Design and Validation of a MR-Compatible Deformable and Multi-Detector Phantom for QA and End-to-End Validation

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ABSTRACT

Purpose: Validation of online plan adaptation is complex, especially in the context of a MR-Linac where there are very few commercial phantoms available. The purpose of this study is to design and manufacture a modular, simple and low-cost phantom for End-to-End validation of the adaptive workflow and machine QA on a Unity (Elekta,UK).
Methods: The phantom is made of a water-filled transparent plastic jar which is sealed with a 3D-printed detector-specific holder. Compatible detectors include ionization chamber (IC) CC13 (IBA, Belgium), and plastic scintillation detector (PSD)(Medscint, Canada). A silicone insert can be placed over the detector to provide contrast in the MR image. Multiple inserts can be used to simulate changes between simulation and treatment, thus testing the dosimetric accuracy of the adaptive workflow. CT-scans of the phantom with PSD and IC were acquired. Geometric validation was achieved by measuring the offset between the center of the detectors and the center of the jar on the 3D images. Dosimetric validation was done by comparing calculated dose from the treament planning system (TPS) Monaco(Elekta, UK), on the corresponding CT-scan, to dose measured with the PSD calibrated on a conventional Linac. Also, MR images of the phantom with the silicone insert were acquired on the Unity.
Results: CT-scans show that both detectors positions are within 1 mm from the phantom center. Dose calculated in Monaco TPS showed good agreement to PSD measurements <1% for simple fields (10x10, 5x5, AP and PA). The phantom MR images showed bright contrast between the silicone insert and the water, making it easy to delineate.
Conclusion: Geometric and dosimetric testing show that this new phantom has the potential to assess the whole adaptive workflow. Furthermore, the integration of a multi-probe scintillator could allow dose measurement in the target volume and in the OAR simultaneously.

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INTRODUCTION

Adaptive radiation therapy (ART) implies the creation of a new plan (MLC sequence and Monitor Units) at every fraction, based on the daily contours. This contouring process can be done either on magnetic resonance (MR) or cone-beam computed tomography (CBCT) imaging. To validate the system capabilities to adapt a treatment plan, a deformable phantom can be used to mimic interfraction anatomical differences[1]. The purpose of this study was to develop a deformable phantom of male pelvis suitable for both imaging modalities.
The Eliphant is a low-cost phantom manufactured from readily available materials. Its modular design supports both end-to-end (E2E) testing and routine machine quality assurance (QA), particularly for the Unity MR-Linac (Elekta, UK).

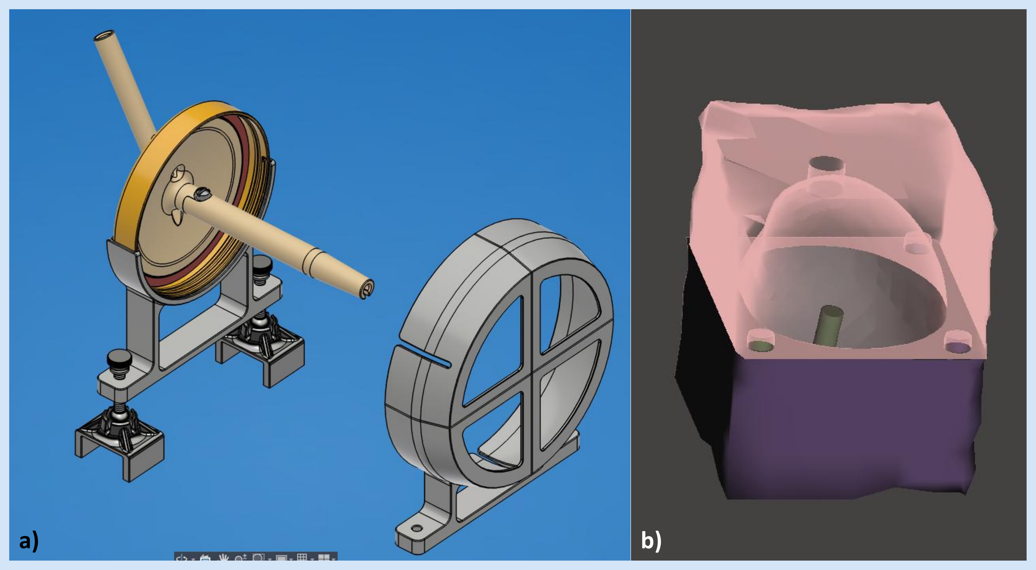

Figure 1. : a) Support parts with the watertight PSD holder and integrated cap b) 3D design of a prostate mold. It is designed so the detector fits in its center.

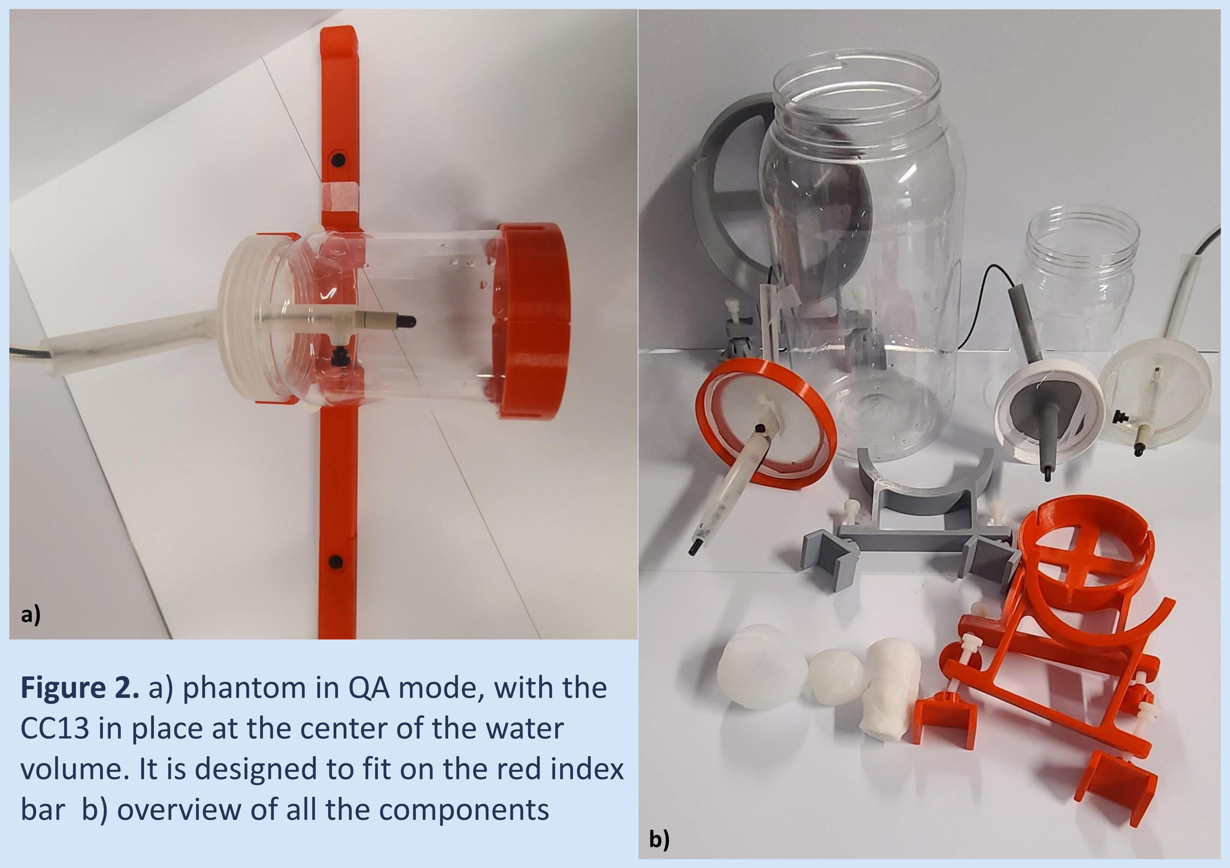

Figure 2. a) phantom in QA mode, with the CC13 in place at the center of the water volume. It is designed to fit on the red index bar b) overview of all the components

METHODS AND MATERIALS

Phantom design

- Water-filled phantom with a transparent plastic housing
- Generic polylactic acid (PLA) was used to fabricate custom 3D-printed support structures, while Tough 1500 resin was employed for stereolithography (SLA) printing (Form 2B, Formlabs) of watertight components.
- The phantom is compatible with both a CC13 ionization chamber (IC) (IBA, Belgium) and a plastic scintillation detector (PSD) (Medscint, Canada) through the use of detector-specific 3D-printed holders. An oblique chimney facilitates the evacuation of residual air during sealing, preventing the formation of air bubbles near the detector or along the beam path.
- MR- and kV-visible targets were fabricated from Dragon Skin silicone (Smooth-On) cast into 3D-printed molds derived from anatomically realistic organ geometries.

Phantom applications

- Machine QA : Output as a function of gantry angle and couch attenuation, with the CC13 in place.
- Adaptive workflow validation : based on PSD measurement inside a prostate silicone target

Geometric Validation

- Geometric validation performed by measuring detector-to-phantom center offsets on CT images.

Dosimetric validation

- Carried out by comparing Monaco TPS dose calculations with PSD measurements for simple open fields, and modulated prostate plans

RESULTS

Machine QA: When assembled for QA, the IC center is within 0.5 mm from the phantom center, as measured on the CT-scan. Output as function of gantry angle was within 0.7% from beam data collection performed by Elekta during installation. Also, couch attenuation in the TPS was validated against measurements at gantry angle of 180 and difference of less that 0.5 % was found.

Workflow validation: A clinical plan template, with aperture and monitor units, was used to generate a reference plan on Monaco (Elekta, UK) treatment planning system (TPS), as shown on figure 3. Based on this plan, multiple scenarios were tested : Adapt To Position (ATP), Adapt-to-Shape (ATS) and completion plan (CP). In all cases, the dose to the detector was calculated by Online Monaco TPS. All PSD-based measurements were within 2% from the dose calculated by the TPS. Tracking proved to stable (jitter < 0.3 mm), as the silicone insert provided a good contrast for the registration algorithm. Figure 4a) shows the contrast in a T2-weighted image of the phantom with a silicone insert.

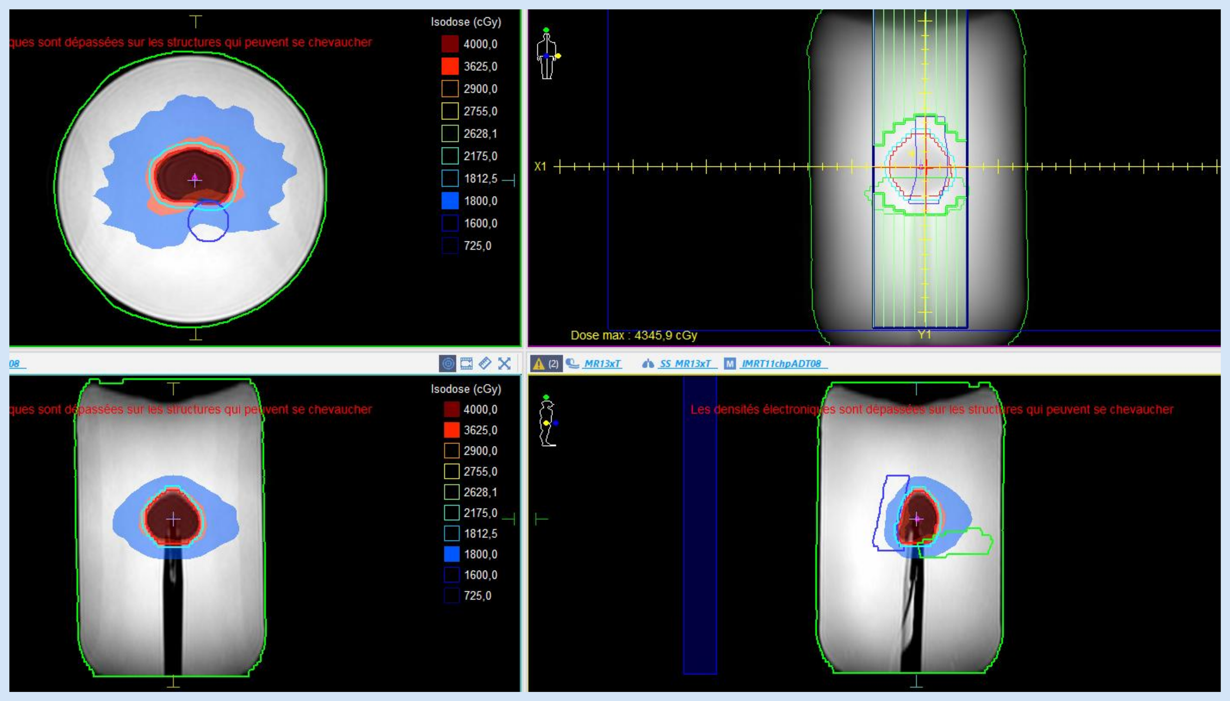

Figure 3. : Screenshot from the TPS showing an overlay of the dose and the tracking structure, in red. The blue cross corresponds to the center of the PSD.

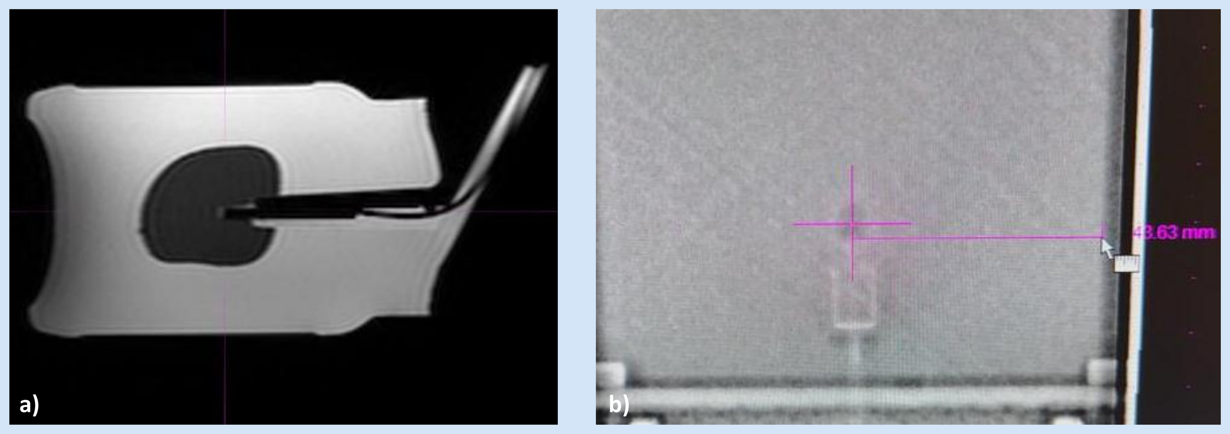

Figure 4. : a) T2-weighted image from the MR-Linac of the PSD inside the silicone insert b) MR-Linac portal verification image of the phantom with the CC13. The cross hair shows the machine imaging isocenter

DISCUSSION

The presence of a magnetic field induces an electron return effect (ERE), where an air bubble near a detector can affect dose measurement. Using the detectors inside liquid water can mitigate this problem, thereby improving accuracy and reproducibility. The use of an oblique chimney is effective to eliminate air inside the phantom.

In QA mode, detector alignment with the phantom and machine isocenter is crucial, as positional offsets may introduce measurement uncertainties. By design, the IC is always at the center of the phantom. Also, the Eliphant was designed to minimize positioning time. The phantom is mounted on a custom indexing bar that fixes its longitudinal position, with reference marks used to guide lateral alignment.

In E2E mode, precise phantom positioning is not critical, as a new treatment plan is generated based on the phantom's actual setup geometry. Since the detector is visible on the acquired images, the corresponding calculated dose can be directly extracted from the adaptive plan of the day. The silicone inserts can be manufactured in various shapes, allowing the simulation of anatomical changes between the reference plan and daily treatment. Alternatively, intentional shifts in phantom positioning can be used to mimic anatomical variations. This phantom therefore enables quality assurance of the adaptive workflow by comparing the dose calculated from the online-adapted plan with the dose actually delivered. it was used to validate both the plan completion workflow and the overall accuracy of the multileaf collimator (MLC) following a baseline shift.

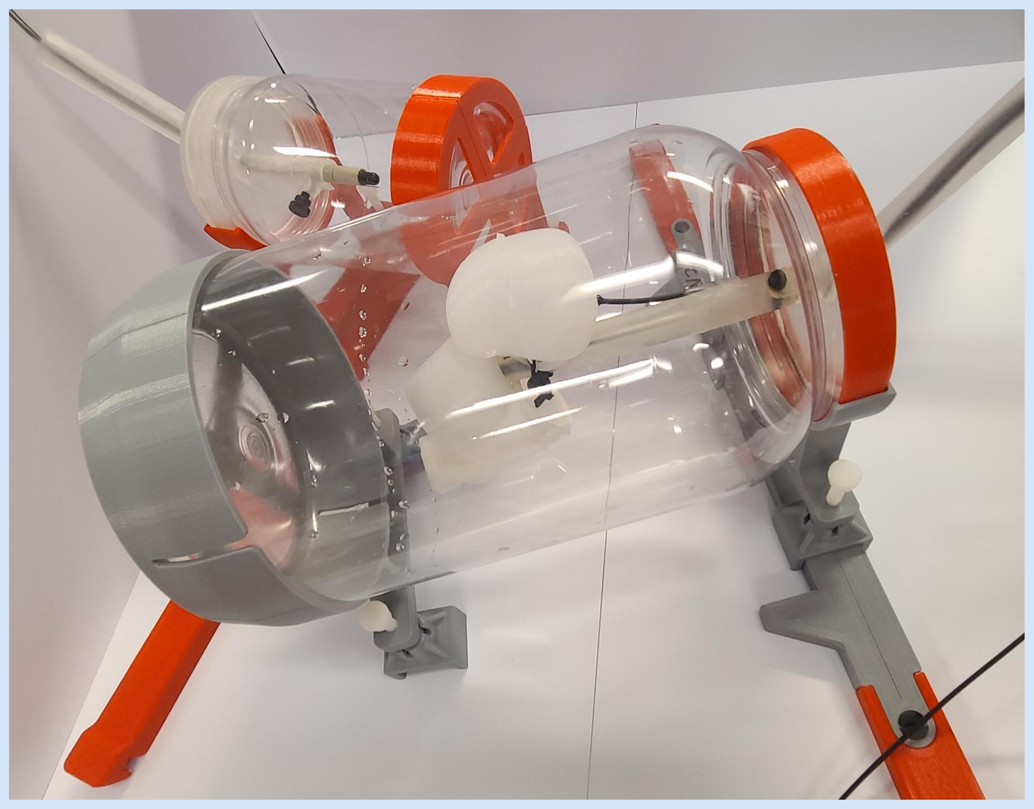

Figure 5 : E2E inserts made of three different pieces : a prostate for tracking, a bladder (on top of the prostate) and a tube, mimicking a rectum.

CONCLUSIONS

The Eliphant was successfully used to commission a new Elekta Unity system. It simplifies the workflow validation and speeds up the machine QA. This modular phantom is suitable for ionization chamber or plastic scintillator and can be modified to allow film dosimetry and motion management QA.

REFERENCES

1. J.M Cunningham et al / J Appl Clin Med Phys (2018) 20(1)265–275