End-To-End Testing of Adaptive Radiotherapy in the Elekta MR-Linac Utilising 3d Printed Phantoms

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JULY 12–16 2020 VIRTUAL JOINT AAPM | COMP MEETING
Improving Health QUALITY, Increasing Global IMPACT
EASTERN TIME [GMT-4]

INTRODUCTION

- Magnetic resonance imaging guided radiotherapy (MRgRT) could be the next development to revolutionise radiotherapy with the integration of magnetic resonance imaging (MRI) and a conventional linear accelerator.
- MRI provides a superior contrast between soft tissue types and allows for a more precise knowledge of locations and shapes of target volumes, and all surrounding organs at risk(OARs) at the time of treatment whilst providing no additional radiation to the patient from imaging.
- Utilising adaptive radiotherapy techniques, online MR images of the patient anatomy can be used to avoid unnecessary irradiation of healthy tissue and more precise treatment of target volumes that have undergone translations and shape deformations.

AIM

This work has aimed to develop and demonstrate a framework for assessing the accuracy of adaptive radiotherapy within an MR guided system. This was achieved through the use of an end to end pelvic phantom that had been designed and developed through a combination of additive and subtractive manufacturing (3D printing) and which was designed to allow imaging in both computed tomography (CT) and MRI, plus dose measurement in structures inside the phantom.

PHANTOM DESIGN

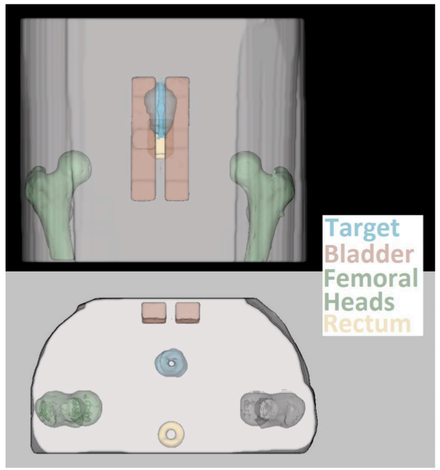

Figure1: Position of the three OARs and target volume when secured into the phantom, with a coronal view (Top) and an axial view (Bottom). The target volume, bladder, femoral heads and rectum are displayed in Blue, red, green and yellow respectively.

An end-to-end pelvic phantom was designed to meet the following criteria:

1. It contained a target volume, specifically designed to mimic the prostate, and all appropriate OARS related to prostate treatment.
2. The target could mimic translations and shape deformations accurately and repeatably.
3. The phantom allowed for measurements of relative dose distributions.
4. It allowed absolute dose measurement.
5. The phantom was robust and reasonably compact for transportability to allow dose measurements at a range of centres.
6. There was good visibility and realistic signal contrast in both CT and MRI.
7. No imaging artefacts were generated in either imaging modality.

The design of the internal components of this phantom are shown in Figure 1.
The phantom was 3D printed using a consumer fused filament fabrication 3D printer. The target volume was made from Ballistic gel, and both the bladder and rectum were filled with agar gels doped with 1 mmol/l of $CuSO_4$ to provide sufficient contrast.

METHOD

Table 1: Phantom measurements made in this study, detailing the target displacement, shape description, and type of treatment plan adaptation used

Experiment Number	Target volume vector displacement (X,Y,Z) /mm	Target volume shape description	Type of treatment plan adaptation
1	0,0,0	Realistic/CT based target shape	Adapt to position
2	0,0,15	Realistic/CT based target shape	Rigid adapt to shape
3	0,30,25	Realistic/CT based target shape	Rigid adapt to shape
4	0,0,0	Spherical	Deformable adapt to shape
5	0,30,25	Spherical	Deformable adapt to shape

The Elekta Unity (Elekta AB, Stockholm, Sweden), MOSAIQ OIS and Monaco TPS were used to plan, adapt and deliver the treatment plans to the phantom using the adapt to position (ATP) and adapt to shape(ATS) workflows.
Treatment plan adaptations were made to the reference plan using online MR images, with the resultant delivered dose distributions measured using gafchromic film for two central slices in the sagittal plane, and 5 alanine pellets positioned within the target volume. Large target displacements were chosen for this investigations to test the systems capabilities.
Five measurement configurations were used to investigate both ATP and ATS, looking at whole body displacements, rigid target translations, and shape deformations, see Table 1.
Verification of the accuracy was performed through global gamma evaluation, comparing output corrected planar dose distributions calculated by the TPS, with the measured dose distribution from the gafchromic film, and direct comparisons between individual alanine measurements and TPS calculations. Corrections were made using an alanine magnetic field correction factor, and a daily output factor for the alanine and TPS respectively.

Figure 2: Anterior view photograph of the end to end phantom, containing a spherical target volume

RESULTS

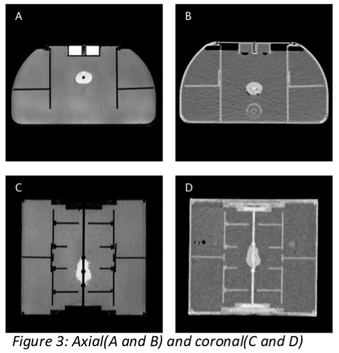

Figure 3: Axial(A and B) and coronal(C and D) view of the T1 weighted MRI (A and C) and CT (B and D) images of the phantom

The target volume appears clearly in both the CT and MR images (figure 3), with no obvious imaging artefacts generated. All volumes possessed well-defined boundaries which ensured that organ contouring for treatment planning could be conducted easily.

The gamma analysis pass rates for the five adaptive plans tested are shown in table 2. Results are shown for both strips of film individually, in addition to the mean pass rate for each experiment.

The pass rates were consistent for both target shape and position changes, showing a very high agreement with an average pass rate of 99% and 95% for criteria of 3%/3 mm and 2%/2mm respectively. This level of consistency demonstrates the accuracy of the complete adaptive radiotherapy workflow for an MR guided system.

RESULTS

Table 3 displays the calculated alanine results from this study, compared with the daily output corrected predicted dose value from the TPS.

Table 2:Gamma evaluation pass rates for each of the investigated treatment plan adaptations

2D Gamma analysis	Vector Displacement	3%3mm		2%2mm		average	
Type of Adaptation	(X,Y,Z)mm	middle	right	middle	right	3%3mm	2%2mm
ATP	0,0,0	99.40%	99.40%	93.50%	97.10%	99.40%	95.30%
ATS(Rigid)	0,0,15	97.50%	99.50%	92.30%	97.10%	98.50%	94.70%
ATS(Rigid)	0,30,25	99%	99.30%	94.10%	96.10%	99.15%	95.10%
ATS(Deform)	0,0,0	97.80%	98.80%	92.10%	94.20%	98.30%	93.15%
ATS(Deform)	0,30,25	99.10%	99.50%	95.30%	97.90%	99.30%	96.60%
Average						98.93%	94.97%

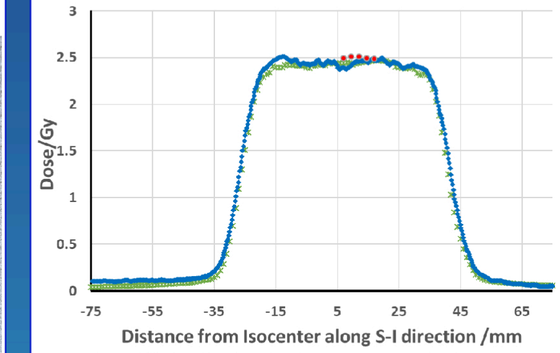

Figure 4: Plot profile of the dose distribution, comparing the gafchromic film measurement (Blue), alanine measurements (red) and TPS calculations

These results are also displayed in the profile, shown in Figure 4, through the centre of the phantom from the first experiment, comparing both the alanine and gafchromic film measurements with the output corrected TPS calculations.
The minimal differences demonstrated over both the high and low dose regions further demonstrate the accuracy of the adapted treatment plans.

Table 3:Measurements from alanine dosimetry compared with calculated values from the TPS

Alanine dose/Gy	TPS predicted dose/Gy	% Difference
2.49	2.47	0.80
2.51	2.46	1.96
2.51	2.44	2.82
2.49	2.43	2.41
2.49	2.44	1.91

CONCLUSION

The high consistency of results achieved through using this framework and end-to end phantom demonstrate its capabilities in assessing the accuracy of adaptive radiotherapy in an MR guided system. The system has been assessed with demanding displacements to test the capability of the system to adapt to changes. Further investigations will be made with small target volume translations, to replicate realistic intrafractional motion of the prostate. Results suggest that this phantom would be suitable for an intercentre comparison.

ACKNOWLEDGEMENTS

The work has been partially supported by Royal Society (INF\R1\191030), and Elekta.

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