Integrating MRI into Radiotherapy: Insights from Clinical Implementation of an MRI-Guided Workflow for Prostate Cancer

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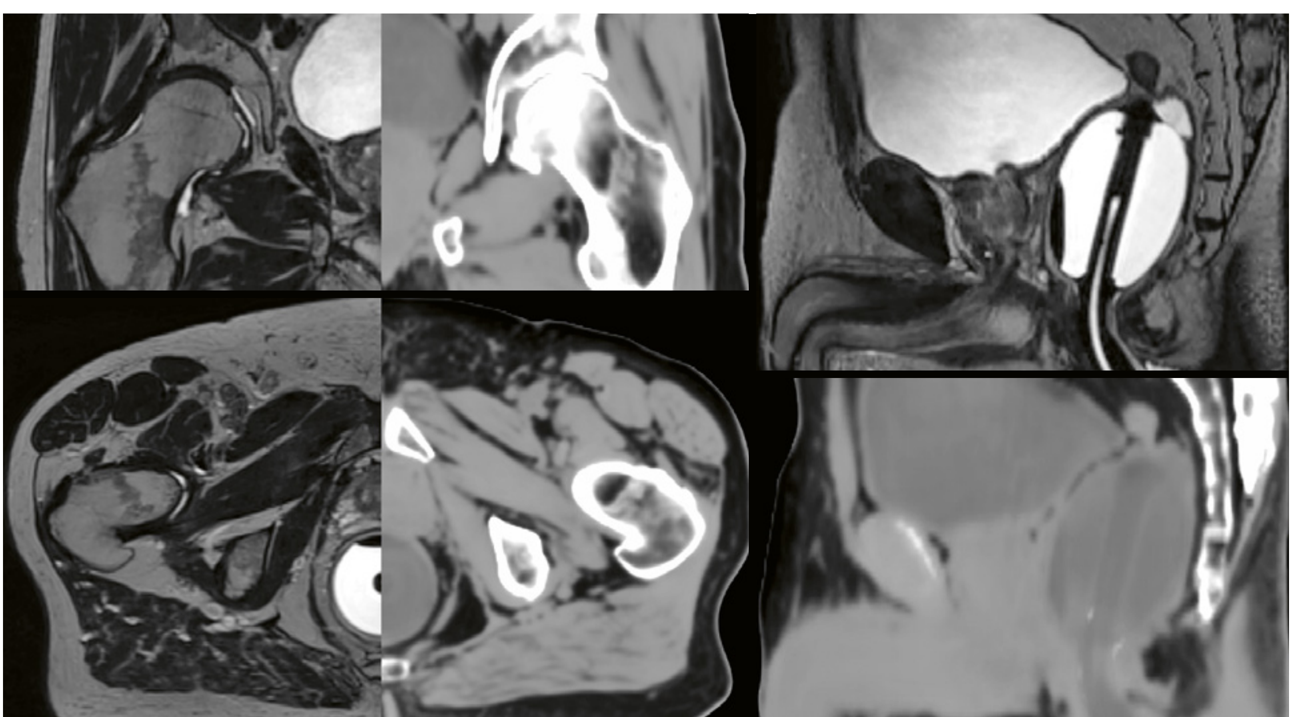
Introduction

Since 2019, the Department of Radiation Oncology at Universitätsklinikum Erlangen has had a dedicated magnetic resonance imaging (MRI) in radiotherapy (RT) program. To facilitate optimal integration of MRI into MR-guided RT protocols, a 1.5T MAGNETOM Sola RT Pro Edition was installed in our department. An interdisciplinary team consisting of radiation oncologists, medical physicists, and radiation therapy technologists (RTTs) collaboratively manage all MR imaging related to RT treatment planning. This specialized approach enables the implementation of RT-optimized imaging setups, tailored protocols, and streamlined imaging-to-treatment workflows designed explicitly to meet RT requirements. Additionally, comprehensive daily, weekly, and monthly quality assurance measures guarantee MRI studies of consistently high quality, providing a reliable basis for precise treatment planning. Beyond its crucial role in planning, the 1.5T MRI system is also used in collaboration with the Institute of Diagnostic Radiology, allowing convenient diagnostic examinations and follow-up imaging for patients treated in our clinic.

MR-guided treatment planning offers several significant advantages, notably the superior soft tissue contrast provided by MRI compared to computed tomography (CT). This enhanced contrast facilitates more precise and personalized delineation of target volumes and improves sparing of organs at risk (OARs), particularly in prostate cancer RT [1, 2]. Synthetic CT (sCT) has enabled MR-only workflows, eliminating the need for traditional CT scans in RT



1 MR-only treatment planning using 3D T2w SPACE and synthetic CT. Note the correct reconstruction of water density for the rectal balloon.

planning. These workflows use MRI alone, with AI algorithms generating the necessary sCT images required for dose calculation. Synthetic CT can streamline treatment planning and reduces patient exposure to additional imaging procedures while eliminating registration uncertainties (Fig. 1). One of the key areas where MRI has significantly improved RT precision is in the treatment of prostate cancer. Prostate tumors often have poor visibility on CT imaging due to insufficient soft tissue contrast, complicating accurate delineation of the target area [3]. This limitation is particularly critical in advanced RT techniques such as stereotactic body radiotherapy (SBRT), where high-dose, hypofractionated regimens demand exceptionally precise targeting. Employing a combination of MRI sequences – including 2D T2-weighted turbo spin echo (T2w TSE), diffusion-weighted imaging (DWI), and dynamic contrast-enhanced T1-weighted GRASP sequences – optimizes localization and delineation of intraprostatic tumors. This approach enables targeted dose escalation to the tumor while simultaneously reducing radiation exposure to adjacent OARs, thereby enhancing treatment efficacy and minimizing toxicity [3]. Notably, a large Phase III trial demonstrated that MR-guided high-dose boosting to intraprostatic lesions reduced biochemical treatment failure rates by more than half (hazard ratio 0.45, $p < 0.001$), highlighting the substantial clinical impact of MR-guided RT planning [1].

A major challenge in prostate RT is the reduction of genitourinary side effects. These effects can significantly impact a patient's quality of life. Erectile dysfunction (ED) is one of the most prevalent toxicities following RT for prostate cancer. It results from endovascular injury, direct neuronal damage, and radiation-induced fibrosis [4]. The neurovascular bundle (NVB), penile bulb (PB), corpora cavernosa (CC), and pudendal arteries (PA) are functionally critical structures, and studies have demonstrated clear dose-toxicity relationships for these tissues. For instance, a mean dose exceeding 20 Gy to the penile bulb or 36 Gy to the pudendal arteries has been associated with an increased risk of post-RT ED [5]. Recent studies have demonstrated the feasibility of MR-guided neurovascular-sparing prostate RT, with promising long-term functional outcomes. For example, Spratt et al. reported that 90% of patients remained sexually active five years after vessel-sparing radiotherapy using MR-based contouring [5]. However, widespread adoption of this approach has been limited by challenges such as MRI accessibility, contouring expertise, and time constraints. Conventional CT-based planning is insufficient for accurately identifying and contouring these delicate structures, due to the limited soft tissue contrast. High-resolution 3D TSE T2w SPACE allows for detailed delineation of anatomical structures for RT treatment planning. Moreover, deep learning MR-based auto-contouring solutions hold the potential to improve accessibility to vessel-sparing radiotherapy and focal dose boost.

With the increasing availability of RT-optimized MRI scanners, the optimal integration of MRI into MR-guided RT treatment protocols is becoming an ever-more important topic. In this article, we outline our experience in establishing an MRI workflow for RT treatment planning, leveraging the capabilities of MR in RT technology from Siemens Healthineers. We describe how dedicated protocols, patient positioning strategies, and deep-learning-supported contouring approaches can contribute to improved RT treatment precision. By sharing our insights, we aim to contribute to the ongoing development of MRI-based RT workflows and to highlight the potential of MR-guided treatment planning for enhancing oncological and functional outcomes in prostate cancer patients.

2 Imaging setup in RT treatment position for prostate cancer patients.

MR-imaging setup in treatment position

Patients receive MRI for RT planning in the RT treatment position to ensure optimal alignment with subsequent therapy sessions (Fig. 2). This approach enhances the accuracy of the target and of the OAR delineation, and improves the reproducibility for patient positioning during treatment. To realize the RT treatment position, a flat tabletop (INSIGHT, CQ Medical, Avondale, PA, USA) and MR-compatible positioning aids are employed. A Body 18 coil within an INSIGHT coil holder is positioned above the patient's pelvic region.

Pre-MRI patient preparation

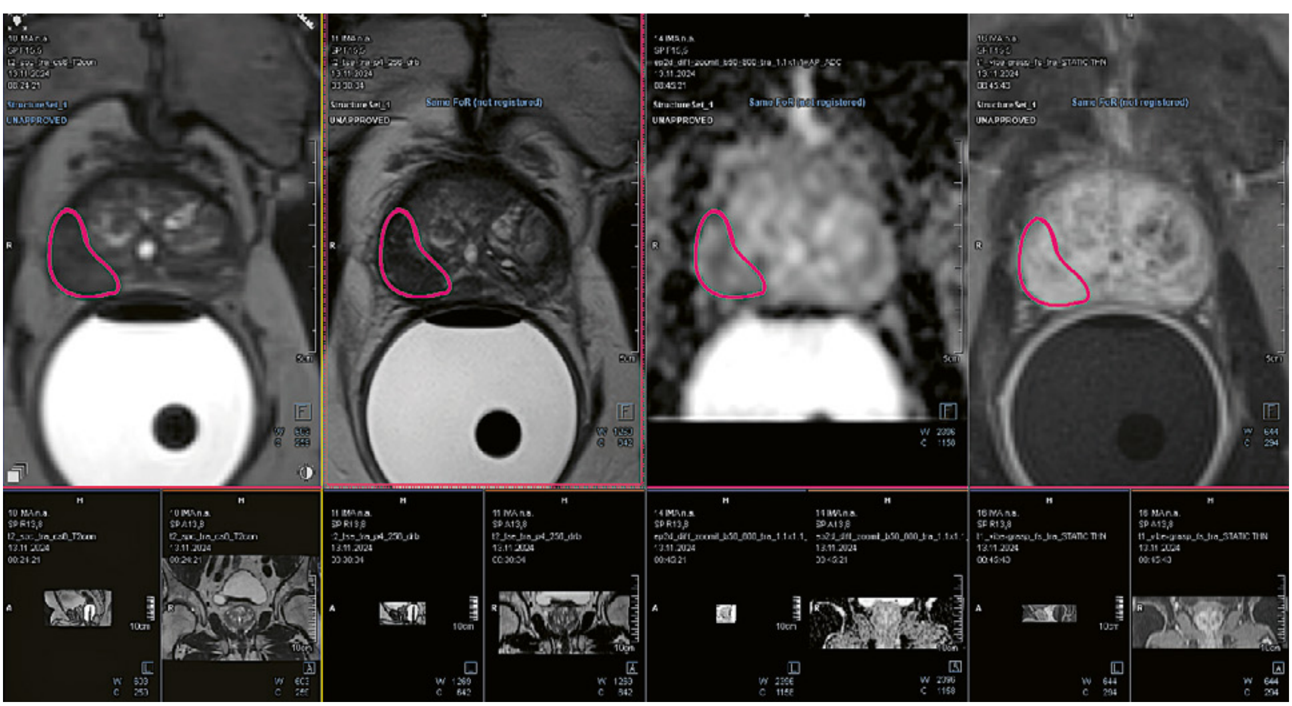
To standardize bladder and rectal conditions, all patients follow a structured preparation protocol prior to the MRI examination and all subsequent RT sessions. This includes:

- Bladder-filling protocol: Patients are instructed to drink a specified volume of water before the scan to ensure consistent bladder filling, as bladder volume can significantly impact prostate position and dosimetric planning.
- Rectal preparation: A rectal balloon (Balloon Rectal Tube, 10 mm/210 mm, Teleflex, Malaysia) is inserted before imaging and filled with 80 mL of water to standardize rectal geometry, reduce prostate motion, and improve treatment reproducibility [6, 7]. This step is particularly important for high-precision techniques such as SBRT, where small changes in prostate position can impact dose delivery and dose distribution [8, 9].
- Pharmacological preparation: To reduce bowel peristalsis and associated image artifacts, patients receive an intravenous injection of butylscopolamin unless contraindicated. Additionally, an intravenous contrast agent is administered to enhance the visualization of the intraprostatic tumor and lymph node metastases on T1w sequences.

MRI acquisition protocol

The primary MRI sequence for treatment planning is a 3D T2w SPACE sequence with Compressed Sensing (CS) acceleration, acquired with an isotropic voxel resolution of $1.0 \times 1.0 \times 1.0\ mm^3$ and a large field of view (FOV) to cover the pelvic region. The T2w SPACE forms the main sequence for treatment planning and is used for general OAR and target volume definition. We also use the T2w SPACE for neurovascular delineation, including the neurovascular bundles and internal pudendal arteries (see below).

Due to its superior in-plane resolution and soft tissue contrast, an additional 2D T2w TSE sequence with Deep Resolve Boost is employed for intraprostatic tumor delineation. DWI is performed using ZOOMit reduced-FOV single-shot echo-planar imaging (EPI) to help identify the intraprostatic tumor for focal dose escalation. A dynamic T1w GRASP VIBE sequence with fat suppression is used to assess dynamic contrast enhancement of intraprostatic lesions. Information from the 2D T2w TSE, the DWI, and the dynamic T1w GRASP is combined to delineate the intraprostatic tumor using the multimodal image viewing capabilities



3 Multiparametric contouring of the intraprostatic tumor using 3D T2w SPACE, T2w TSE DRB, ZOOMit EPI DWI, and dynamic T1-GRASP in *syngo*.via RT Image Suite.

of *syngo*.via RT Image Suite (Fig. 3). Finally, in patients with suspected or known lymph node metastases, a high-resolution, large-FOV 3D T1w VIBE with Dixon fat saturation is used. All protocols are transversal to ensure optimal compatibility with RT treatment planning systems.

This combination of RT imaging setup, dedicated patient preparation, and RT-optimized protocols aims to maximize the benefits of MRI in RT, particularly for specialized RT treatment modalities such as SBRT and vessel-sparing prostate radiotherapy.

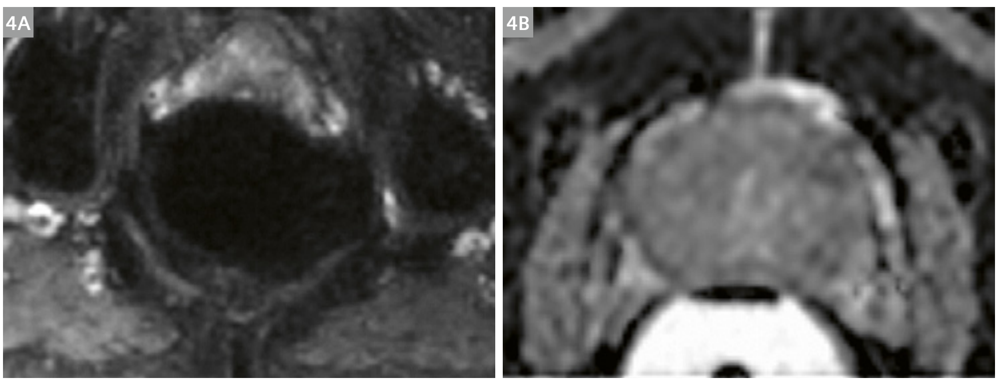
Name of protocol	sCTp1-Dixon-HR	t2_spc_tra_cs8_T2con	t2_tse_tra_p4_256_drb	t2_tse_sag_p4_256_drb	ep2d_diff_zoomit	t1_vibe-grasp_fs_tra_2.1s_3mm	t1_vibe_dixon_tra_p2_352_lymph_nodes
Acquisition type	3D	3D	2D	2D	2D	3D	3D
Orientation	Transverse	Transverse	Transverse	Sagittal	Transverse	Transverse	Transverse
Field of view (cm^2)	50.0 × 37.5	44.8 × 32.0	20 × 20	20 × 20	8.8 × 24.0	24.0 × 24.0	25.5 × 32.0
Acquisition matrix	320 × 240	448 × 320	256 × 256	256 × 256	42 × 114	224 × 224	280 × 352
Acquisition in-plane resolution (mm^2)	1.56 × 1.56	1.0 × 1.0	0.78 × 0.78	0.78 × 0.78	2.11 × 2.11	1.07 × 1.07	0.91 × 0.91
Slice thickness (mm)	2.0	1.0	3.0	3.0	3.0	3.0	2.0
Slice resolution (%)	66%	100%	/	/	/	79%	100%
Echo time (ms)	2.39 / 4.77	255	97	97	51	1.83	2.39 / 4.77
Repetition time (ms)	6.23	2200	7410	6060	3500	4.09	6.91
Flip angle (°)	15	120 / 90	160 / 90	160 / 90	90	12	10
Averages	5	1	4	4	1	1	3
Gradient nonlinearity distortion correction	3D	3D	3D	3D	3D	3D	3D
Shimming of B0 inhomogeneities	Patient-specific	Patient-specific	Patient-specific	Patient-specific	Patient-specific	Patient-specific	Patient-specific
Readout bandwidth (Hz)	1120	558	199	201	1828	500	470
Acceleration factor	4 (CAIPIRINHA)	8 (CS)	4 (GRAPPA)	4 (GRAPPA)	None	CS	2 (CAIPIRINHA)
Deep Resolve Boost	No	No	Yes	Yes	No	No	No
Acquisition time (min)	04:12	05:27	05:13	04:16	04:07	04:16	07:35
Contrast agent	None	None	None	None	None	Gadovist	Gadovist
RT planning indication	Synthetic CT	Main sequence for MR-only contouring, OAR delineation	Intraprostatic tumor delineation	Optional: Urogenital diaphragm (lower target volume boundary)	Intraprostatic tumor delineation	Intraprostatic tumor delineation	Optional: Nodal metastases delineation

Table 1: Sequence protocol parameters for prostate cancer treatment planning. CS: Compressed Sensing

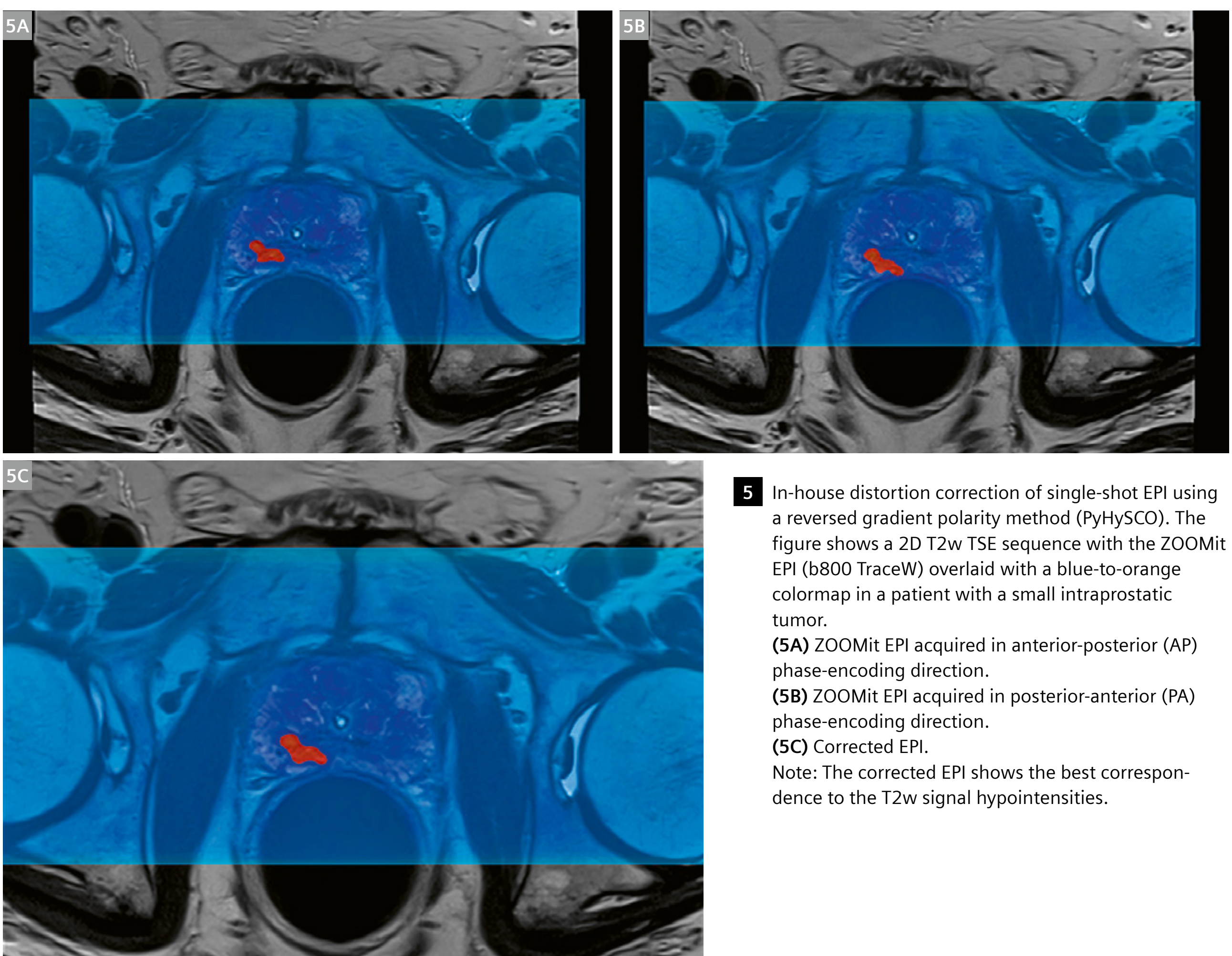
Optimizing MR imaging for RT planning: Lessons learned and practical improvements

Over the course of implementing MRI for RT treatment planning in prostate cancer, we identified several modifications to improve image quality and geometric accuracy. One significant adjustment was the optimization of the medium used for filling the rectal balloon. Initially, air was used as a filling material, following the conventional CT-based workflow, but we observed that this led to increased distortions, particularly in DWI. To mitigate this, we transitioned to filling the rectal balloon with water (Fig. 4). This change significantly improved signal homogeneity and reduced susceptibility artifacts, leading to more reliable diffusion images and better visualization of intraprostatic diffusion restrictions.

Improved single-shot EPI distortion correction was subsequently introduced via an in-house postprocessing



4 Air vs. water in the rectal balloon. **(4A)** Air-filled rectal balloon; **(4B)** water-filled rectal balloon.



5 In-house distortion correction of single-shot EPI using a reversed gradient polarity method (PyHySCO). The figure shows a 2D T2w TSE sequence with the ZOOMit EPI (b800 TraceW) overlaid with a blue-to-orange colormap in a patient with a small intraprostatic tumor.
(5A) ZOOMit EPI acquired in anterior-posterior (AP) phase-encoding direction.
(5B) ZOOMit EPI acquired in posterior-anterior (PA) phase-encoding direction.
(5C) Corrected EPI.
Note: The corrected EPI shows the best correspondence to the T2w signal hypointensities.

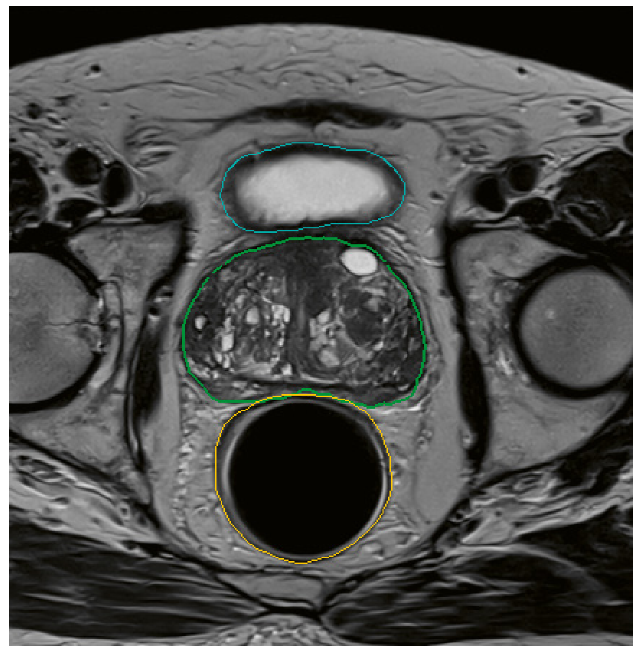
solution. Geometric distortions in EPI along the phase-encoding direction can complicate the precise localization of intraprostatic tumors for target volume definition. To mitigate these issues, we implemented a reversed gradient polarity correction method using the GPU-enabled susceptibility artifact distortion correction python library PyHySCO [10]. An in-house application was built that loads the two EPI series with opposite phase-encoding direction in DICOM format and outputs corrected series (Fig. 5).

Another important observation during the implementation of our MR-based planning protocol was the sequential order between fiducial marker implantation and planning MRI acquisition. It was observed that performing the MRI after marker placement could compromise intraprostatic tumor delineation. These early post-interventional scans often revealed localized hemorrhage around the fiducials, as well as artifacts on DWI. Such effects may mimic or obscure intraprostatic lesions, thus hampering accurate tumor delineation. To address this, the MR-guided prostate treatment planning workflow was changed to perform any fiducial marker implantation after planning MRI.

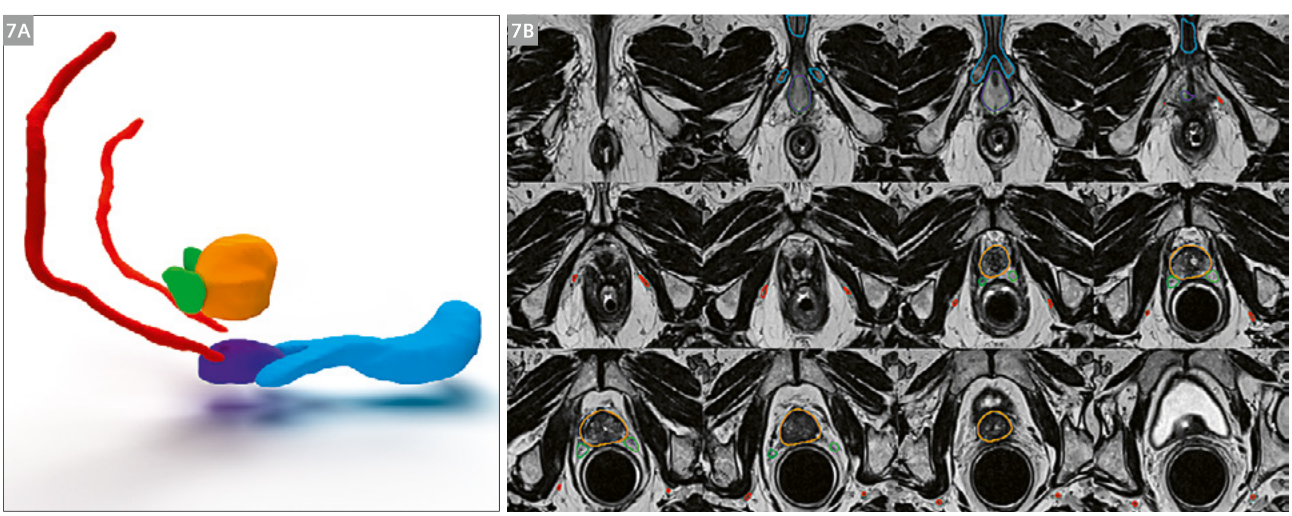
Introducing artificial intelligence for MRI-guided radiotherapy planning

The integration of artificial intelligence (AI) into MRI-guided RT planning is transforming the way treatment is designed and optimized. At the Department of Radiation Oncology at Universitätsklinikum Erlangen, we have implemented deep learning approaches to enhance image analysis and support EBRT and brachytherapy planning [11]. We recently introduced MR-based autocontouring for OARs[1] in male pelvis patients via the *syngo*.via VC10A CUT version (Siemens Healthineers, Forchheim, Germany). In prostate cancer patients, we observed a significantly reduced manual workload, with MR-based OAR autocontouring being particularly valuable for MR-only workflows (Fig. 6).

An interesting novel application for AI in radiotherapy is the automated contouring of delicate neurovascular



6 MR-based OAR autocontouring for the male pelvis using *syngo*.via VC10A CUT[1] in clinical treatment planning.



7 Deep learning neurovascular OAR autocontouring on high-resolution T2w SPACE for a prostate cancer test case. **(7A)** 3D rendering of autosegmented neurovascular OARs. **(7B)** Transverse cross-sections. The nnU-net model was trained in-house on 40 manually delineated T2w SPACE datasets to autosegment the internal pudendal artery (red), the neurovascular bundle (green), the corpora cavernosa (blue), the prostate (orange), the penile bulb (violet), and the seminal vesicles (green).

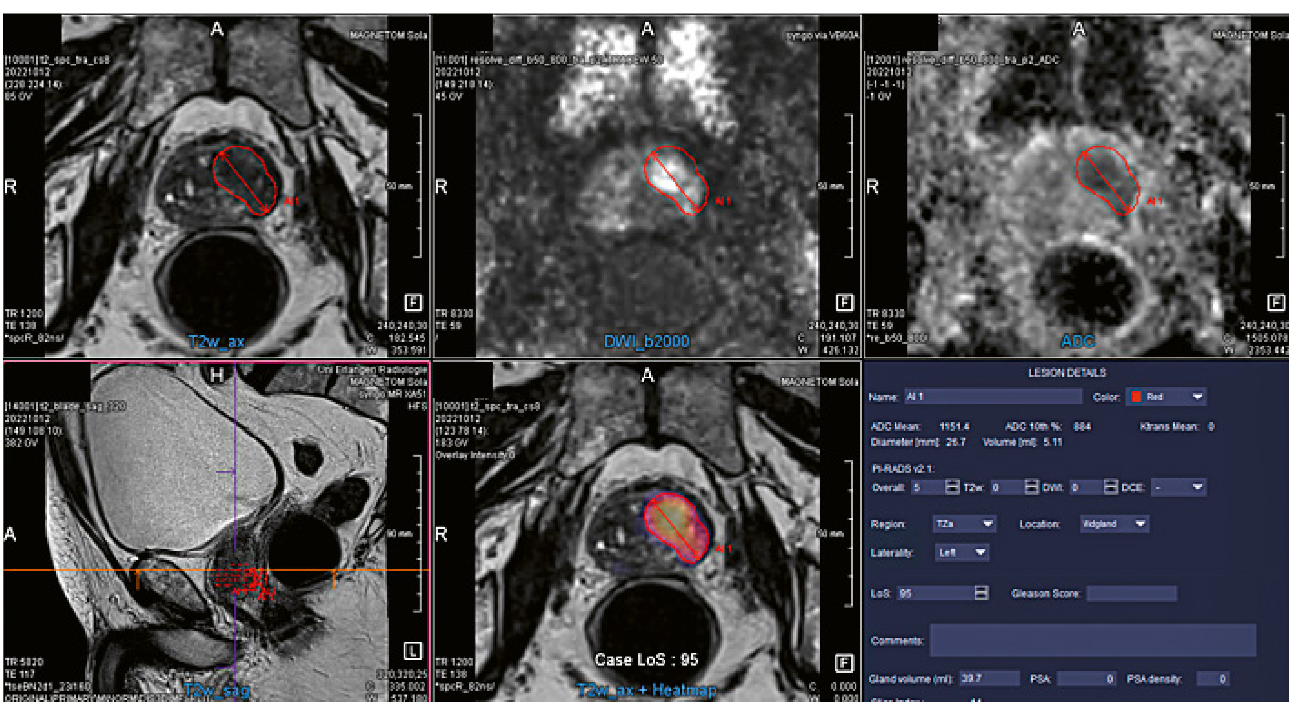
[1] *Work in progress. The application is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.*

OARs that are visible thanks to the detailed image information provided by MRI. Traditional manual segmentation of high-resolution image datasets is time-consuming and prone to interobserver variability. Deep learning architectures, such as 3D U-Net [12], can assist in automatically delineating the OARs and target volumes. We developed and validated an in-house model for automatic segmentation of neurovascular OARs in high-resolution 3D T2w SPACE datasets based on the nnU-net pipeline [13], confirming its robustness and accuracy (Fig. 7). The model can autosegment neurovascular OARs including the internal pudendal arteries, penile bulb, and neurovascular bundles with high accuracy, and is currently being introduced into our clinical treatment workflow. Similar solutions will be interesting to integrate into commercial solutions to facilitate vessel-sparing radiotherapy in prostate cancer.

As well as supporting OAR delineation, AI could also play an important role in identifying dominant intraprostatic lesions (DILs) for focal dose escalation. Multiparametric MRI can enable personalized treatment planning for precisely targeting high-risk tumor regions with selective dose escalation. Techniques such as the simultaneous integrated boost (SIB) enable focused intensification of the radiation dose directly to these critical areas, improving biochemical cure rates in prostate cancer [1]. However, radiation oncologists frequently lack expert knowledge on interpreting multiparametric prostate images. Deep learning applications might serve as a robust decision-support tool throughout this process. We are currently evaluating the *syngo*.via Prostate AI Frontier[1] application for automatic segmentation of intraprostatic lesions for RT treatment planning. The Prostate AI Frontier application can detect and autosegment intraprostatic tumors by combining T2w, DWI, and contrast-enhanced T1w input series (Fig. 8). Clinical integration of similar autosegmentation solutions could increase precision and standardization in prostate cancer RT, while reducing manual planning time to facilitate single-day treatment planning and adaptive MR-guided protocols.

Conclusion

Integrating MRI into RT planning has significantly advanced prostate cancer treatment. Superior soft tissue contrast enables precise delineation of the prostate, accurate identification of dominant intraprostatic lesions, and clear differentiation of surrounding organs, resulting in highly personalized treatment strategies. At our center, we developed a combined MRI planning and RT treatment planning workflow, which includes standardized patient preparation, dedicated imaging in the treatment position, synthetic CT, and deep learning postprocessing. While implementing the comprehensive MR-guided planning protocol, we learned to optimize multiple aspects. This included changing the medium used for filling the rectal balloon, avoiding fiducial implantation before MRI, and implementing an in-house solution for reversed gradient polarity correction of single-shot EPI sequences. The recent



8 The *syngo*.via Prostate AI Frontier[1] application can autodetect and autosegment intraprostatic tumors on multiparametric MRI input data. AI applications could improve accessibility to MR-guided focal dose escalation in prostate cancer.

incorporation of MR-based pelvic OAR autocontouring has considerably reduced clinical workload and is particularly promising for MR-only workflows. Combining RT-optimized MRI with AI postprocessing applications could be crucial in facilitating advanced MR-guided treatment concepts such as focal dose boost and neurovascular sparing.

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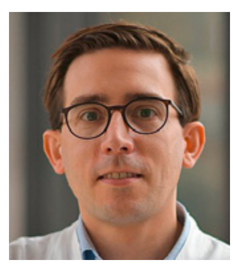

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