our data-where head and thoracic plans were among the most common-reinforce the growing clinical adoption of VMAT for anatomically complex sites.

Our Gamma pass rates also compare favorably to those reported by Chan et al.,[6] who found average institutional VMAT pass rates exceeding 97% using TG-218 guidelines across a multi-center QA survey. The consistently high rates in our data underscore the quality of implementation and protocol adherence at our center. Furthermore, Childress et al.[12] reported similar results in 2D patient-specific IMRT QA, with average pass rates in the range of 95-98%, affirming that our IMRT verification outcomes fall within internationally accepted standards.

The equipment upgrade in 2021 that interrupted QA data collection highlights the importance of technology renewal in sustaining high treatment quality. This is echoed by Knöös,[8] who emphasized that QA practices must evolve alongside technical advancements to maintain dosimetric reliability.

Recent studies also support the integration of predictive QA tools. For instance, Chen et al.[13] used 1D complexity metrics and 3D dose prediction to forecast gamma pass outcomes, while Granville et al.[16] successfully applied support vector classifiers trained on machine and planning parameters. These innovative approaches suggest future pathways for optimizing QA beyond conventional measurement tools.

In summary, the high gamma passing rates achieved in this study are consistent with leading reports in the literature, supporting the robust implementation of both TPS platforms (MONACO and PRECISE), effective QA instrumentation, and the transition toward advanced delivery techniques such as VMAT. These findings not only validate current clinical workflows but also suggest that integrating complexity metrics and predictive analytics could further enhance QA reliability and efficiency in modern radiotherapy.

Conclusion

In conclusion, the retrospective evaluation of 1574 radiotherapy plans using both IMRT and VMAT techniques over a seven-year period reveals a high level of treatment precision and QA reliability at Akdeniz University Hospital. The consistently high Gamma pass rates achieved through both the PRECISE and MONACO planning systems confirm the robustness of clinical workflows and support the institution's transition toward greater adoption of VMAT technology. The findings affirm the critical importance of patient-specific QA as a cornerstone of modern radiotherapy practice, providing assurance of accurate dose delivery and optimal patient outcomes. The methodologies and results presented in this study may inform broader efforts to standardize QA protocols and enhance treatment consistency across radiotherapy centers.

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Conflict of Interest

The authors declare no conflict of interest.

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