Technical Note

An End-to-end Quality Assurance Procedure for Ethos Online Adaptive Radiotherapy

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Abstract

Purpose: Online adaptive radiation therapy (OART) poses unique challenges for quality assurance (QA), requiring innovative methodologies beyond traditional techniques. This study introduced an end-to-end (E2E) QA test for the Ethos OART system. **Materials and Methods:** Initial treatment plans were developed using deformed computed tomography (CT) images of standard phantoms. During treatment sessions, adaptive plans were created and delivered using undistorted physical QA phantoms equipped with measuring detectors. Our approach was demonstrated using standard QA phantoms – OCTAVIUS-four-dimensional (PTW, Freiburg, Germany), ArcCHECK (Sun Nuclear Corp., FL, USA), and the RUBY (PTW, Freiburg, Germany) – to evaluate the accuracy of contouring, synthetic CT (sCT), and dosimetry of adaptive plans in the Ethos OART system. **Results:** Our findings demonstrated the superior performance of the Ethos OART system, with a gamma pass rate exceeding 96% (2% local/2 mm) and point dose deviations below 0.5%. The Dice coefficients for body contours between the sCT and reference CT were above 0.9, and the sCT accuracy was confirmed by mean absolute errors of <27 Hounsfield unit. **Conclusion:** This approach establishes a straightforward E2E test to assess the workflow accuracies essential for preclinical validation/monthly QA of OART systems.

Keywords: Adaptive, end-to-end, Ethos, online, quality assurance, radiotherapy

Received on: 31-10-2024 **Review completed on: 04-01-2025** **Accepted on: 15-01-2025** **Published on: 24-03-2025**

Introduction

Interfractional anatomical changes are inevitable during radiotherapy treatment and pose significant challenges in delivering accurate dose delivery.[1] Online adaptive solutions offer a promising approach to addressing daily anatomical variations in both targets and nearby critical organs.[2] Currently, the most widely used systems for online adaptive radiotherapy (OART) leverage magnetic resonance imaging (MRI) guidance[3] and cone-beam computed tomography (CBCT) guidance.[4] Ethos (Varian Medical Systems, Palo Alto, CA, USA) is a commercial OART system that utilizes the CBCT of the day to generate adaptive plans.[5]

The OART workflow is inherently more complex than conventional image-guided radiotherapy, involving multiple steps such as imaging, registration, contouring, electron density mapping, plan generation, and treatment delivery for each session.[6] Given the time constraints, OART processes are heavily automated. Ensuring precise execution at each step is critical for accurate and reliable adaptive treatment. Furthermore, the OART workflow introduces higher risks compared to standard RT, as highlighted by a study showing increased risk in OART-related failures.[7] Moreover, certain systems, like Ethos ART, function as a "black box," limiting access to detailed evaluations beyond inputs and outputs.[8] Therefore, thorough quality assurance (QA), procedures are essential for evaluating the adaptive workflow. While established guidelines exist for machine QA and patient-specific QA in standard RT, these methods may not directly apply to OART. Novel QA procedures are required to address the unique challenges of OART.

Recent studies have introduced workflows and phantoms specifically designed to evaluate OART and the deformable

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Access this article online

Quick Response Code:

Website: www.jmp.org.in

DOI: 10.4103/jmp.jmp_188_24

How to cite this article: Yoganathan SA, Khemissi A, Paloor S, Hammoud R, Al-Hammadi N. An end-to-end quality assurance procedure for Ethos online adaptive radiotherapy. J Med Phys 2025;50:140-7.

image registration.[9-16] For instance, Niebuhr *et al*.[11] developed the ADAM-pelvis phantom, which is anthropomorphic, deformable, and multimodal, suitable for both MR and computed tomography (CT) imaging. Subsequent studies, such as those by Hoffmans *et al*.[12] utilized this phantom for end-to-end (E2E) evaluation of MRI-guided adaptive RT. Conversely, existing studies related to Ethos have primarily focused on evaluating specific aspects of the system, particularly concerning contouring accuracy, plan quality, and efficiency.[8] Therefore, we have developed an E2E QA test to evaluate the Ethos OART system.

Materials and Methods

Phantoms

The feasibility of our approach has been demonstrated using standard QA phantoms: The OCTAVIUS- four-dimensional (4D) (PTW, Freiburg, Germany), ArcCHECK (Sun Nuclear Corp., FL, USA), and RUBY head phantom (PTW, Freiburg, Germany). The OCTAVIUS-4D incorporates a two-dimensional-array (SRS 1000) comprising 1000 vented ionization chambers spaced at 5 mm intervals over an 11 cm × 11 cm area within a cylindrical polystyrene phantom. The ArcCHECK phantom, a cylindrical polymethyl methacrylate device, features a helical array of 1386 sun-point diodes at 1 cm intervals. The RUBY head phantom had a System QA insert (type T40072.1.300). This insert includes three MR-visible inserts (with diameters of 1, 1.5, and 2.5 cm) and three CT-visible inserts representing lung, bone, and brain, all housed within a cubic polystyrene structure. This insert also allows for dosimetric measurements using a semiflex- three-dimensional (3D) ionization chamber (0.07cc) (PTW, Freiburg, Germany).

Ethos system

The Ethos System (Varian Medical Systems, Palo Alto, CA, USA) is a comprehensive, online adaptive radiation therapy solution that includes a treatment machine, an independent treatment planning system (TPS), and secondary check software. The treatment machine shares key specifications with the Halcyon system, including a 6FFF beam, double-stacked multi-leaf collimators, and 3D kV CBCT imaging, allowing for precise online adaptive treatments. The system is enhanced with advanced software that automates contouring and treatment planning during online adaptive sessions. This automation enables rapid adjustments based on the session's CBCT data, ensuring optimal treatment delivery. In addition, the system includes Mobius3D for secondary plan checks, providing thorough QA during the online adaptive sessions. The Ethos system also features an independent TPS for pretreatment planning and ongoing treatment monitoring.

Online adaptive workflow

Our Ethos OART treatment workflow [Figure 1] is outlined below.[17,18] The initial preplanning process is similar to that of non-OART treatments, including CT simulation, contouring, and treatment planning. The treatment planning begins with the Ethos TPS, which utilizes an intelligent optimization engine (IOE) for autoplanning. This system streamlines the design and management of optimization tasks. Initially, clinical goals for both the targets and organs at risk (OARs) are defined, typically using predefined templates. The IOE then generates objective functions for the photon optimizer, allowing the planner to adjust the clinical goal priorities to influence the optimization process. During optimization, real-time visualizations of the dose distribution and dose-volume histograms are provided for a 9-field IMRT plan. Once the planner is satisfied with the plan, the clinical intent is approved, leading to the final autoplan generation. The Ethos system offers multiple autoplan configurations, including three fixed-field IMRT options (7, 9, and 12 equally spaced fields) and two VMAT plans (2 and 3 full arcs). In addition, users can import custom beam geometries from third-party TPS. The final dose calculation is performed using the Acuros algorithm.

The OART session begins with the Ethos treatment machine, starting with the acquisition of a CBCT. The Ethos system automatically generates contours for relevant OARs based on the treatment site (e.g. prostate, seminal vesicle, bladder, rectum, bowel, etc.). These autocontoured OARs are reviewed and potentially edited by the radiation oncologist (RO) for accuracy. The system then employs deformable image registration to transfer tumor contours gross tumor volume/clinical target volume (GTV/CTV) from the planning CT (pCT) to the CBCT image. The RO may modify the transferred tumor contour if necessary. After finalizing the CTV, a predefined margin is applied to automatically derive the planning target volume (PTV). The current Ethos system (version 1.1) generates a synthetic CT (sCT) based on the deformed pCT, and the auto-segmented OARs and targets from the CBCT are copied onto the sCT. This sCT, now containing both the copied OARs and deformed target volumes, is used for dose calculation and replanning.

During the adaptive planning phase, the Ethos system uses a similar beam geometry as in the initial preplanning stage. The Acuros algorithm is employed for dose calculation. Two plans are generated: a scheduled plan (the original plan, recalculated using the current session's anatomy) and an adaptive plan (a fully reoptimized plan). If the adaptive plan is selected, it requires two approvals: a "clinical approval" from the RO and a "technical approval" from the medical physicist. The adaptive plan is then automatically transferred to the Mobius system for secondary dose calculation verification. Mobius recalculates the dose distribution using the collapsed cone algorithm and compares it with the Ethos calculation using a 3% (global)/2 mm, 10% tolerance gamma evaluation. Finally, a CBCT scan is performed just before beam delivery to verify the patient's final position. Couch shifts are applied if necessary.

Overview of the proposed end-to-end quality assurance procedure

Figure 2 depicts the proposed E2E QA procedure. Initially, the original CT images and contours of the phantom underwent

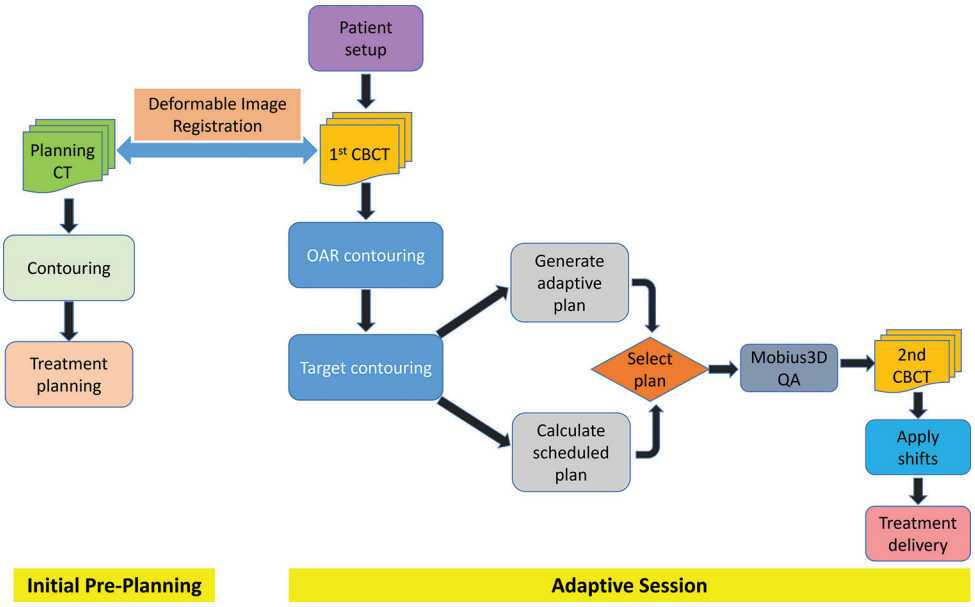

Figure 1: Typical workflow of an online adaptive treatment using Ethos. CBCT: Cone-beam computed tomography, CT: Computed tomography

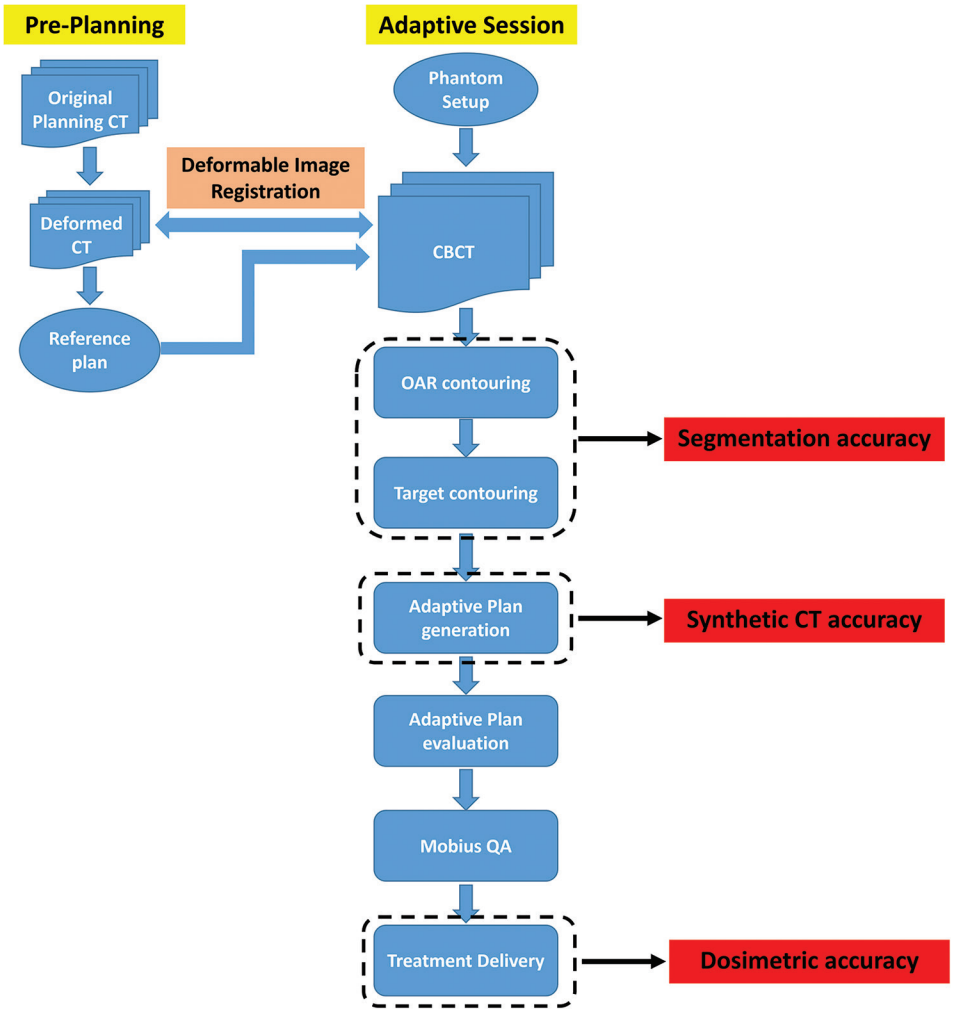

Figure 2: Flowchart of the end-to-end quality assurance procedure. CBCT: Cone-beam computed tomography, CT: Computed tomography, QA: Quality assurance

deformation. Initial treatment plans (further discussed in the below section 'Preplanning') were subsequently generated on these deformed CT images. The physical QA phantom (undistorted) was positioned during the adaptive phase (further discussed in the below section 'Adaptive treatment delivery'), and a CBCT scan was acquired. This CBCT scan was then registered with the pCT images. The Ethos OART system transferred contours from the pCT to the CBCT, deforming the pCT to align with the session CBCT to create a sCT. Subsequently, an adaptive treatment plan was generated based on these transferred contours and the sCT and delivered to the phantom. The dosimetry of the delivered treatment was measured using detectors placed inside the phantom. The accuracy of the Ethos OART system was evaluated based on various parameters (further discussed in the below section 'Evaluation').

Preplanning

A CT scan of the RUBY phantom, incorporating inserts and a semiflex-3D ionization chamber, was performed using a CT simulator (Somatom Definition AS, Siemens Healthineers, Germany). The scan parameters included a slice thickness of 3 mm, a field of view of 500 mm × 500 mm (512 × 512 pixels), and a voltage of 120 kV. To reduce artifacts caused by the ionization chamber, metal artifact reduction techniques were applied during the CT reconstruction process. For the OCTAVIUS and ArcCHECK phantoms, planning utilized virtual CT images provided by their respective vendors. The Hounsfield unit (HU) /mass density values of these virtual CT images were adjusted to 25 HU/1.047 g/cm3 for OCTAVIUS and 270 HU/ 1.185 g/cm3 for ArcCHECK. These specific HU values were determined based on measurements taken with the phantom on the Ethos machine. In addition, absolute dose calibration for the OCTAVIUS and ArcCHECK was performed following the guidelines provided by the vendors.

All the phantom images were imported into the Ethos TPS. Dummy OAR structures, such as the bladder and rectum, and target structures, such as the prostate, were manually delineated on OCTAVIUS and ArcCHECK phantom images. In addition, the abdomen site was chosen for the RUBY phantom to illustrate our approach compatibility with other clinical scenarios involving OARs such as kidneys, liver, bowel, heart, spinal canal, and duodenum, as well as the target structure (stomach). From the target, a PTV was derived with an additional margin (5 mm). These original CT images and contours served as a baseline reference for subsequent evaluations.

The original CT images of the phantoms, along with their corresponding contours, were exported from the Ethos TPS. MATLAB (MathWorks, Natick, MA, USA) was then used to intentionally distort the CT images and contours, thereby simulating interfractional anatomical variations. Subsequently, these distorted CT images and contours were imported into the Ethos TPS for preplanning.

Clinical objectives were defined, specifically targeting 60 Gy/20 fractions for the prostate and 54 Gy/27 fractions for the abdomen. The deformed CT images and the contours for the RUBY, OCTAVIUS, and ArcCHECK phantoms can be accessed on our GitHub repository: https://github.com/yoganathansa/Online-Adaptive-Radiotherapy-QA.

After this, an optimization procedure was executed, followed by the final treatment plans generation which used three full arcs for both the RUBY and ArcCHECK phantoms. For OCTAVIUS, a custom beam geometry was utilized, consisting of an arc spanning from 0° to 70° and a half-arc from 70° to 290°. The starting gantry angle of "zero" was specifically chosen to accurately initialize the OCTAVIUS 4D-rotation unit, ensuring precise alignment and synchronization during beam delivery. To avoid beam entry through the posterior air cavity, all beams were directed anteriorly. Typically, the posterior air cavity is not included in the virtual CT for patient-specific QA with OCTAVIUS. However, including it was essential for accurate deformable image registration during the adaptive session.

Adaptive treatment delivery

A CBCT scan of the phantoms was acquired with iterative reconstruction using Ethos. In the case of the OCTAVIUS, the array was aligned with the gantry at zero degrees, and subsequent rotation was fixed during CBCT acquisition.

After the CBCT acquisition, the Ethos system automatically generated OAR. However, manual adjustments were made to these autocontours due to discrepancies between phantom and human anatomy. The PTV was generated based on predefined margins. The Ethos employed deformable image registration to fuse the pCT (deformed phantom) with the CBCT (undistorted phantom), generating a sCT for dose calculation purposes.

Treatment plans were created using consistent beam geometries as in preplanning, employing the Acuros algorithm for dose calculations. Two plans were generated: a scheduled plan the original plan recalculated on the sCT and an adaptive plan that underwent complete reoptimization. Adaptive plans were chosen for all phantoms. Both clinical and technical approvals were done for the adaptive plan and it was transferred to the Mobius system for secondary dose calculation verification. For the OCTAVIUS measurement, the rotation lock was released, allowing the OCTAVIUS rotation to initialize with a 0° gantry. Furthermore, the scheduled plans were delivered in a separate session to illustrate how the dose variations resulted from the deliberate deformation.

Evaluation

Dosimetric accuracy was evaluated by comparing doses measured in the phantom with those calculated by the TPS for both scheduled and adaptive sessions, using gamma evaluation 2%/2 mm and 3%/3 mm with a 10% tolerance. For contouring evaluation, we adhered to the AAPM Task Group 132 guidelines,[19] comparing contours from the online session with those from the reference nondeformed CT images using the dice similarity coefficient and mean distance agreement (MSD) metrics. This comparison also assessed the

effectiveness of deformable image registration and the overall adaptive workflow. In addition, sCT accuracy was determined by comparing sCT images with the original nondeformed CT images, using mean error (ME), mean absolute error (MAE), and standard deviation.

Results

Figures 3 and 4 illustrate the results of the preplan, scheduled, and adaptive plans using the OCTAVIUS and ArcCHECK phantoms, whereas Figure 5 displays images of the RUBY phantom. For the OCTAVIUS phantom, the preplan was based on a deformed (shrunken) phantom, whereas the scheduled plan was delivered to an undistorted phantom. This discrepancy resulted in a lower-than-expected dose compared to the preplan. In contrast, the ArcCHECK phantom's deformed state, which included an enlarged region, led to a higher dose than anticipated during the scheduled delivery. However, the adaptive plans successfully addressed these deformations, ensuring accurate dose distributions for both phantoms. Table 1 presents the gamma evaluation results for each phantom. For the RUBY phantom, which used an enlarged CT image for the initial plan, the scheduled plan showed an increased dose with a point dose deviation of + 13.5%. The adaptive plan, which corrected for the geometric discrepancies, achieved a point dose deviation of − 0.35%, indicating precise dose delivery.

For the OCTAVIUS and ArcCHECK phantoms, the Dice values for body contours were >0.99, with the MSD being <2 mm.

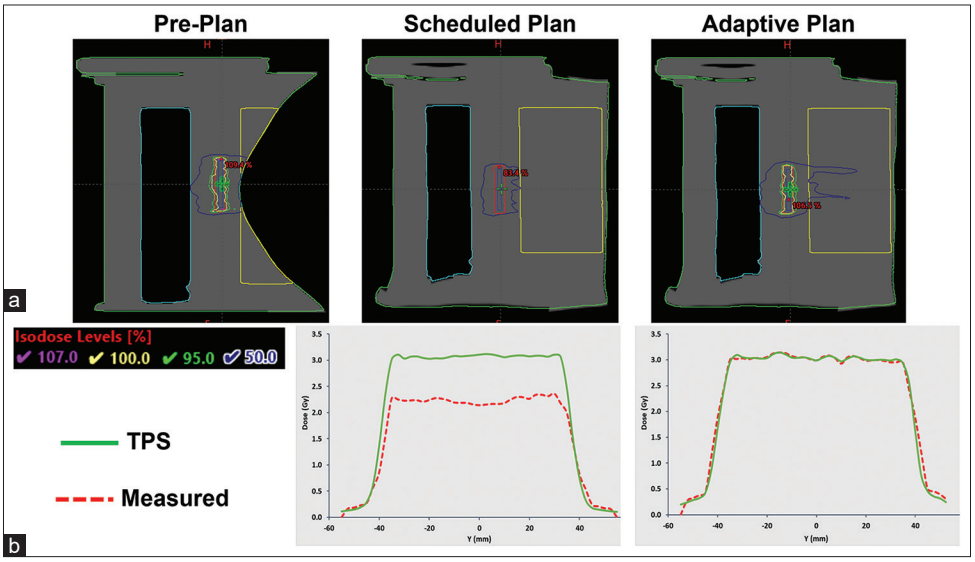

Figure 3: OCTAVIUS phantom results for preplan, scheduled, and adaptive plans, (a) sagittal computed tomography image views and (b) vertical profiles across the center of the target. TPS: Treatment planning system

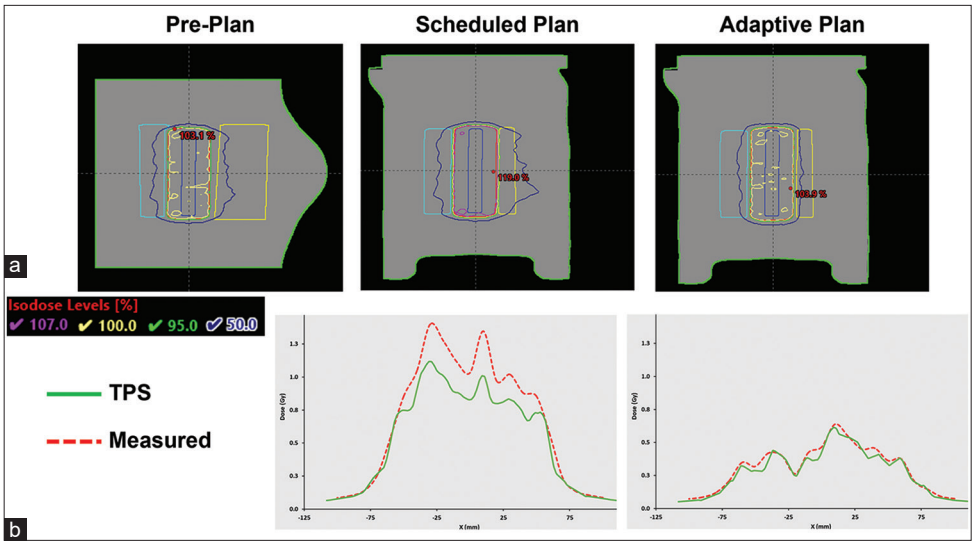

Figure 4: ArcCHECK phantom results for preplan, scheduled, and adaptive plans, (a) sagittal computed tomography image views and (b) vertical profiles across the center of the target. TPS: Treatment planning system

The sCT ME and MAE values were 5 HU and 11 HU for the ArcCHECK, and 3 HU and 6 HU for the OCTAVIUS.

The results of the RUBY phantom, which included various density inserts, are detailed in Table 2. The MSD for body contours and inserts was below the TG-132 recommended limit of 3 mm. Larger inserts generally achieved acceptable Dice values (≥0.8) and fell within the limits established by the TG-132 guidelines. However, smaller inserts, such as those with diameters of 1 cm and 1.5 cm, as well as a chamber volume, showed Dice values in the range of 0.5–0.6. Despite these uncertainties for small-volume inserts, the dosimetric results (point dose < 0.5%) confirmed that they did not impact the accuracy of the OART delivery.

Discussions

We developed an E2E QA procedure for Ethos OART and demonstrated its feasibility using standard QA phantoms: OCTAVIUS, ArcCHECK, and the RUBY phantom. This procedure allowed us to evaluate session contours, sCT accuracy, and dosimetry for Ethos OART delivery. Our results showed high accuracy, with gamma pass rates exceeding 96% (2% local/2 mm) and point dose deviations < 0.5%.

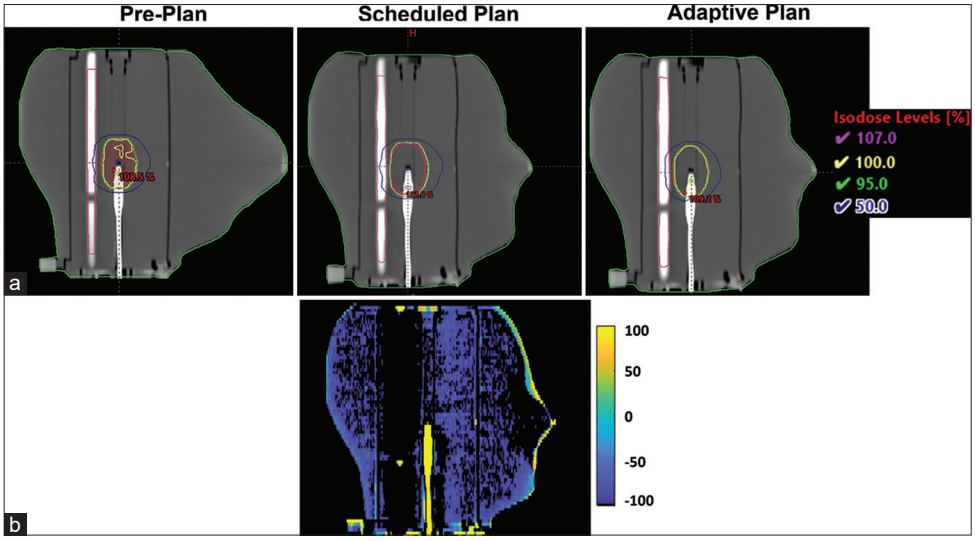

Figure 5: RUBY phantom, (a) Sagittal computed tomography (CT) image views of preplan, scheduled, and adaptive plans, (b) CT difference map hounsfield unit between the original nondeformed CT and synthetic CT

Table 1: Gamma evaluation results

Normalization	Criteria	OCTAVIUS		ArcCHECK	
		Scheduled	Adaptive	Scheduled	Adaptive
Local	2%/2 mm	21.2	97.2	30.1	96.1
	3%/3 mm	32.8	99.0	41.5	97.8
Global	2%/2 mm	22.6	98.1	34.3	97.4
	3%/3 mm	35.1	99.2	46.8	98.2

Table 2: RUBY phantom evaluation results

Structures	sCT accuracy			Contouring accuracy	
	Mean error (HU)	Mean absolute error (HU)	SD (HU)	Mean surface distance (mm)	Dice
External body	8.1	27.1	21.7	2.3	0.96
MR-insert (2.5 cm)	12.0	19.2	1.4	2.9	0.80
MR-insert (1 cm)	43.4	47.3	4.1	2.8	0.55
MR-insert (1.5 cm)	27.5	35.7	2.3	2.8	0.60
CT-insert (brain)	15.3	20.3	1.8	2.5	0.82
CT-insert (lung)	−5.6	5.7	1.4	2.9	0.86
CT-insert (bone)	98	122.8	115.2	2.5	0.81
Chamber volume	50.9	95.8	17.0	2.3	0.50
PTV	−4.4	140.2	110.5	2.0	0.81

PTV: Planning target volume, CT: Computed tomography, MR: Magnetic resonance, HU: Hounsfield unit, SD: Standard deviation, sCT: Synthetic CT

Table 3: Comparison of our proposed end-to-end quality assurance approach with the traditional deformable phantom approach

E2E tests	Approach	Benefits	Drawbacks
Deformable phantoms	Initial planning on the undistorted phantom image and the adaptive session on the distorted phantom	Traditionally used, easy to understand Anthropomorphic phantoms – simulate actual human anatomy	Cost Availability limited Sometimes, limited distortion options
Proposed E2E approach	Initial planning on the distorted phantom image and the adaptive session on the undistorted phantom	Cost-effective - no need for new phantoms - existing phantoms can be used-Distortion scenarios are not limited	Approach is opposite to the traditional dynamic phantom approach, which may make it slightly difficult to understand If the phantom is not anthropomorphic, actual human anatomy cannot be simulated

E2E: End-to-end

Contouring accuracy, measured by the Dice coefficient, was > 0.9, and the sCT accuracy for body contours, indicated by the MAE, was below 27 HU.

The E2E QA procedure we propose is well-suited for integration into routine monthly QA and is particularly valuable during major system upgrades or maintenance. A significant advantage of this method is its simplicity and practicality, as it leverages commonly used QA phantoms in routine radiotherapy practices. Although our study used three specific phantoms, the methodology can be adapted to any phantom with appropriate inserts for contour evaluation and detectors for dose verification. While anthropomorphic phantoms would be an ideal choice for OART QA, their limited availability makes our method a practical alternative for initial evaluations and provides a solid foundation for further investigation. While the manual deformations used in this study were notably larger than those typically encountered in clinical scenarios, this approach was intentional to rigorously test the Ethos system's adaptive capabilities. Defining what constitutes an adequate deformation for OART QA remains an important and open question. Developing guidelines or benchmarks for "good" deformation would be instrumental in standardizing QA procedures across various sites and represents a crucial area for future research.

A few studies have developed custom dynamic deformable phantoms for evaluating OART delivery.[9-13] Table 3 provides a concise comparison between our proposed approach and the traditional deformable phantom method. Other common QA methods for OART often rely on secondary dose calculations conducted before treatment delivery.[20,21] While these secondary calculations provide useful information about dose distribution, they do not replace E2E QA procedures involving direct dose measurement and treatment workflow assessment, as outlined in our study. Maraghechi *et al*.[22] developed a QA procedure to assess the dose accumulation capability of Ethos OART using an electron density phantom and an anthropomorphic pelvis phantom. They compared manual dose accumulation results with those generated by the Ethos TPS and found that over 99% of pixels passed the gamma evaluation (2%/2 mm). While their approach provides a direct method for verifying dose accumulation, it does not encompass the full spectrum of QA necessary for adaptive radiotherapy.

Conclusion

Our proposed QA procedure offers a straightforward and effective method for validating OART systems. It is suitable for routine monthly QA assessments and can be utilized during significant system upgrades or maintenance, thereby enhancing confidence in the clinical effectiveness and operational performance of OART systems.

Acknowledgment

The authors would like to acknowledge Varian Medical Systems for their support through a research grant.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

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