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A Novel, Rigid Phantom for Comprehensive End-To-End Verification of Adaptive Radiotherapy Systems

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INTRODUCTION

Online adaptive radiotherapy (ART) techniques are currently experiencing rapid technological development and clinical implementation to better address daily changes in anatomy and positioning. Numerous subsystems comprise the ART workflow: deformable image registration is utilized to propagate contours onto the daily acquired image which is then used for optimization and dose calculation of an adapted plan. Tools capable of evaluating these subsystems individually and in combination will be integral to the implementation of online ART technologies.

AIM

To develop and demonstrate the use of a novel, rigid phantom for comprehensive end-to-end verification of online adaptive radiotherapy systems. Created entirely in-house, the phantom was designed to validate the complete process and all associated subsystems of emerging ART technology through end-to-end testing.

METHOD

Phantom Construction

- High-density polyethylene slabs with multiple acrylic and high-density insertable objects
- Objects are related through known differences in size, position, and/or shape (Figure 2)
- Allows for multiple types of dosimeters (e.g. various ion chambers and OSLDs) to be placed in the center of each object
- Film can be placed between the phantom's slabs to measure axial dose distributions

Treatment Planning System Evaluation

- Clinical plans were created in the treatment planning system (TPS) for a reference phantom configuration
- The phantom was rotated in the TPS to calculate the reference plans on an alternative configuration, simulating a change in anatomy
- An adapted plan designed for this alternative configuration was created

Phantom Measurements

- An ion chamber was used to take measurements in the center of the target object for treatment plans designed for both the reference and adapted phantom configurations
- The measurements were compared to the TPS calculated dose

RESULTS

Phantom Design

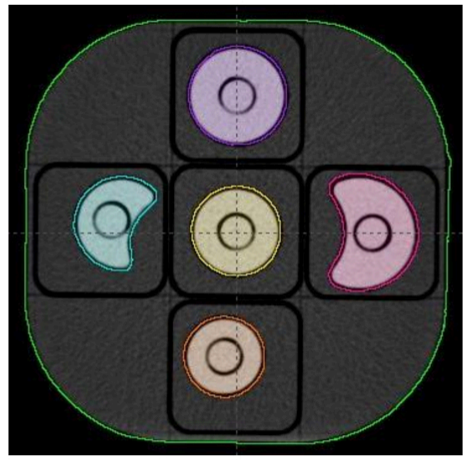

Figure 1: Axial CT slice of phantom with multiple peripheral objects and central soft-tissue target object

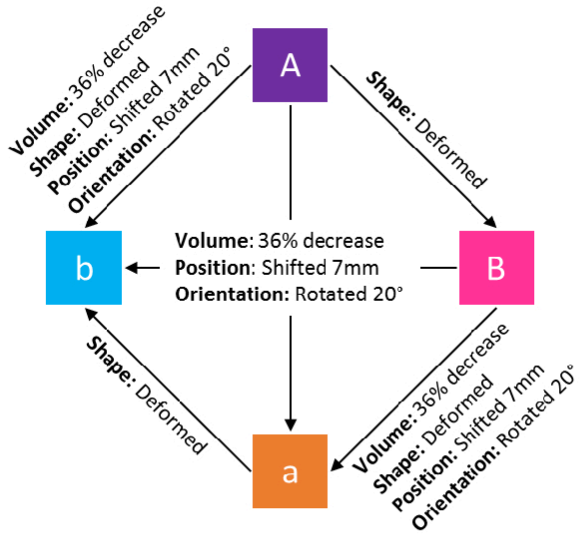

Figure 2: Quantitative morphological relationships between peripheral objects of Figure 1

Treatment Plan Evaluation

Target Analysis		Treatment Plan Object A	Treatment Plan Object B	Treatment Plan Object a	Treatment Plan Object b
Treatment Delivery Object	A	**95.0** *0.97*	**79.5** *1.03*	**59.3** *0.65*	**54.9** *0.65*
Treatment Delivery Object	B	**79.5** *0.94*	**95.0** *0.99*	**50.5** *0.63*	**54.8** *0.62*
Treatment Delivery Object	a	**90.8** *1.47*	**82.6** *1.56*	**95.0** *0.96*	**81.9** *0.98*
Treatment Delivery Object	b	**85.2** *1.48*	**88.3** *1.57*	**83.0** *0.99*	**95.0** *0.98*

Table 1: Target coverage and conformity of plans generated on one peripheral target (columns) and delivered on another object (rows). Plan coverage (V100%) is in bold, and the conformity index is in italics.

Table 2: Mean OAR dose to the object located at the top of the delivered plan from the TPS relative to that of the reference plan. All plans were generated to target the central object.

OAR Analysis		Treatment Plan Object A	Treatment Plan Object B	Treatment Plan Object a	Treatment Plan Object b
Treatment Delivery Object	A	100%	103%	94%	94%
Treatment Delivery Object	B	99%	100%	94%	92%
Treatment Delivery Object	a	109%	111%	100%	101%
Treatment Delivery Object	b	107%	109%	100%	100%

ART Workflow Demonstration

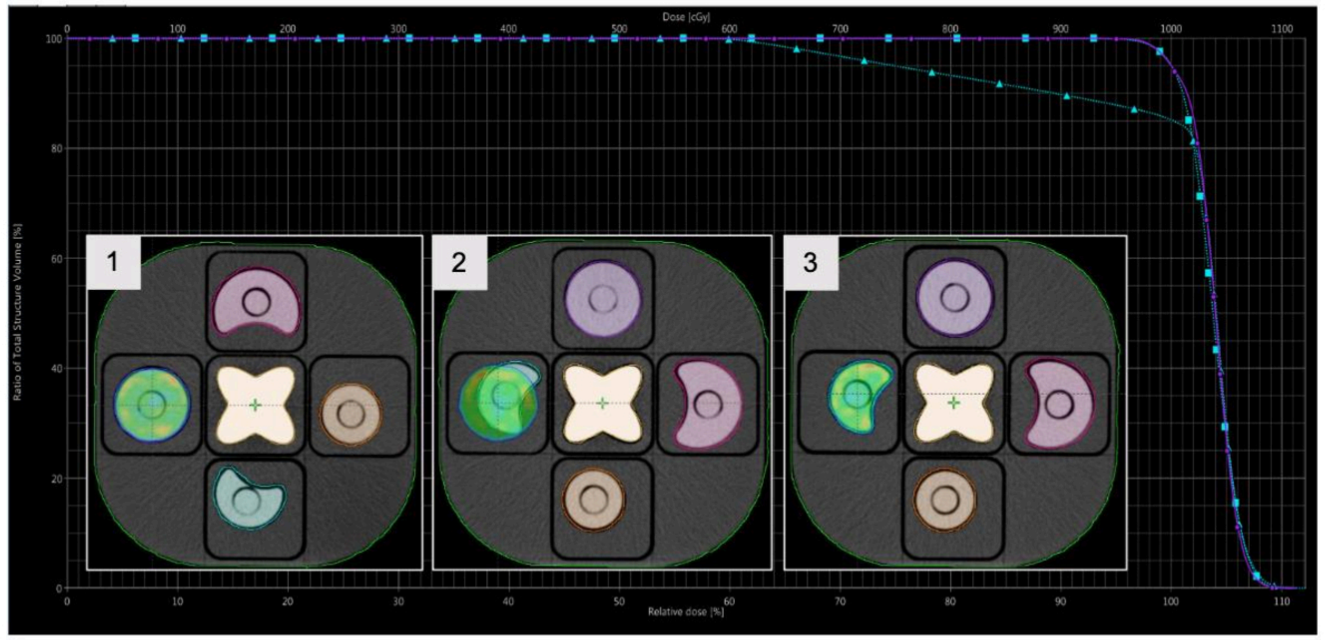

Figure 3: Example ART workflow using the phantom to change target geometry.

1. *A treatment plan created on object A delivered to object A. Dose ≥ 95%. DVH: purple dots.*
2. *The plan created on object A delivered to alternative object b. This simulates a change in anatomy which compromises target coverage and prompts adaptation. Dose ≥ 95%. DVH: blue triangles.*
3. *An adaptive plan created on object b delivered to object b. This regains the desired target coverage. Dose ≥ 95%. DVH: blue squares.*

DISCUSSION

- We have successfully used our in-house phantom to validate the ART process including imaging, contouring, plan optimization, and dose calculation.
- The phantom's rigid nature allowed for the precise definition of geometric relationships between anatomic objects that simulate changes in targets (high-density insert) and organs at risk (soft-tissue insert), demonstrating the need for treatment plan adaptation.
- Wide variations were seen in the coverage and conformity of the original plans with the high-density object when compared to the adapted plans (as seen in Table 1), which can simulate a clinical head and neck tumor that may shrink and migrate as treatment progresses.
- The treatment plans created using the soft tissue insert can simulate a prostate tumor with peripheral varying OARs. Table 2 demonstrates the differences in mean dose to the OAR directly above the targeted object using the reference plan on each phantom configuration.
- The phantom was used for validation through the ART workflow (Figure 3): a plan was created with ideal target coverage on one object ($V_{100\%}$=95%), a change in anatomy decreased the coverage by 19±15%, and then a new plan adapted to this configuration regains original coverage.
- The ART workflow was observed in the TPS, and measured doses closely matched the TPS calculations (1.1±1.3%).
- The compatibility of the phantom with multiple types of dosimeters allows for adapted plan delivery verification.
- We continue to develop and utilize the full range of functionality of our phantom.

CONCLUSIONS

- Complete evaluation of the subsystems that comprise online ART technologies is integral for their safe and effective clinical implementation.
- We demonstrated the design, creation, and use of our in-house phantom that features multiple configurations of targets and organs at risk with known morphological relationships.
- A phantom with this functionality can effectively evaluate a system's ability to adapt to daily changes in anatomy.

CONTACT INFORMATION

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