Enhancing Precision in Radiation Therapy by Integrating MRI into Treatment Planning

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Imaging is an integral part of radiation planning. It provides information about the target volume and the adjacent organs at risk (OARs), which is critical at multiple points in the radiation therapy (RT) workflow. Historically, RT planning used plain X-rays, but this was largely replaced by computed tomography (CT) in the 1990s. Today, CT imaging is still the major modality for treatment planning and dose calculation. However, magnetic resonance imaging (MRI) provides unique advantages in certain clinical situations, thanks to its superior soft tissue contrast and provision of additional functional information. MRI is nowadays used for planning both external beam RT (EBRT) and brachytherapy. It is commonly used for RT planning in the prostate, brain, nasopharynx, liver, pancreas, rectum, cervix, and spine. The following overview provides some case-based examples to highlight the role of MRI in radiation dose planning and delivery. The challenges and solutions (Table 1) are also discussed.

MRI helps oncologists accurately contour the tumor and surrounding OARs. The common sequences used in RT planning are as follows:
- **T1-weighted MRI** to define anatomical structures
- **T2-weighted MRI** to highlight tumors and edema
- **Diffusion-weighted imaging (DWI) and perfusion MRI** to provide functional insights into tumor biology

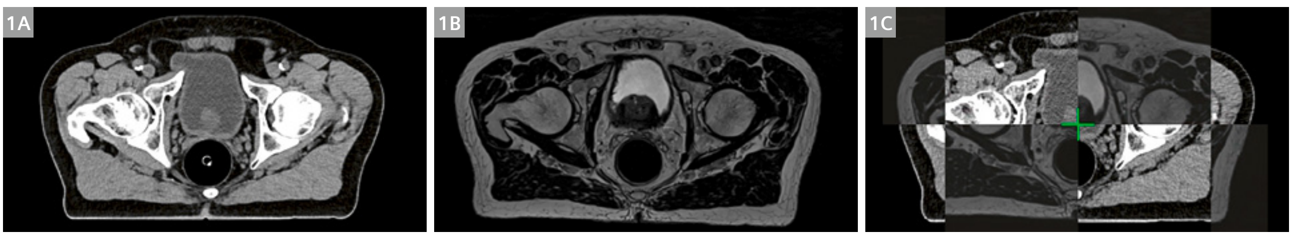
Workflow

The most common workflow involves performing both a CT and an MRI scan of the patient in the planning position. The two images are then fused for contouring and planning. Depending on the clinical situation, either rigid or deformation registration is used for image fusion. While MRI provides excellent soft tissue contrast for contouring the target and/or the OARs, CT imaging is still required for electron density information to enable accurate dose calculation.

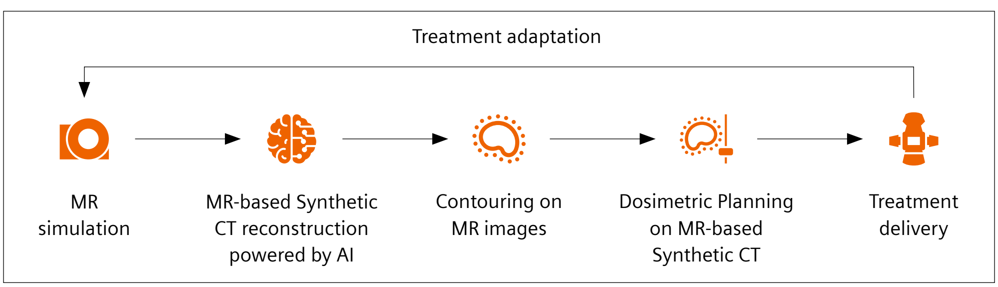
Challenge	Solution
Geometric distortions in MRI	MRI-CT fusion
	Distortion correction algorithm with in-plane resolution of 1–2 mm
Lack of electron density information for dose calculation	MRI combined with CT imaging for accurate dose planning
	Deep learning algorithm to create MR-based synthetic CT imaging
Motion artifacts	Motion management techniques, such as 4D MRI

Table 1: Challenges and solutions of MRI in RT.

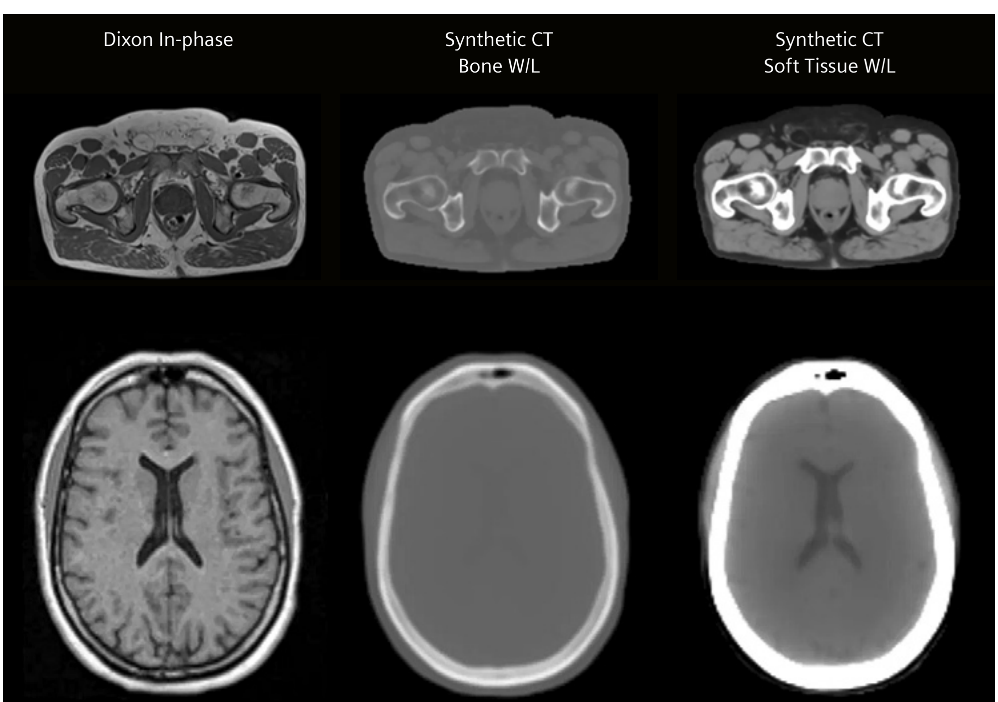
However, fusing CT and MRI scans can make the workflow more complicated and may introduce uncertainties to the planning process. MR-based synthetic CT imaging offers the possibility of combining dosimetric planning with the superior soft tissue contrast of MRI for OAR and target delineation. An MR-only workflow eliminates the need for CT-to-MRI registration, reducing systematic registration errors and unnecessary ionizing radiation from the CT scan. Synthetic CT imaging has been developed and evaluated in support of MR-only treatment planning in a variety of anatomical sites, including the brain and pelvis. The key sequence for MR-based synthetic CT reconstruction is the T1-weighted VIBE-Dixon sequence. It takes 3 to 5 minutes to acquire these images. A deep learning algorithm is used to create synthetic CT imaging with an in-plane resolution of 1.0 × 1.0 mm (brain) and 2.0 × 2.0 mm (pelvis). The result has excellent geometric and HU fidelity for dose calculation in the brain and pelvis.



1 **(1A)** CT scan and **(1B)** MRI of the pelvis with **(1C)** deformation fusion of the prostate. Variations in bladder and rectum filling can be seen in the two scans.



2 MR-only workflow with synthetic CT imaging for dose calculation and daily cone beam CT (CBCT) match.

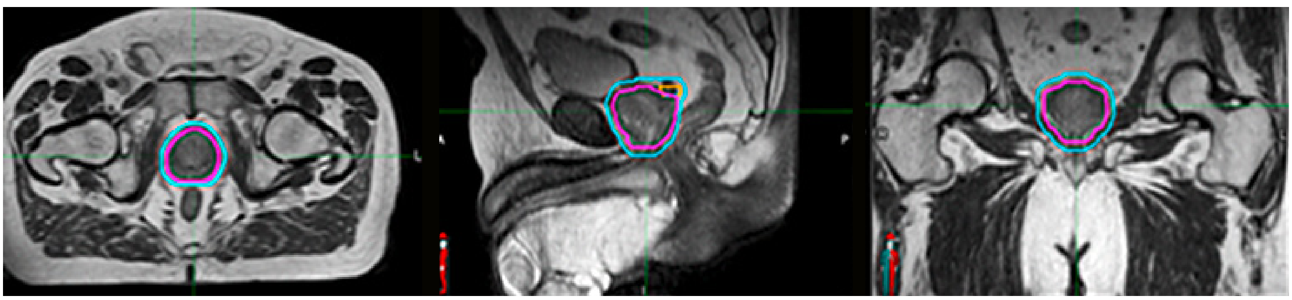


3 Dixon in-phase MRI with synthetic CT scan.

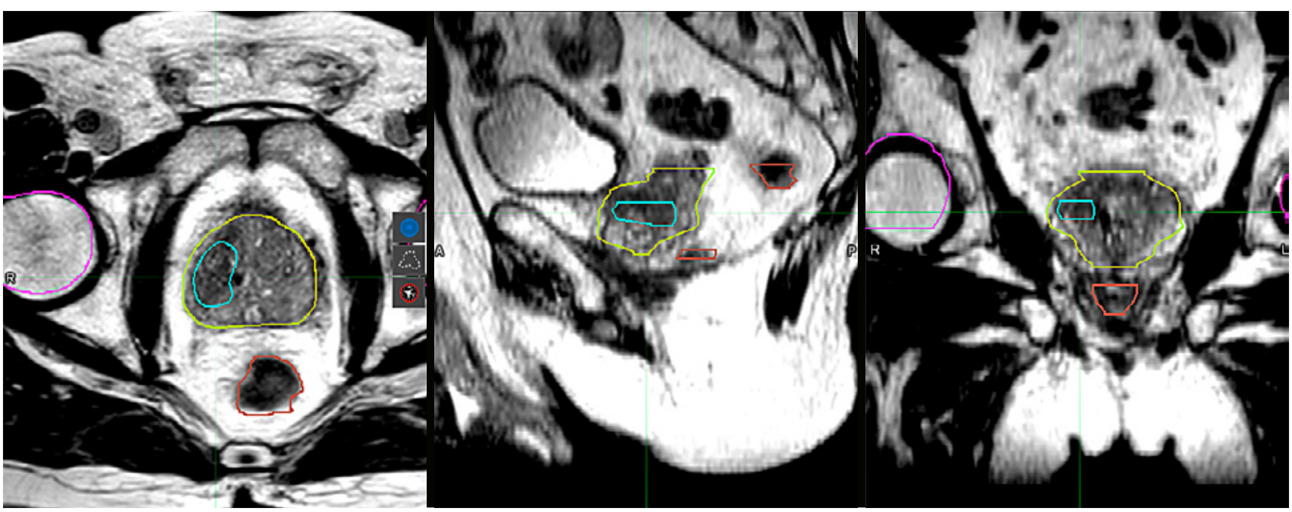
Clinical examples

Prostate cancer

Prostate cancer is one of the most common cancers where MRI is used for RT planning. The delineation of the prostate is better, especially at the base and apex, which leads to a 20%–30% reduction in target volume compared to CT imaging. This is important, as prostate EBRT has moved to hypofractionation (20 fractions) or ultrafractionation (5 fractions), and accurate volume delineations add to the precision of RT delivery and expose less healthy tissue to radiation. MRI also allows to deliver isotoxic microboost to dominant lesions, which can be contoured on MRI using a combination of T2-weighted and diffusion-weighted images. This has been shown to reduce local recurrence without significantly increasing morbidity.



4 MRI of the pelvis showing target contouring of the prostate (dark pink), proximal seminal vesicles (light orange), and planning target volume (blue).

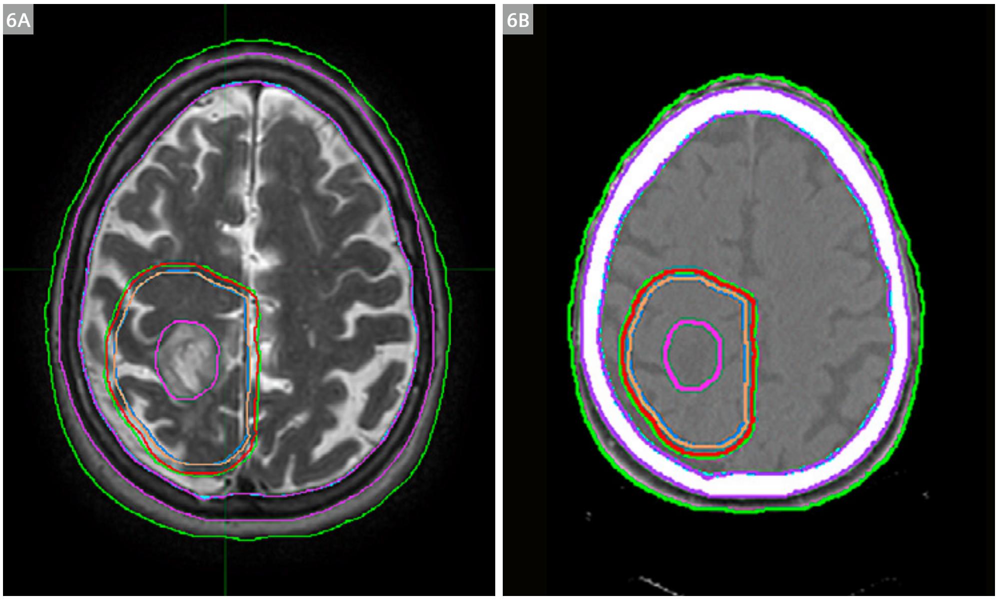


5 MRI of the pelvis with contouring of the prostate (green) and the dominant lesion for microboost (blue).

Brain

MRI is the gold standard for both primary brain tumors and metastases. Contrast-enhanced T1 sequences and T2-weighted FLAIR sequences are routinely used for contouring in primary brain tumors. MRI also helps to better define OARs such as the optic chiasm, nerves, pituitary, brainstem, and hippocampus. Hippocampal-sparing RT for brain metastases has been shown to reduce cognitive decline.

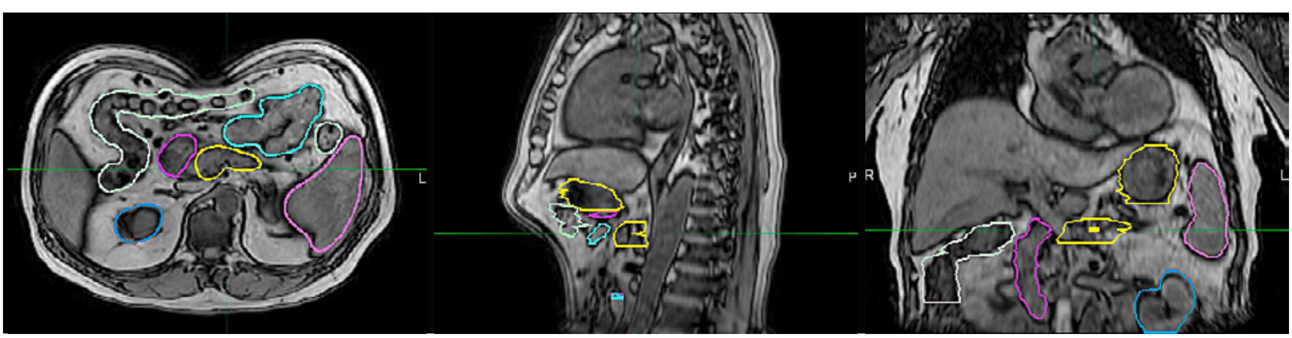
Stereotactic radiosurgery is one of the most common techniques used in brain metastases. For Linac-based radiosurgery, fusion of MRI (3D MPRAGE) and CT scans is currently required for contouring, planning, and treatment. The outcomes are very good, with local control > 80%, but this workflow can sometimes lead to delays of one to two weeks between the MRI scan and treatment. Data shows that a delay of more than one week between MRI and radiosurgery can lead to changes in volume in a significant number of patients. The MR-only workflow can potentially allow us to compress the time between simulation and treatment, and therefore treat these patients on the same day.



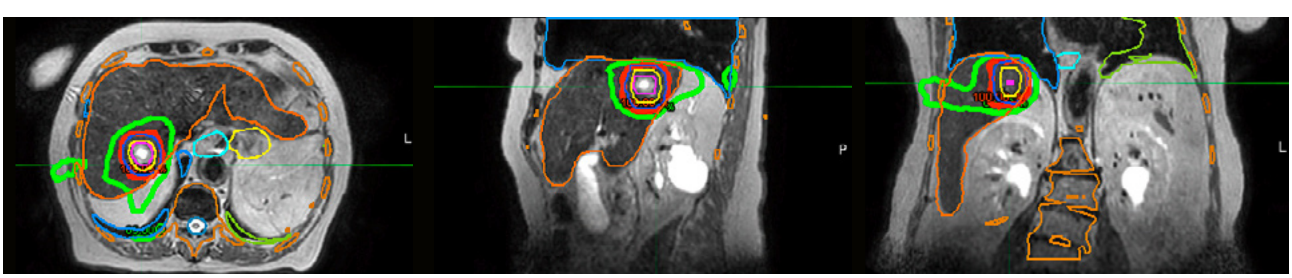
6 **(6A)** T2-weighted MRI showing the gross tumor volume (GTV) in pink with the clinical target volume (blue) and the planning target volume (red), compared to **(6B)** CT scan of the brain showing an inconspicuous GTV (pink).

Pancreas and liver

MRI is better suited to delineating liver and pancreatic lesions, and is routinely fused with planning CT imaging to help contour the target volume. Four-dimensional MRI can further help this workflow to better define targets and OARs by accounting for positional changes caused by breathing.



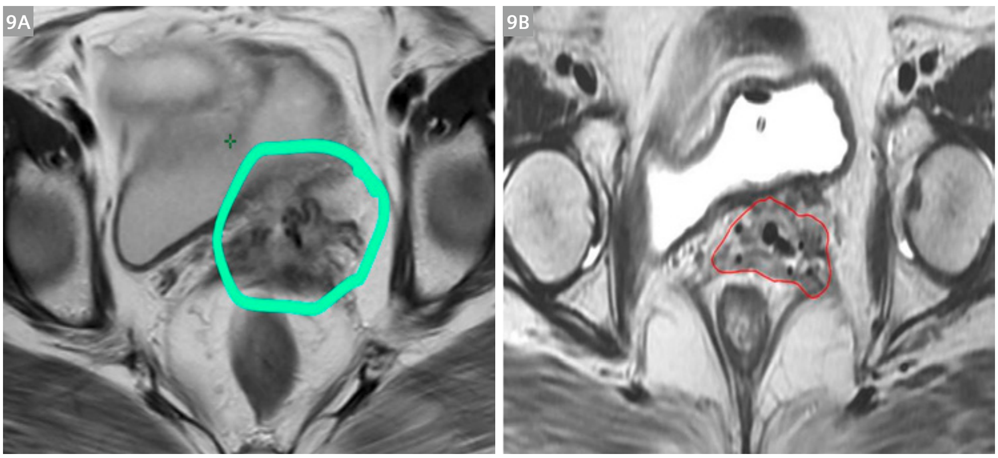
7 MRI of the abdomen showing the pancreatic gross target volume (yellow), and the duodenum (pink), small bowel (green), and stomach (blue).



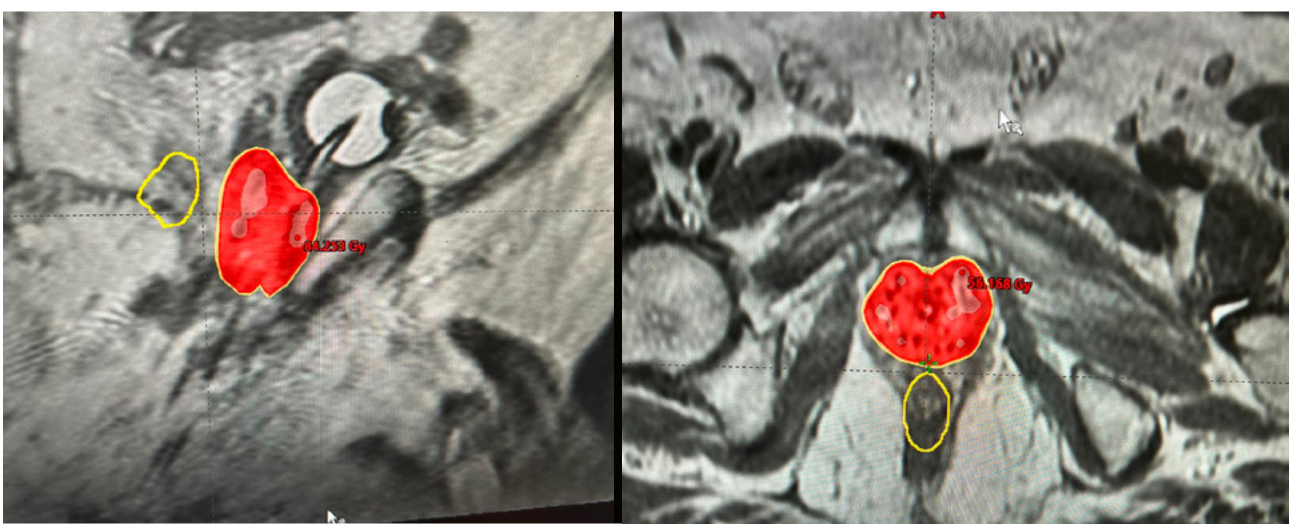
8 Liver metastases (pink: metastases, and green: 50% isodose line) with prescription dose covering the target.

Brachytherapy

MRI is now commonly used for gynecological and prostate brachytherapy. The EMBRACE studies have shown that MR-based adaptive brachytherapy for cervical cancer helps improve local control and reduce morbidities. The target volume is smaller compared to CT imaging, and residual disease is visible, which can help with focal dose escalation. With modern MR-based planning, local control is almost 90% for locally advanced cervical cancer. Similarly, MRI is used for prostate brachytherapy, both for a boost after EBRT and/or as salvage for radiorecurrent disease. The visibility of lesions on MRI helps to boost or better treat the radiorecurrent area.



9 **(9A)** Prebrachytherapy MRI showing eccentric tumor in the cervix, with a hybrid applicator (Aarhus Applicator Set) with straight and oblique needles to cover **(9B)** the high-risk clinical target volume (red).

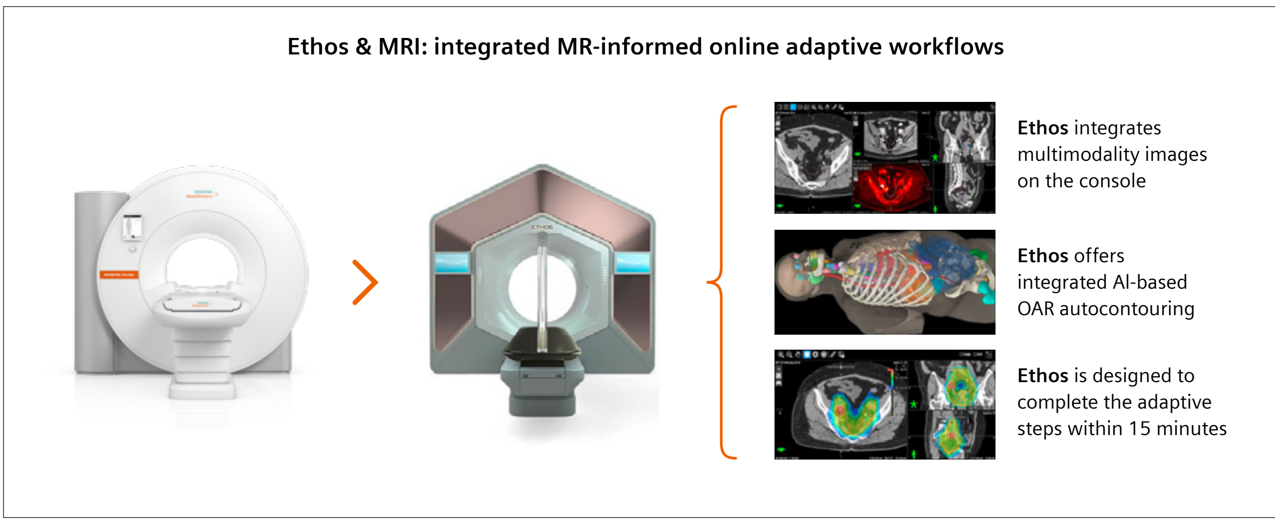


10 MRI of the prostate, with a high-dose-rate brachytherapy boost of 15 Gy covering the target (yellow and solid red) and sparing the rectum (yellow).

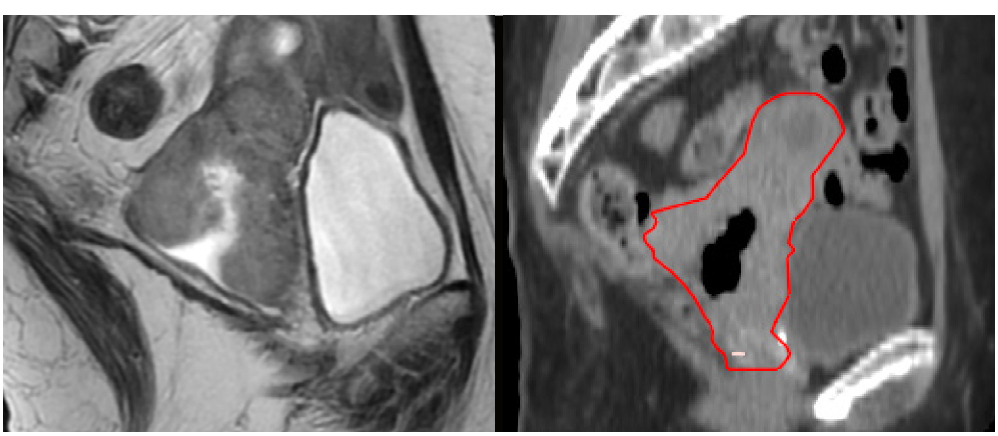
Adaptive radiation therapy

In adaptive RT, the treatment is adapted in response to anatomical changes during the course of RT. Adaptation while the patient is still on the treatment couch is called online adaptive RT(oART). If the adaptation is done in between fractions, it is called offline adaptive RT.

Ethos (Varian, a Siemens Healthineers Company, Palo Alto, CA, USA) is an online adaptive technology. Recent integration of state-of-the-art HyperSight imaging (Varian, a Siemens Healthineers Company, Palo Alto, CA, USA) has opened up significant scope to include MRI in the workflow (Fig. 11). Since HyperSight has excellent soft tissue contrast and can be used for dose calculation, it could enhance online adaptation through an efficient MRI-CBCT workflow. Weekly MRI using fusion with HyperSight CBCT can be used to adjust the contouring in diseases like brain tumors, cervical cancer, and rectal cancer, as significant changes can occur during the course of radiation. This makes it possible to combine the efficiency of Ethos for oART with MR-based volumes for adaptation. The same concept can also be used for offline adaptive RT using TrueBeam. During the course of RT in certain cancers such as cervical cancer, tumor volumes can regress by as much as 60%–80% during EBRT. Integrating weekly MRI scans can help us treat to reduced margins and thus improve therapeutic ratios.



11 Dedicated MRI for RT. Generate and MR image for potential treatment adaption and send to Ethos. This Workflow is applicable to all RT Pro Editions (1.5T MAGNETOM Sola, 3T MAGNETOM Vida, and 0.55T MAGNETOM Free.Max RT).



12 The difference between MRI and CT imaging in cervical cancer, and how MRI helps with contouring.

Conclusion

The role that MRI plays in radiation oncology will continue to grow as we move toward precision and personalized care. It helps to define targets and OARs for treatment planning, boosts volume definition, and enables early assessment for response and online adaptive RT. Ongoing studies are conducting MRI scans throughout the course of RT to enable adaptive EBRT for CBCT-based linear accelerators, to establish the impact on patient outcomes. Incorporating MRI into adaptive workflows for disease sites where we expect to see changes in the target volume (anatomical and/or functional) during RT can potentially help us improve therapeutic ratios, either by reducing the margins or changing the prescription dose. An MR-only workflow also obviates the need for a CT scan, even in adaptive workflows. Rapidly expanding AI-based MRI autosegmentation will also help with efficiency and with incorporating this technology into practice.

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