Combining Cone Beam CT-Based Treatment Delivery on a C-Arm Linac with Offline MRI-Guided Adaptive Radiotherapy

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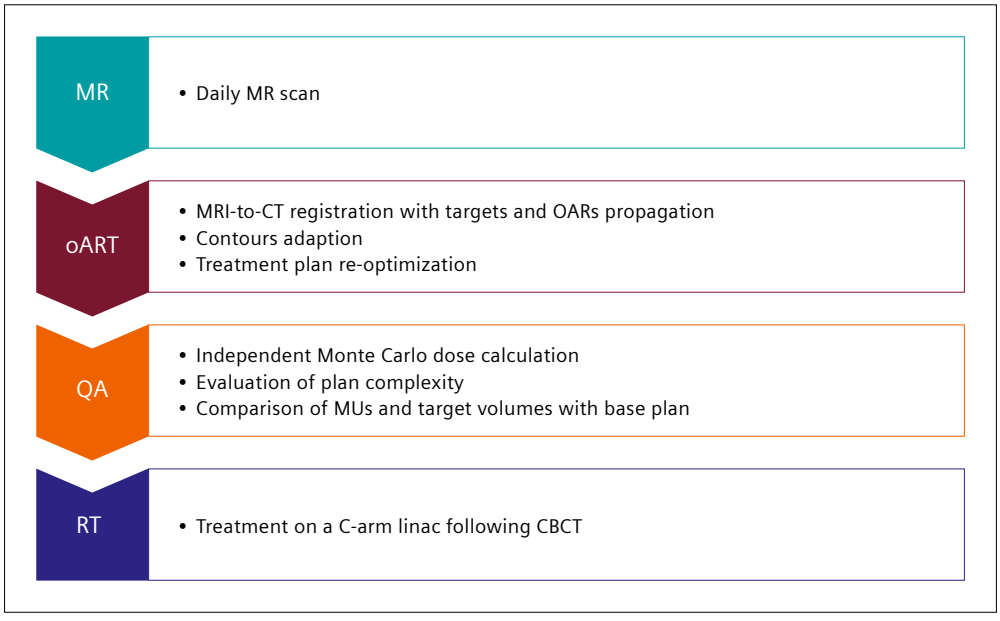
Introduction

Prostate cancer is the most common non-skin cancer in men and is often diagnosed at an early stage thanks to advancements in screening and imaging [1]. Treatment options have evolved significantly, with stereotactic body radiation therapy (SBRT) emerging as a highly effective, non-invasive approach [2, 3]. SBRT delivers high doses of radiation in a few sessions with remarkable precision, minimizing damage to surrounding organs such as the bladder and the rectum [4].

Magnetic resonance (MR)-informed adaptive radiotherapy further enhances treatment accuracy by using real-time MR imaging to track and adapt intrafractional anatomical changes, such as prostate motion and variations in adjacent tissues. This combination of technologies reduces side effects and improves clinical outcomes, representing a cutting-edge solution for prostate cancer management.

However, the widespread adoption of hybrid MR-linear accelerators remains limited due to the high costs of construction, purchase, and maintenance [5–7]. Moreover, the substantial time and resource demands of each treatment session reduce patient throughput [8]. As a more accessible alternative, this study proposes adaptive radiotherapy on a cone beam computed tomography (CBCT)-guided linear accelerator, using MR images acquired in the treatment position, immediately before treatment, for contouring and plan adaptation (Fig. 1).



1 MR-guided adaptive radiotherapy in a CBCT-guided C-arm linac workflow.

Materials and methods

Base-plan generation

The treatment planning process begins with the acquisition of a planning CT scan. In addition, T1-weighted and T2-weighted MR imaging is performed on the department's 1.5T MAGNETOM Sola scanner (Siemens Healthineers, Erlangen, Germany). The imaging data are then transferred to the Eclipse treatment planning system (v.16.1; Varian Medical Systems, Palo Alto, CA, USA) and are rigidly registered. Following the delineation of target volumes and organs at risk (OARs) on the planning CT based on the MR images, a base plan for SBRT is created. This plan is generated according to a checklist to ensure compliance with internal quality standards. Any necessary auxiliary structures for plan optimization are generated using an ESAPI script that was developed in-house. Hence, dose calculation is performed using the Acuros XB v.16.1.0 algorithm (Varian Medical Systems, Palo Alto, CA, USA). The plan is then reviewed by a physicist and approved by a physician.

At our institution, patient-specific quality assurance (PSQA) includes an independent Monte Carlo dose calculation and an evaluation of the plan's complexity. Depending on the complexity, portal dosimetry may be performed prior to the first treatment.

As the planning system does not support online adaptive treatments, the base plan is then prepared for online adaptation through the following steps:

- Detailed notes are made on the auxiliary structures used in the optimizer and on any dose compromises made due to critical OARs.
- Optimization objectives are saved in a patient-specific template.
- Two copies of the CT scan are created: one containing target contours to be rigidly copied onto the adaptation MR images, and another for deformable structures (e.g., gastrointestinal structures).

Daily MR-guided adaptive radiotherapy on a CBCT-guided linear accelerator

On the day of treatment, T2-weighted MR imaging is acquired in the treatment position using the department's 1.5T MAGNETOM Sola scanner. This MRI is then registered to the original planning CT scan. Target contours from the original plan are rigidly transferred to the new MR imaging, while OAR contours are mapped using deformable registration. The physician then adapts the target contours on the new MRI and, if necessary, adjusts any OARs within a 2 cm margin of the tumor. The adapted structure set is subsequently assigned to the original planning CT scan, and a planning target volume (PTV) is generated.

Next, a physicist uses the ESAPI script to automatically generate all auxiliary structures required for plan optimization, following the planning notes. The base plan with the adapted structure set is then re-optimized on the original planning CT scan using the saved optimization objectives. If dosimetric goals and constraints are not met, the optimization objectives are adjusted iteratively until an acceptable plan is achieved. Once optimized, the adapted plan undergoes a final dosimetric review and is approved by the physician.

To ensure accurate and safe treatment delivery, patient-specific quality assurance is performed as it was for the base plan. Additionally, the ESAPI script automatically verifies plan normalization and conducts a comparative analysis of key parameters – including dose per fraction, target volumes (with an internal threshold of 20%), and monitor units (with an internal threshold of 20%) – against the base plan.

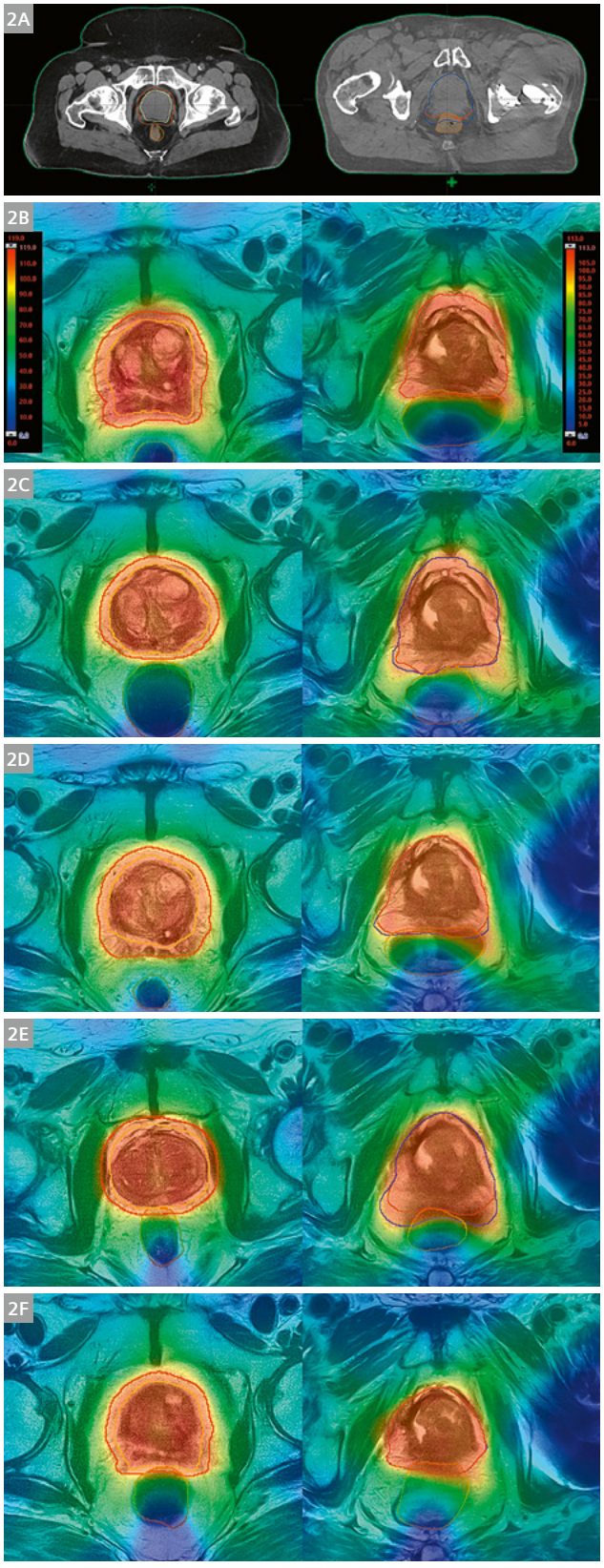
Finally, prior to radiation delivery, a verification CBCT scan is acquired to aid patient positioning on either a Varian Edge or TrueBeam linear accelerator (Varian Medical Systems, Palo Alto, CA, USA).

Clinical cases

We have used this new workflow for treating patients with pelvic lesions that are expected to benefit from online adaptive radiotherapy that takes account of variations in bladder and rectum filling. Here, we present two clinical cases of prostate cancer.

Patient 1 is a 70-year-old male with a medical history of seropositive rheumatoid arthritis, hypertensive heart disease with paroxysmal atrial fibrillation, Type 2 diabetes mellitus, and psoriasis vulgaris. He was diagnosed at our institution with prostate adenocarcinoma (pT2c cN0 cM0, Gleason Score 7a, "unfavorable intermediate risk") and underwent weekly primary stereotactic radiotherapy for one month. The total prescribed dose was 40.0 Gy to the clinical target volume (CTV) and 37.5 Gy to the PTV in 5 fractions. No significant acute radiation-induced toxicities were observed. Planned follow-up includes prostate-specific antigen (PSA) monitoring and multidisciplinary care.

Patient 2 is an 89-year-old male with a history of localized prostate adenocarcinoma (cT2c cN0 cM0) under active surveillance since 2010. His medical history includes multiple prostate interventions, bladder tamponade, and comorbidities including diverticulosis, erectile dysfunction, and chronic kidney changes. He presented at our institution with a PSA increase to 53 µg/L, and prostate-specific membrane antigen (PSMA) PET/CT confirmation of localized disease. He underwent primary SBRT with 5 × 7/7.25 Gy every other day to avoid androgen deprivation therapy. At six-month follow-up, PSA had decreased to 30.1 µg/L.



2 Planning CT scans for Case 1 (left) and Case 2 (right), showing target volumes and main OAR contours **(2A)**. Adapted contours and dose distributions for fractions 1 to 5 **(2B–2F)**.

Results

Figure 2A shows the planning CT scans for cases 1 and 2, respectively, with the target volumes and main OARs highlighted. All treatment fractions were adapted (Figures 2B–2F). Tables 1A and 1B summarize the institutional clinical goals for cases 1 and 2, respectively. In both cases, adaptation made it possible to achieve plans comparable to the base plan. Without adaptation, target coverage could have been compromised, and OARs might have received a higher dose. On average, for Case 2, the coverage of the PTV_high would have decreased by 54%, while for Case 1, the rectum would have received a 9% higher dose.

PSQA was passed for all fractions, with an average relative change in PTV/PTV_low volume of 1.1% and 19.1%, and in monitor units (MU) of 4.5% and 0.1%, compared to the base plan for cases 1 and 2, respectively. Independent Monte Carlo dose calculations yielded an average passing rate of 99.1% and 99.3% for the two cases.

The median total session time was 128 minutes for Case 1, and 116 minutes for Case 2 (Fig. 3). Notably, patients remained on the treatment table only during image acquisition and radiation delivery. Figure 3 also shows the median times for the individual workflow phases. It can be seen that planning is currently the most time-intensive phase owing to the multiple optimizations that are typically required to meet the OAR dose constraints.

Discussion

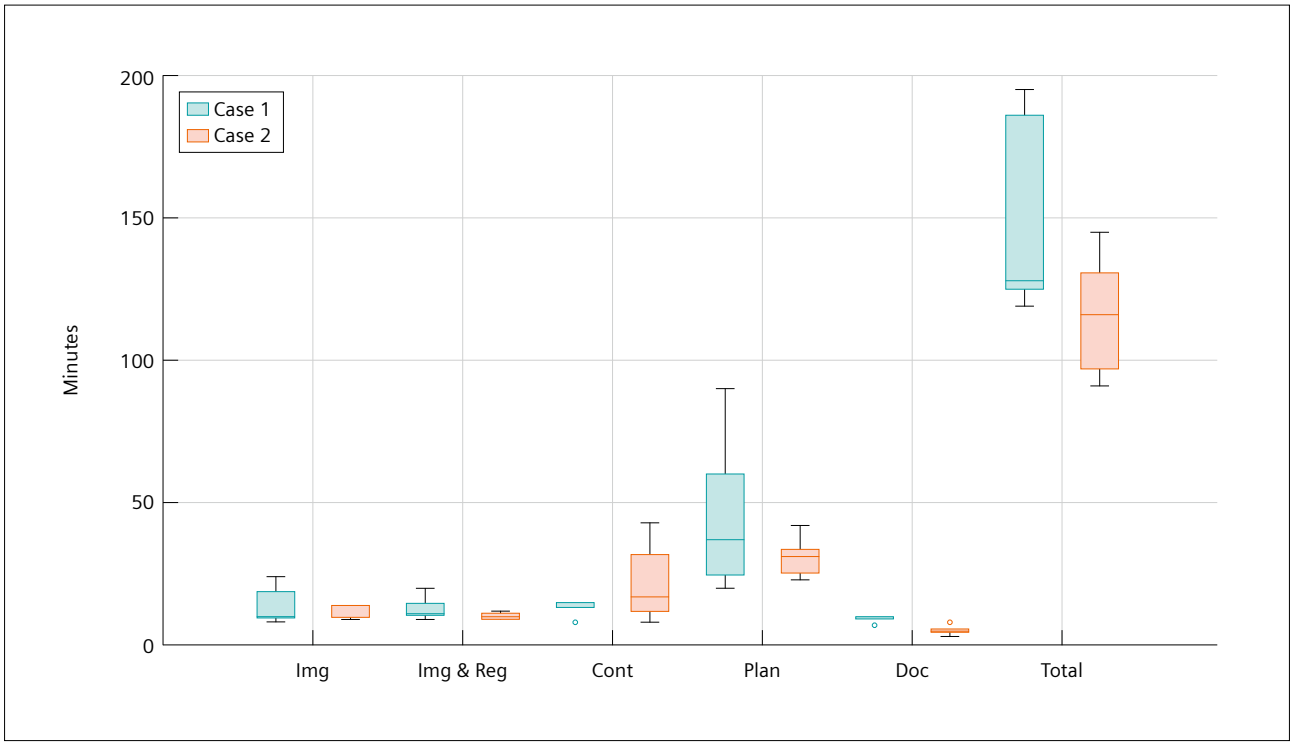
We presented our experience with adaptive radiotherapy (ART) using a CBCT-guided linac with offline MR guidance, detailing the workflow and clinical integration of this approach.

Unlike MR-linac-based adaptive radiotherapy, this approach lacks real-time imaging during beam delivery, as cine MRI is not available for tumor tracking. Additionally, the reported average session times exceed those documented for adaptive radiotherapy [9–11]. However, this method may be more readily implemented in standard radiotherapy departments, offering greater flexibility and leveraging higher-quality MR images for plan adaptation. Furthermore, it has the potential to enhance accessibility and optimize resource use.

In general, ART is particularly promising for managing pelvic cancers, as it enables adaptation to intrafractional anatomical changes, such as variations in bladder and rectal filling. In the future, we plan to conduct a clinical trial to validate the feasibility and efficacy of this approach in patients with pelvic lymph node metastases. This study will incorporate an AirShuttle system (CQ Medical, Avondale, PA, USA) for transferring patients between imaging and treatment, potentially improving workflow efficiency by eliminating the need for patient repositioning [12].

A	Case 1			
		Plan		
Structure	**Clinical goal**	**Base**	**Recalculated**	**Adapted**
CTV	D 95% ≥ 40 Gy	40.28	39.86	40.45
PTV	D 95% ≥ 37.5 Gy	37.5	35.94	37.74
Bladder	D 5 cc < 38 Gy	39.67	37.00	39.54
Bowel	D 1 cc < 25 Gy	1.23	1.95	1.75
Rectum	D 0.5 cc < 38 Gy	40.02	42.79	39.41
B	**Case 2**			
		Plan		
Structure	**Clinical goal**	**Base**	**Recalculated**	**Adapted**
PTV_high	D 95% ≥ 36.25 Gy	36.25	16.51	36.25
PTV_low	D 95% ≥ 33.25 Gy	35.66	14.88	35.26
Bladder	D 5 cc < 38 Gy	37.43	34.24	37.38
Bowel	D 1 cc < 25 Gy	1.80	1.75	3.94
Rectum	D 0.5 cc < 38 Gy	37.67	37.68	37.72

Table 1: Clinical goals for Case 1 **(A)** and Case 2 **(B)**. Dose statistics for the adapted plans are averaged across all fractions.



3 Median duration of the five phases of an adaptive session: imaging (Img), image import and registration (Imp & Reg), contouring (Cont), planning (Plan), and documentation (Doc). "Total" represents the time from MRI acquisition to the completion of radiation treatment.

Conclusion

The approach proposed in this study for ART presents a promising alternative to hybrid systems, offering easier integration into standard radiotherapy settings. It has the potential to improve resource use and increase patient throughput while leveraging high-quality MR imaging. Although adaptation times could still be refined, the new workflow may enhance patient comfort by reducing the time spent on the treatment table.

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