Development of a Phantom-Based End-to-End QA Workflow for Online Adaptive Radiotherapy incorporating High-Resolution 2D Detector Measurements

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ABSTRACT

Purpose: The development and assessment of an end-to-end quality assurance (QA) procedure for online adaptive radiotherapy (oART), integrating high-resolution detector-based dose verification with interchangeable anthropomorphic phantom inserts.

Methods: A new QA workflow was developed using the myQA® SRS phantom with a 2D CMOS detector and a custom 3D-printed anthropomorphic pelvis insert. A synthetically deformed planning CT was created to mimic anatomical changes, serving as the basis for the adaptive workflow. The procedure spans CBCT acquisition, manual contour adaptation, adaptive plan generation, and dose delivery. Measured and calculated dose distributions were compared using Gamma Analysis. Workflow reproducibility was assessed through repeated measurements, and the procedure's sensitivity to errors was examined by modifying gantry and collimator angles, monitor units (MU), phantom positioning, and CBCT presets. Following AAPM TG-119 methodology, Gamma Pass Rates (GPR) were evaluated using Confidence Limits as plan-specific thresholds.

Results: Repeated workflow executions yielded consistently high GPR values across all criteria (3%/2mm, 2%/2mm, 3%/1mm, 2%/1mm). Confidence Limits served effectively as thresholds for detection of plan deviations. Most simulated errors, including gantry angle deviations >3°, collimator angle deviations ≥3°, MU changes ≥3 %, incorrect CBCT presets, and 3 mm setup shifts, were detectable. Minor variations, such as 1° angular changes or 1 % MU alterations, were not detected, with GPRs remaining above the respective Confidence Limit. Manual contouring was necessary, as Ethos auto-contouring did not generate accurate contours on the phantom geometry.

Conclusions: The developed workflow is practical, reproducible, and capable of identifying plan-specific deviations in Ethos oART. High-resolution dose measurements and Gamma analysis provided robust verification of adaptive dose calculation and delivery. Although constrained by manual contouring requirements and data-handling limitations of the Ethos system, this approach offers a viable solution for implementing clinical end-to-end QA in oART.

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INTRODUCTION

Motivation

- Anatomical changes during treatment require daily adaptation in **online adaptive radiotherapy (oART)**, plan-specific QA cannot be performed with measurements during on-couch adaptation.
- Recent guidelines[1] recommend **end-to-end QA including independent dose measurements.**

Objective

- A **detector-based end-to-end QA workflow** (figure 1) using an interchangeable **insert,** combining a **virtually deformed CT with high-resolution measurements.**
- An evaluation of the workflow's **plan-specific errors detectability** using gamma pass rates (GPRs) determined with different gamma criteria.

METHODS AND MATERIALS

Equipment & Treatment System (figure 2)

- 3D-printed **anthropomorphic insert**, based on a **pelvis anatomy CT** (Phantom X, Berlin, Germany).
- Water-equivalent myQA® **SRS phantom** with rotatable slot (IBA Dosimetry, Schwarzenbruck, Germany).
- MyQA® 12 x 14 cm^2 **SRS detector array** (IBA Dosimetry) with **0.4 mm resolution.**
- MyQA® software (IBA Dosimetry) for measurement acquisition and analysis.
- **Virtually deformed CT** of pelvis insert and SRS phantom geometry.
- **Ethos** adaptive radiotherapy platform (Varian Medical Systems, Palo Alto, USA) and CBCT imaging with **HyperSight.**

Workflow Validation

1. **Ethos auto-contouring** on **planning CT** and **CBCT** of the workflow.
2. **Reproducibility** by comparison of calculated and measured dose distribution (**gamma criteria:** 3%/2mm, 2%/2mm, 3%/1mm, 2%/1mm).
3. **Error sensitivity** by plan modifications of gantry/collimator angle, MU scaling, detector misalignment and CBCT preset variations. Definition of **confidence limits**, according AAPM TG-119 methodology[2]. **DVH-based evaluation** of dosimetric impact on PTV and OARs.

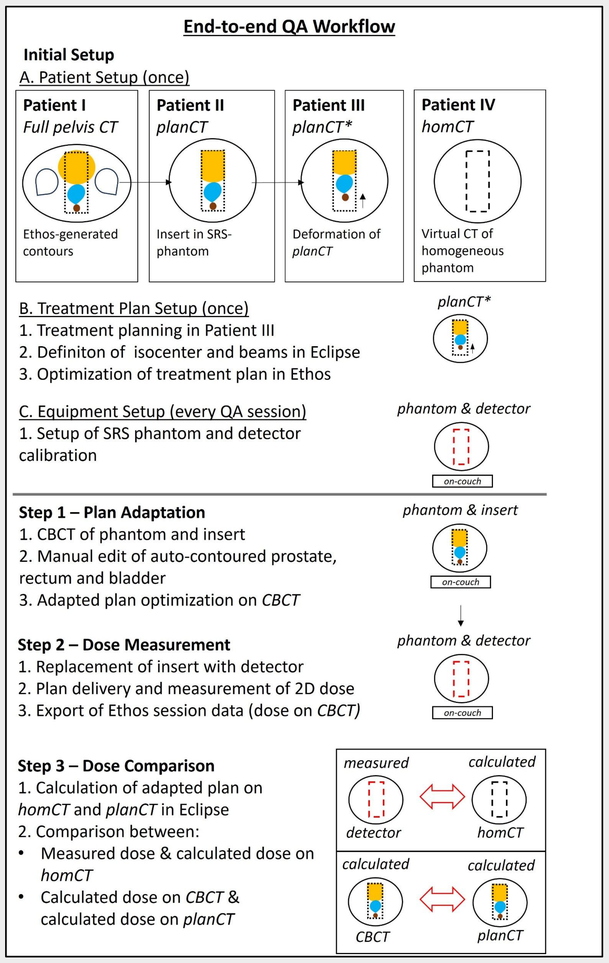

Figure 1. End-to-end QA workflow for Ethos

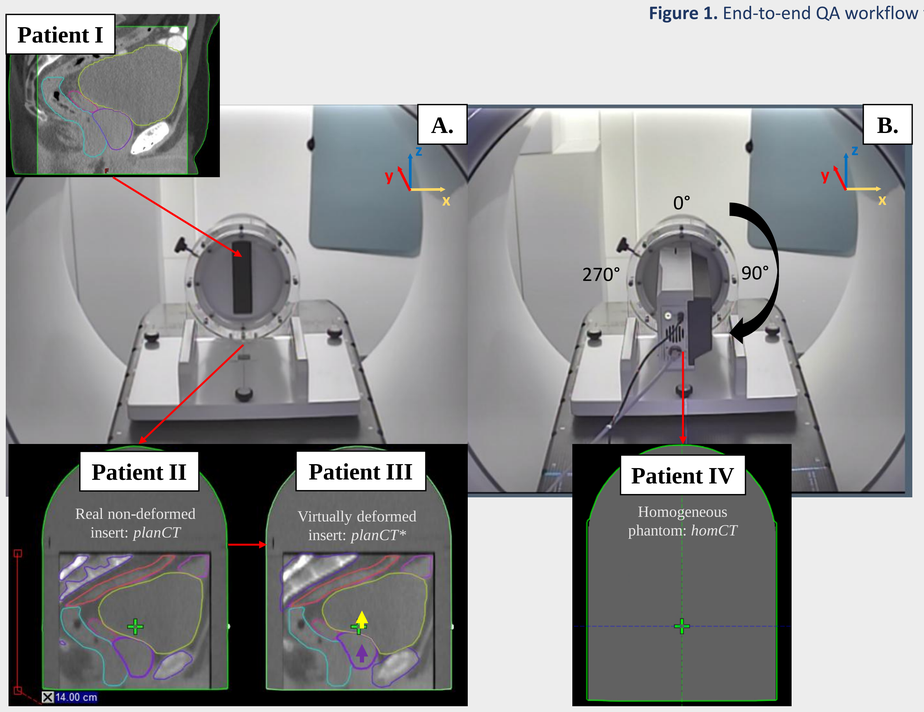

Figure 2. Workflow setup - SRS phantom with pelvis insert (A) and detector (B) positioned on Ethos couch

RESULTS

1. Ethos auto-contouring:

- **Credible** contouring on **full pelvis** planning CT.
- **No** contouring on (deformed) **insert in phantom** geometry.
- **No credible** contouring on **CBCT** (contours were mainly propagated), hence **manual** contouring required.

2. Reproducibility:

- **High agreement** between calculated and measured dose distributions across **all gamma criteria** with **mean GPRs above** the **confidence limit.**

3. Error sensitivity & DVH-based evaluation (table 1):

- Only **minor** deviations reside **above confidence limit.**
- **Larger** deviations = **detectable & larger** dosimetric impact, **minor** deviations **= undetectable & small** dosimetric impact

Table 1. Calculated GPRs and DVH parameters for modified plans

Changed Parameter	Magnitude	GPR (%)				DVH Parameter	
		3%/2mm	2%/2mm	3%/1mm	2%/1mm	PTV-D98% (|Δ%|)	OAR-V95% (|Δ%|)
	Confidence Limit	**99.8**	**98.1**	**96.7**	**93.5**		
Gantry	1°	100.0	99.0	99.2	96.4	0.1	1.4
Gantry	3°	99.8	99.0	98.5	95.1	1.2	5.5
Gantry	5°	97.6	95.7	94.3	89.8	3.3	10.6
Gantry	7°	92.1	88.6	87.1	81.5	7.1	17.0
Gantry	9°	84.3	80.2	78.5	72.5	12.7	24.8
Collimator	1°	99.9	98.4	98.2	94.3	0.5	0.0
Collimator	3°	98.1	95.4	93.6	87.4	2.8	5.6
Collimator	5°	92.8	87.8	83.8	74.4	6.4	16.7
Collimator	7°	84.0	77.0	72.1	61.3	11.8	25.9
Collimator	9°	73.3	63.6	60.8	51.7	18.1	35.2
MU	1 %	100.0	98.4	98.7	93.6	1.0	5.6
MU	3 %	93.2	74.0	83.9	60.1	3.1	14.8
MU	5 %	68.8	60.1	55.9	42.3	5.3	24.1
MU	7 %	59.2	52.1	42.6	31.2	7.5	31.5
MU	9 %	51.6	47.0	32.7	25.8	9.9	40.7
Cranial	3 mm	81.6	74.7	59.9	51.7	7.1	55.6
Anterior	3 mm	79.1	72.7	66.1	57.3	10.1	38.9
Right	3 mm	91.2	87.5	84.8	78.6	4.9	2.3
CBCT	140 kV	98.5	96.8	92.3	87.4	2.5	3.8
CBCT	100 kV	93.1	90.9	82.6	76.6	23.1	10.8
CBCT	80 kV	96.4	93.5	83.9	77.1	12.7	8.6

DISCUSSION

- **High** and **consistent GPRs** confirm robustness and reproducibility of proposed workflow.
- **Virtually deformed CT** enables simulation of inter-fractional changes with single insert.
- **Plan-specific errors** are **detectable** via high-resolution measurements.
- **Good agreement** between **GPR sensitivity** and DVH-based **dosimetric impact.**
- **Confidence limits** proved suitable for error detectability.
- **Limitations**: No auto-contouring on insert, phantom geometry not fully patient-equivalent, manual data handling

CONCLUSIONS

- Workflow is **clinically feasible**, **reproducible** and executable within **treatment-like timeframes** as end-to-end QA for oART with **Ethos** system.

REFERENCES

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