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LETTER

Proof-of-concept delivery of intensity modulated arc therapy on the Elekta Unity 1.5 T MR-linac

C Kontaxis[1], P L Woodhead[1,2], G H Bol[1], J J W Lagendijk[1] and B W Raaymakers[1]

[1] Department of Radiotherapy, University Medical Center Utrecht, Heidelberglaan 100, Utrecht 3584 CX, The Netherlands
[2] Elekta AB, Stockholm, Sweden

E-mail: c.kontaxis@umcutrecht.nl

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Abstract

In this work we present the first delivery of intensity modulated arc therapy on the Elekta Unity 1.5 T MR-linac. The machine's current intensity modulated radiation therapy based control system was modified suitably to enable dynamic delivery of radiation, for the purpose of exploring MRI-guided radiation therapy adaptation modes in a research setting. The proof-of-concept feasibility was demonstrated by planning and delivering two types of plans, each investigating the performance of different parts of a dynamic treatment. A series of fixed-speed arc plans was used to show the high-speed capabilities of the gantry during radiation, while several fully modulated prostate plans—optimised following the volumetric modulated arc therapy approach—were delivered in order to establish the performance of its multi-leaf collimator and diaphragms. These plans were delivered to Delta^4 Phantom+ MR and film phantoms passing the clinical quality assurance criteria used in our clinic. In addition, we also performed some initial MR imaging experiments during dynamic therapy, demonstrating that the impact of radiation and moving gantry/collimator components on the image quality is negligible. These results show that arc therapy is feasible on the Elekta Unity system. The machine's high performance components enable dynamic delivery during fast gantry rotation and can be controlled in a stable fashion to deliver fully modulated plans.

1. Introduction

Intensity modulated radiation therapy (IMRT) has been able to produce conformal dose distributions around the target ensuring coverage while sparing the adjacent organs at risk (OARs) when compared to conventional box field approaches (Schubert *et al* 2011). This is achieved by using a multi-leaf collimator (MLC) to shape the beam across several gantry angles while varying the beam intensity (Bortfeld 2006).

Intensity modulated arc therapy (IMAT) was later proposed combining the motion of the gantry, MLC leaves/diaphragms and doserate modulation during delivery (Yu 1995). Various IMAT implementations, such as volumetric modulated arc therapy (VMAT) (Otto 2008), have been introduced to the clinic by different vendors, which can achieve similar dosimetric performance to fixed-beam IMRT techniques utilizing one or more arcs depending on the treatment site (Yu and Tang 2011).

In terms of plan quality VMAT generally yields similar plans to IMRT, with equal target coverage while in some cases being able to spare more of the surrounding (Teoh *et al* 2011). At the same time VMAT is able to drastically reduce delivery times (Palma *et al* 2010), making it a standard delivery technique in many institutes around the world. Faster delivery leads to smaller intrafraction motion making it ideal for image guided radiation therapy (IGRT) applications where online kV/MV imaging is used to position the patient at the start of the treatment fraction.

The introduction of MR-linacs which combine an MRI with a linear accelerator (linac) has enabled the use of online replanning based on the daily patient anatomy during every fraction (Sahin *et al* 2019, Werensteijn-Honingh *et al* 2019).

Moreover, 3D imaging during the radiation delivery can be utilised for the accurate reconstruction of the delivered dose to the patient (Kontaxis *et al* 2020), and eventually for the treatment plan modification in multiple timepoints during the fraction.

The commercially available MR-linac machines (Lagendijk *et al* 2014, Mutic and Dempsey 2014), are limited to support exclusively fixed-beam IMRT delivery. In our clinic the Elekta Unity MR-linac consists of a 1.5 T MRI and a 7 MV linac The Elekta Unity's hardware design includes state-of-the-art gun, gantry and collimating components, the performance of which has not yet been investigated under a dynamic therapy setting. Dynamic types of radiation delivery on the MR-linac would lead to faster delivery times, which could help to mitigate the intrafraction motion effects on the daily adapted plan. While delivery time in the current workflows is not the most time-consuming step (Werensteijn-Honingh *et al* 2019, Intven *et al* 2020), the development of more efficient methods for contouring and plan optimization as well as the shift to more extreme hypo-fractionation treatments will eventually lead to a demand for significantly faster delivery speeds. Moreover, the Unity's hardware characteristics could enable dynamic therapy suitable for advanced adaptive intrafraction workflows utilizing frequent adaptation points between partial/full arcs.

In this work we explore Elekta Unity's hardware capabilities and present the first proof-of-concept arc therapy implementation on an MR-linac system by modifying the machine's control system software. We demonstrate that the machine is capable of delivering plans leading to dose distributions similar to the VMAT approach in conventional accelerators. Moreover, we show the system's ability to deliver accurately radiation at much higher gantry speeds opening the way to further explore the feasibility and value of adaptive arc treatments.

2. Materials and methods

The Unity MR-linac consists of a 1.5 T MRI and a 7 MV Flattening Filter Free linac The linac is able to pause and unpause the radiation instantaneously due to its triode electron gun and has currently a doserate of approximately 425 monitor unit (MU) min^{-1}. The MRI is based on the wide bore 1.5T Philips Ingenia system appropriately modified to allow the perpendicular linac configuration. The linac along with all the beam generating components is mounted on the gantry around the MRI cryostat using a slip-ring design enabling uninterrupted rotation around the patient at a maximum 6 revolutions per minute (rpm). A 160 leaf MLC is mounted perpendicular to the gantry travel direction with a leaf width and travel distance of 7.15 and 220 mm respectively at the isocenter. A diaphragm perpendicular to the leaf travel direction is also present.

In this work we have used a set of dynamic plans designed to test different operating modes of the machine ranging in delivery complexity. Each plan's control points containing the leaf/diaphragm positions, dose and MLC/gantry angles were sent to the modified treatment control system of the MR-linac using an in-house developed client.

2.1. Linac control system

Several modules of the linac's control system software were modified to allow for dynamic arc delivery. First of all, the system had to be modified to be able to accept the dynamic stream of control points generated when sending a treatment plan to the linac.

Then, having uploaded the plan, a processing algorithm was developed in order to properly feed the dynamic information to the various components of the machine. During this phase the dynamics of the system are taken into account, including gantry acceleration, MLC/diaphragm speed, doserate etc in order to ensure smooth operation between the components and, thus, close-to-optimal delivery.

Finally, various changes were performed to the real-time layers—operating at a 40 ms clock cycle—interacting with the gantry, MLC, diaphragm and beam generation modules to ensure the accurate delivery. During delivery, the gantry position and MU count were set to follow each other simultaneously while the MLC and diaphragm follow the MU count. During each delivery the MU, dose rate, gantry position/speed and leaf/diaphragm position were logged for each clock cycle.

Our modified system allows for unrestricted continuous rotations including going through 180 degrees, a feature which is currently not yet available in the clinical IMRT system.

2.2. Treatment planning

Multiple plans were made using our in-house developed MRL Treatment Planning system modified to generate arc therapy plans. They included plans targeting a cylinder placed in the cranial caudal direction and thus featuring low amplitude MLC motion as well as modulated prostate plans.

For all plans a two-step optimization method was used consisting first of calculating the optimal fluence distributions for a configuration of multiple gantry angles and then sequencing them to extract deliverable MLC shapes (segments) per angle that have to be geometrically connected (Kontaxis *et al* 2018). The shapes that were not connectable were then replaced by means of interpolation, finally followed by a re-optimization of the control point weights to account for the changes.

In the case of multi-arc plans, the consecutive arcs were connected by pausing radiation over the angles between 357 and 30 degrees in order to avoid irradiating through the cryostat pipe which is centered around 13 degrees. The actual zero-dose arc interval depends on the MLC shape being delivered over the pipe, but in this work an extra margin was used for safety reasons. Thus all plans contained one or more clockwise arcs that span from 30 to 357 degrees.

2.2.1. Fixed gantry speed

In order to test the gantry's performance at different speeds while remaining unconstrained by other parameters, we generated a set of plans targeting a cylindrical target. Constant gantry speed, and thus fixed delivery time, was selected by setting equal MU and gantry increments in all control points for each plan. This led to five single-arc plans configured to run at 1, 2, 3, 4, 5 rpm and two multi-arc plans, one with two arcs at 2 rpm and one with three arcs at 3 rpm.

2.2.2. Prostate plans

We also calculated a range of arc therapy plans for 10 existing prostate MR-linac patients that were previously treated in our clinic with either 20×3.1 Gy or 5×7.25 Gy fractionation schemes. These were planned using the clinical planning constraints from the respective clinical protocol. Similar to the VMAT approach, variable MU/doserate was used per control point yielding deliveries constrained to dose instead of the cylinder ones which were constrained to gantry speed.

2.2.3. Evaluation

For a quantitative comparison, the differences between prescribed and actual control system values of all the above parameters were calculated to establish the dynamic performance of the machine. Its dosimetric accuracy was assessed via the Quality Assurance (QA) methods currently used for fixed-beam IMRT treatments in our clinic. These included the delivery of three 5×7.25 Gy prostate plans on Gafchromic$^{\text{TM}}$ EBT3 film and of all plans on the Delta^4 Phantom+ MR (ScandiDos, Sweden) modified to support arc therapy deliveries on the MR-linac.

2.3. MR imaging

Besides the evaluation of the linac delivery, we also performed an initial investigation on the quality of MR imaging during dynamic therapy. We have replicated the B0 homogeneity and image distortion experiments performed in Jackson *et al* (2019). The B0 measurements were performed using a large 40 cm phantom and a dual echo transverse fast field echo (FFE) sequence while for the image distortion experiments we used the 20 cm diameter Philips periodic image quality test phantom imaged with a transverse balanced FFE sequence. The baseline imaging metrics were collected with the gantry set at 10 degree intervals over one full arc. Then prostate plans and fixed speed cylinder plans were delivered while acquiring the respective imaging data. For a detailed overview on the underlying methods we kindly refer the reader to Jackson *et al* (2019).

3. Results

In total 17 plans including the cylinder and prostate plans were delivered and analysed. Figure 1 shows the delivery timeline for two of these plans, including the gantry position, dose and doserate as a function of time. For all runs the maximum speed of the leaves and diaphragms was set to 12.5 cm s^{-1} and 4.5 cm s^{-1} respectively which were found to be the optimal operational values.

3.1. Fixed gantry speed

Seven fixed gantry speed cylinder plans (figure 1(a)) were delivered including 1, 2, 3, 4, 5 rpm and 2 multi-arc ones, a two-arc at 2 rpm and a 3-arc at 3 rpm. Delivery times were 56.4, 32.2, 23.2, 19.5, 17.2, 62.8 and 64.5 s respectively, close to the ideal time when operating at these fixed speeds, increasingly affected by the gantry acceleration and deceleration time.

The average absolute positioning error of the open leaves was 0.3 ± 0.8 mm and 0.1 ± 0.3 mm for the diaphragms among all cylinder plans. The gantry positional error was 0.1 ± 1.0 degrees.

3.2. Prostate plans

Ten prostate plans with two modulated arcs each were delivered (figure 2(b)), five prescribed at 3.1 Gy and five at 7.25 Gy. Average delivery times for the two prescriptions were 181 and 445 s with an average MU count of

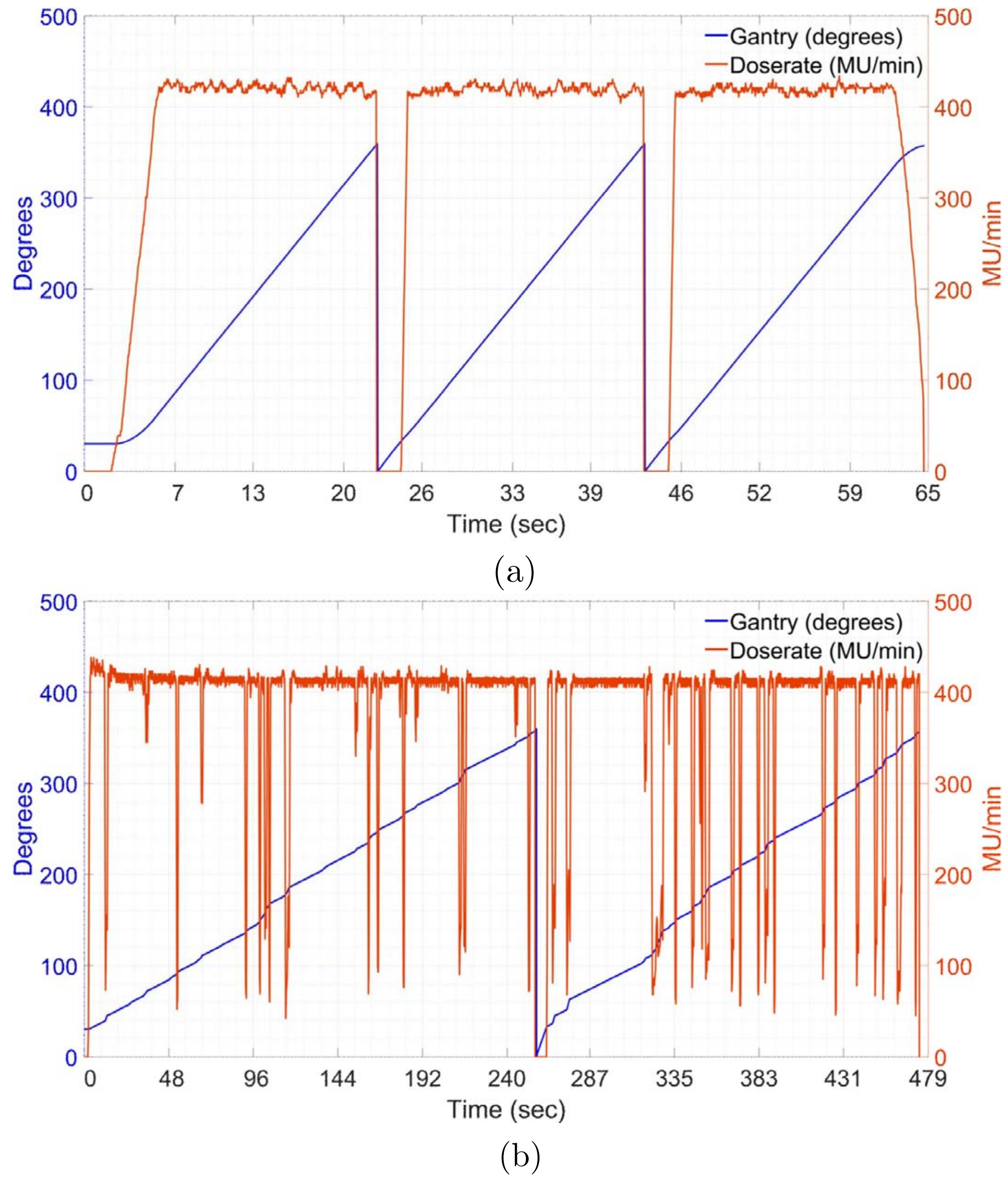

Figure 1. Cylinder and prostate plan deliveries. The lines indicate gantry position (left *y*-axis) and doserate (right *y*-axis). The gaps correspond to intervals where the radiation was paused in order to avoid irradiating through the cryostat pipe in-between arcs. (a) Cylinder delivery of a three-arc 3 rpm plan with constant gantry speed. (b) Prostate delivery with two modulated arcs.

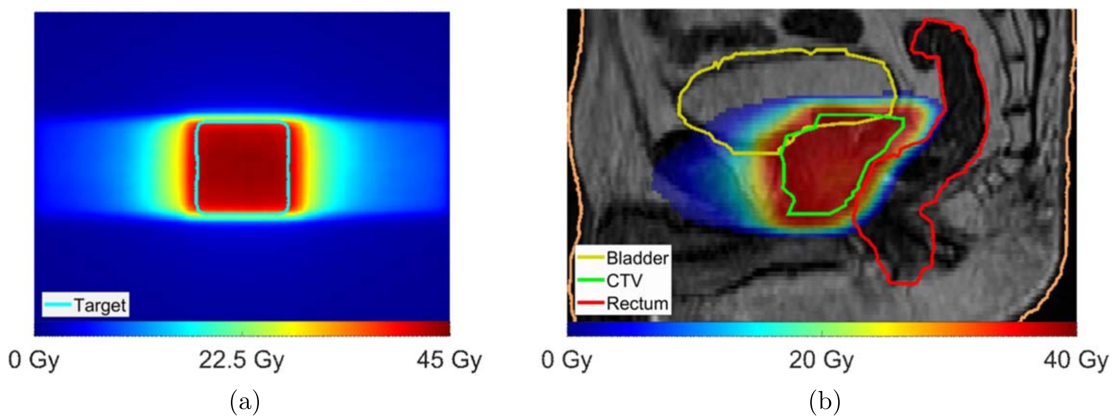

Figure 2. Central sagittal PTV slice from the 3D dose for one cylinder and one prostate case. (a) Cylinder dose from the three-arc 3 rpm plan. The target contour is visible on the slice. (b) Prostate dose. CTV, bladder and rectum contours are visible on the slice.

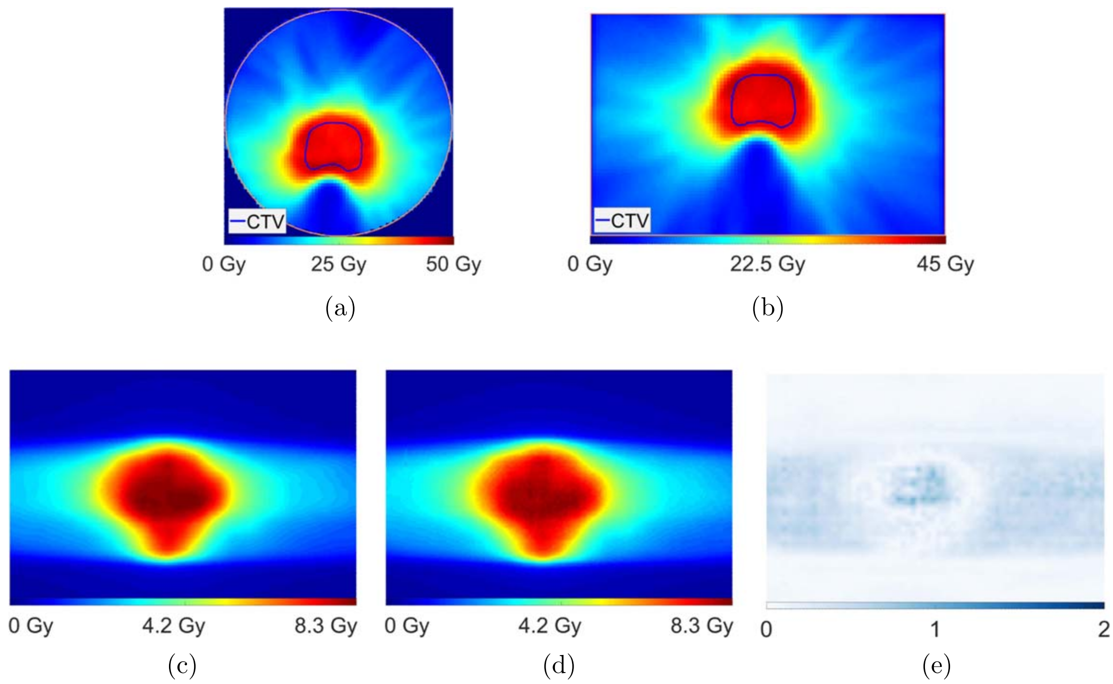

Figure 3. Plan QA analysis for one prostate case. (a) Central CTV transversal dose slice from the Delta[4] phantom. (b) Central CTV transversal dose slice from the film phantom. (c) Coronal slice from the planned dose. (d) Measured film. (e) Film gamma analysis at 3%/3 mm.

926 and 2794 respectively. The average absolute positioning error of the open leaves was $0.6 \pm 0.1.5$ mm and 0.2 ± 0.7 mm for the diaphragms among all plans while the gantry positional error was 0.1 ± 0.6 degrees.

3.3. QA

All 17 plans were delivered to the Delta[4] phantom for 3D dosimetry while three prostate plans were delivered to Gafchromic™ EBT3 films. The planned dose distributions were also calculated on the respective phantom and were then used as the reference dose (figures 3(a)–(b)).

All Delta[4] measurements resulted in pass rates of 100% in 3%/3 mm gamma analysis currently used in our clinic for prostate treatments. The film measurements were analysed with an in-house developed tool and had gamma pass rates of at least 98% at a 3%/3 mm analysis while including all points between 10% and 100% of dose maximum (figures 3(c)–(e)).

3.3.1. MR imaging results

Figure 4 shows the peak to peak deviation-from-average B0 inhomogeneity as well as the measured extent and center of the phantom during the dynamic delivery for one 5×7.5 Gy prostate plan and a fixed speed 2-arc plan at 2 rpm. The B0 deviation for the dynamic plans was very similar to the baseline values of the static gantry positions, generally remaining below 0.3 ppm (figure 4(a)).

For the same plans, the center and extent of the phantom remained almost identical during delivery, with the calculated differences falling within the extent of a single acquired pixel (figure 4(b)).

4. Discussion

We presented the first proof-of-concept arc therapy delivery on an MR-linac and specifically on the Elekta Unity. We evaluated the machine's performance quantitatively in terms of control system performance and qualitatively in terms of dosimetric accuracy in both 3D and 2D QA.

The cylinder plans were designed to drive the gantry at fixed speeds and demonstrated the system's ability to deliver accurately dose while in high-speed motion. This was possible due to our pre-processing algorithm able to adjust each control point's doserate taking into account the acceleration and deceleration of the gantry.

Furthermore this work shows that the system is capable of modulated arc therapy, accurately delivering dose distributions for prostate patients, who were previously treated on the MR-linac In this mode we established suitable speeds for the MLC and diaphragms, which enable them to run fast in a smooth controlled fashion.

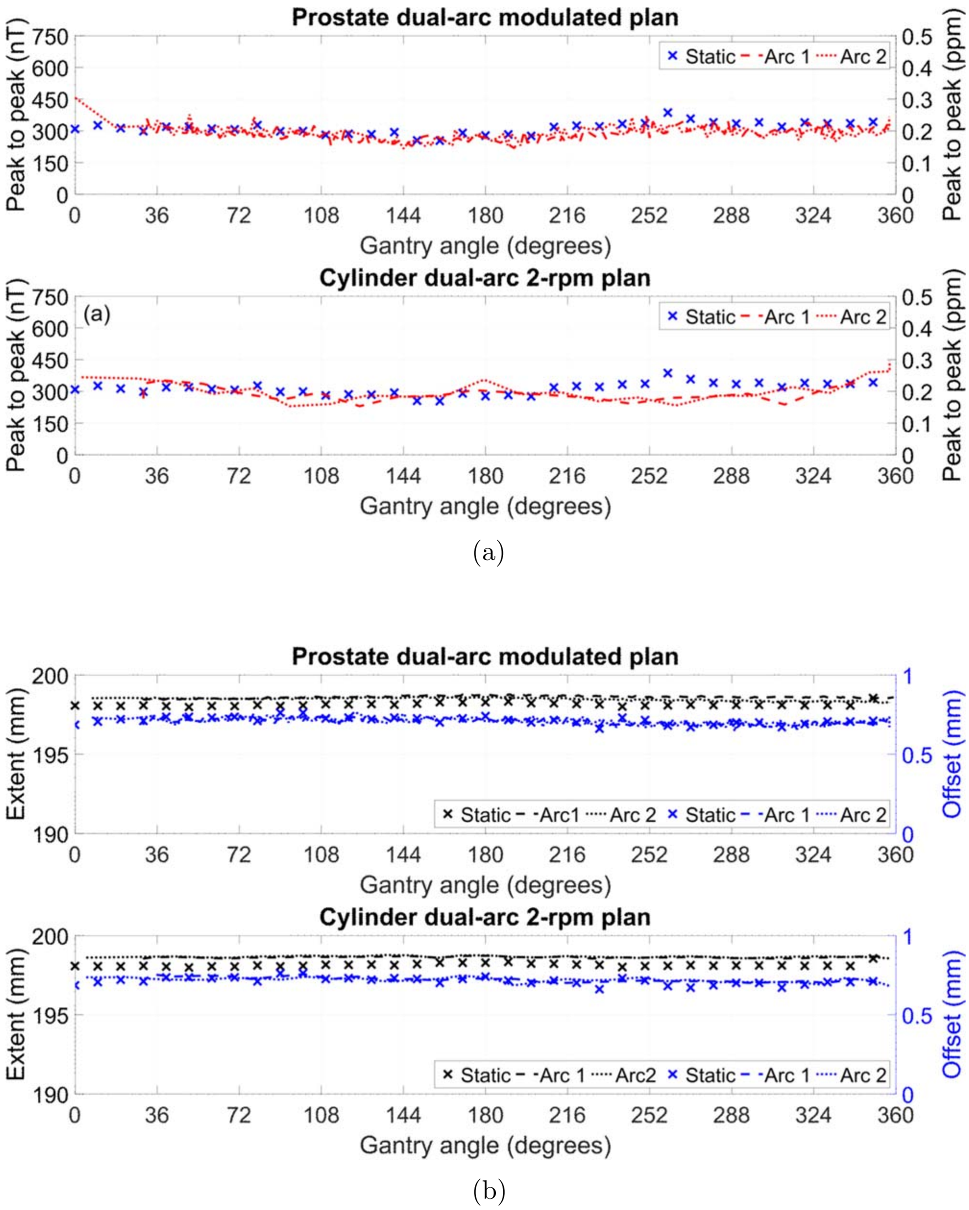

Figure 4. Initial MR imaging quality evaluation during dynamic arc therapy on the Unity MR-linac B0 homogeneity (a) and geometric distortion measurement (b). The baseline data from the static gantry at 10 degree angular intervals are plotted as crosses. (a) B0 homogeneity data. Peak to peak deviation-from-average inhomogeneity against gantry angle during delivery at 1.5 s intervals (dashed and dotted lines) of a fully modulated 2-arc 5×7.5 Gy prostate plan delivery (top) and a 2-arc 2 rpm cylinder plan (bottom). (b) Geometric distortion data. Measured extent of the phantom (left *y*-axis) and shifts of the phantom center position (right *y*-axis) in the phase encode (left–right) direction for a balanced fast field echo (bFFE) sequence. Dashed and solid lines represent the data of the dynamic plan deliveries at 1 s intervals. A fully modulated 2-arc 5×7.5 Gy prostate plan delivery (top) and a 2-arc 2 rpm cylinder plan (bottom) are shown.

These values outperform conventional Elekta systems and potentially enable a greater degree of modulation by utilizing more rapidly varying shapes.

The logging mechanism used to report the planned and actual values of the MLC, diaphragms and gantry positions at each delivery timepoint is essential for the proper tuning of the machine's internal parameters during this experimental phase but also to ensure the proper operation of the machine during normal operation. The reported geometric differences are generally very small with momentary larger values at points of sudden motion mainly due to the latency in the readout of the actual positions. The final internal parameters needed to ensure stable long-term utilization of the system have to be determined in respect to the underlying delivery mode/application.

These results show that the Elekta Unity's control system could be modified and tuned similarly to conventional linac machines to fully support VMAT therapies. The actual performance of the system for clinical grade VMAT has to be further explored along with a thorough comparison to VMAT on conventional machines, with dedicated planning studies for prostate and more complex sites like head and neck.

Moreover, the machine's dynamic performance should be compared to the current MRI-guided IMRT standard, in terms of both quality and delivery speed. Although outside the scope of this work, in a preliminary evaluation of the delivery speed between IMRT and VMAT on Unity for a few prostate patients, VMAT was faster by 20% up to 50% depending on the dose per fraction used and the plan parameters like number of IMRT angles/segments. A potential reduction in delivery time would be beneficial for the current IMRT-based treatments, limiting the build-up of intrafraction motion during radiation (Kontaxis *et al* 2020).

On top of that, by fully exploiting the high-performance linac and gantry components a new type of arc therapy could potentially be developed beyond VMAT. The Unity's linac components, as demonstrated in this work, in terms of gantry and collimator speeds greatly exceed the performance of conventional IGRT linac systems like the Elekta Versa HD series (Bedford *et al* 2013). The triode gun present on the system also allows for instantaneous beam-on/off which could be beneficial for online gating/tracking applications. At the same time the fixed-angle MLC and especially the dose rate—currently set at 425 MU min^{-1}—could be a potential limitation for future treatments. Delivering higher-speed arcs decreases the maximum dose each arc can deliver, which is bound to the maximum available doserate. The balance between dose per arc, arc speed and number of arcs will depend on the treatment site and dose per fraction and is part of our future work.

In our future work we will utilise our adaptive sequencer (ASEQ) optimization methodology, previously applied on IMRT (Kontaxis *et al* 2015), to explore these new adaptation possibilities. Multi-arc adaptive treatments can be formulated, in which we deliver a fast full or partial arc and then update the next arc based on live dose accumulation and the latest anatomy as captured by the online MRI. Such a regime could provide more adaptation intervals and degrees of freedom compared to IMRT while still delivering a smooth dose distribution without discontinuities, which would prevent instabilities during plan optimization.

We have previously shown that the MR imaging is barely affected by radiation (Tijssen *et al* 2019), and continuous gantry rotation (Jackson *et al* 2019). Although the focus of this work was on the linac and its control system, we additionally performed an initial investigation on the impact of dynamic/VMAT delivery on the MR imaging, by replicating the B0 homogeneity and image distortion experiments performed in Jackson *et al* (2019). These results demonstrate that the homogeneity of the magnet (figure 4(a)) as well as the geometric shift and extent of a cylindrical phantom under a clinical-grade bFFE sequence (figure 4(b)) are negligibly affected during dynamic radiation delivery.

We will further quantify the performance of the Unity's MR and linac subsystems as we explore multi-arc adaptive MRI-guided workflows. Depending on the underlying treatment scenario, the specific delivery mode and online MR imaging should be individually evaluated to establish safe and accurate online applications.

5. Conclusion

We demonstrated the first proof-of-concept delivery of arc therapy on the 1.5 T Unity MR-linac We have successfully delivered fully modulated prostate plans and multi-arc ones at fixed gantry speeds exceeding 1 rpm and up to 5 rpm. The performance of the individual machine components was evaluated along with the dosimetric accuracy via 3D and 2D QA tests of several plans all fulfilling our clinical criteria. An initial investigation on the MR imaging during arc therapy showed negligible impact in terms of B0 homogeneity and image distortion. This work shows that the machine is capable of dynamic deliveries and enables us to investigate multi-arc adaptive therapies for MRI-guided radiotherapy.

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ORCID iDs

C Kontaxis https://orcid.org/0000-0002-7300-6513

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