

White paper

MR-only RT planning for the brain and pelvis with Synthetic CT

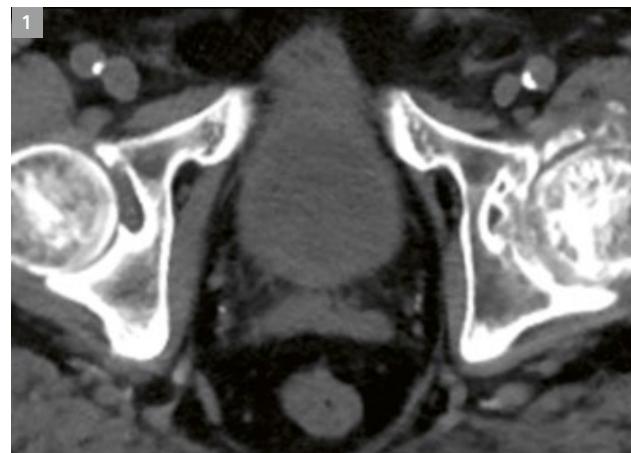
Over the past decades, the use of magnetic resonance (MR) imaging to support radiation therapy (RT) treatment planning has increased significantly. As an example, MRI utilization in RT treatment planning in the United States increased from 6 % to 24 % between 2006 and 2017 [1]. This growing trend can be attributed in part to the superior soft-tissue contrast of MRI compared to CT imaging. This can potentially allow more accurate delineation not only of a patient's target volume, but also of the surrounding organs at risk (OARs), as indicated in Figures 1 and 2a. MR imaging can additionally offer information on tumor activity such as cellular density and tumor biology with functional imaging, Figure 2b.

Until now, the inherent limitation of MR imaging for RT planning compared to CT imaging has been its inability to provide the electron density information that is needed for dose calculation in a treatment planning system. CT imaging provides it, therefore CT has been utilized in almost 100 % of RT planning [1].

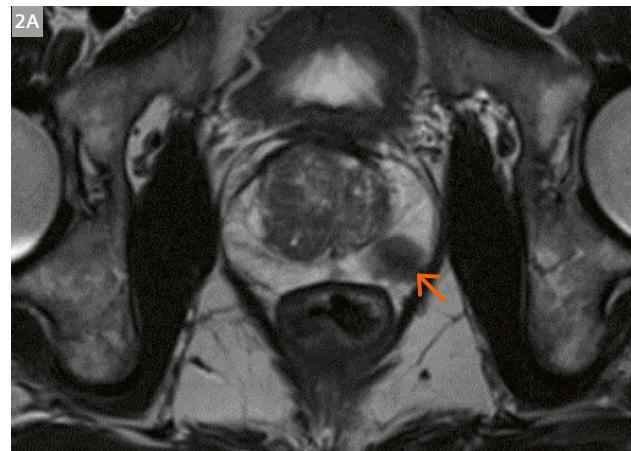
To benefit most from the additional information that MR can provide, clinical institutions are increasingly including MR images in their workflow. Until recently, the required electron density information could only be provided by CT imaging. Therefore, a combined workflow is used that includes both traditional CT simulation for dose calculation and MR imaging for superior and more precise delineation of targets and surrounding soft tissue (OARs) is the current standard when using MR images for radiotherapy.

A combined MR and CT workflow includes image registration to align the images from both modalities to the same coordinate system. The target volumes and some OARs defined in the MR image can then be transferred to the CT image, in which the plan optimization and the dose calculation can be performed. In summary, the electron density information required for accurate dose calculation and the digitally reconstructed radiographs (DRR) used for patient positioning are obtained from the CT scan and excellent soft-tissue contrast as well as functional imaging for contouring and treatment assessment are provided by MR imaging. However, several challenges arise from a combined MR and CT workflow. These challenges include:

- Accurate image registration between MR and CT, given that the two images contain different information that make it challenging to identify common features
- Patient scheduling: due to organs filling over time and other physiological processes, imaging slots need to be booked close to one another
- Financial issues such as bundled reimbursement schemes not awarding the use of additional imaging in the course of a patient's radiotherapy treatment



1 CT image of prostate provides electron density information for dose calculation



2 (2A) MR image of prostate with superior soft-tissue contrast for more accurate delineation of the prostate, surrounding organs at risk, and lesion (indicated by an arrow)

(2B) Anatomical MR image with diffusion weighted imaging overlaid showing an area of strongly restricted diffusion, suggesting active tumor

Images courtesy of Radiologische Allianz, Hamburg, Germany

In close collaboration [2,3,4] with our clinical partners, Siemens Healthineers has co-developed Synthetic CT, enabling MR-only radiotherapy workflows for the brain as well as for both the male and the female pelvis. In Figures 3 and 4, an example of Synthetic CT is shown for the brain and pelvis respectively. Synthetic CT provides images generated from MR scans that emulate CT images regarding electron density information. The images contain different Hounsfield units (HU) for different materials and these HU can be converted to electron density in the treatment planning system (TPS) using a calibration curve. The purpose of Synthetic CT images is to provide the electron density information to obtain dose calculations with the same accuracy as that of a CT image, enabling MR-only radiotherapy planning without needing additional CT images.

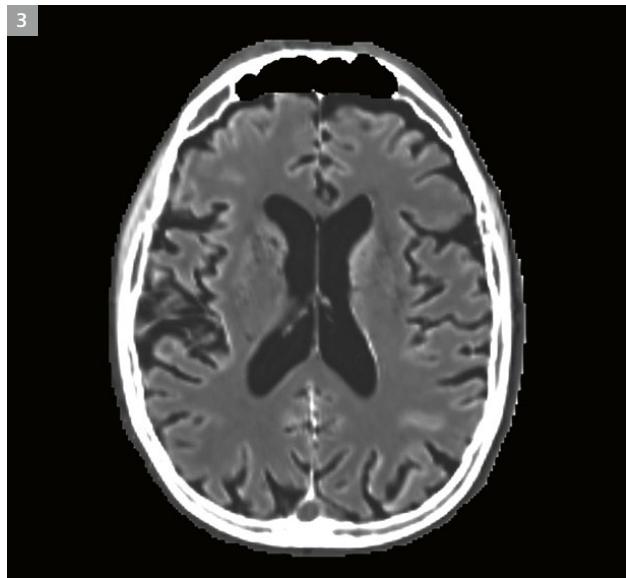
MR-only radiotherapy planning workflow

MR imaging for simulation and treatment planning

Imaging starts with the MAGNETOM RT Pro edition, a dedicated MR platform for radiation therapy, which includes:

- The RT Dot Engine with workflow guidance and dedicated protocols optimized for RT applications, including sequences to generate Synthetic CT images. The sequences included in the RT Dot Engine are optimized for spatial integrity of the acquired images, applying automatic 3D distortion correction for robustness and reproducibility. In addition, the images are automatically reconstructed in the axial orientation to make images compatible with the therapy planning software of all vendors.
- Dedicated RT patient table top overlays and immobilization devices and an optional external laser bridge to assist in consistent and reproducible patient positioning.
- Coil bridges developed for consistent imaging in the treatment position.
- Quality assurance (QA) procedure recommendations enable the system to operate safely and deliver images within specification.

In the following, we present a more detailed description of the generation of the Synthetic CT image for both the brain and the pelvis.



3 Synthetic CT for brain

Image courtesy of Centre Hospitalier de l'Université de Montréal – CHUM, Montreal, Canada

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4 Synthetic CT for pelvis

Image courtesy of the University of Tübingen, Tübingen, Germany

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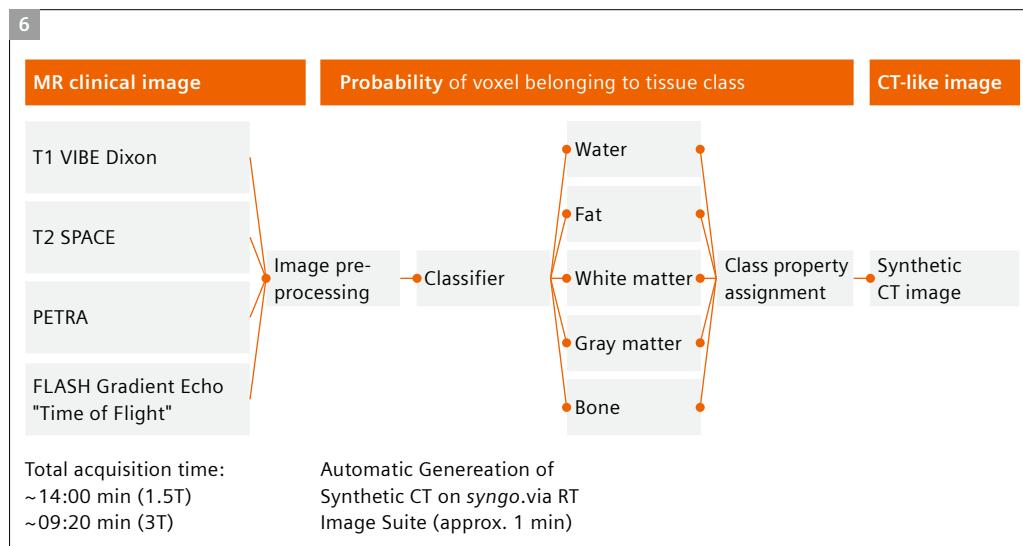
5 MAGNETOM RT Pro edition for MAGNETOM Vida with patient table top overlay and coil positioning aids (Qfix) and external laser bridge (LAP)

Synthetic CT generation for the brain

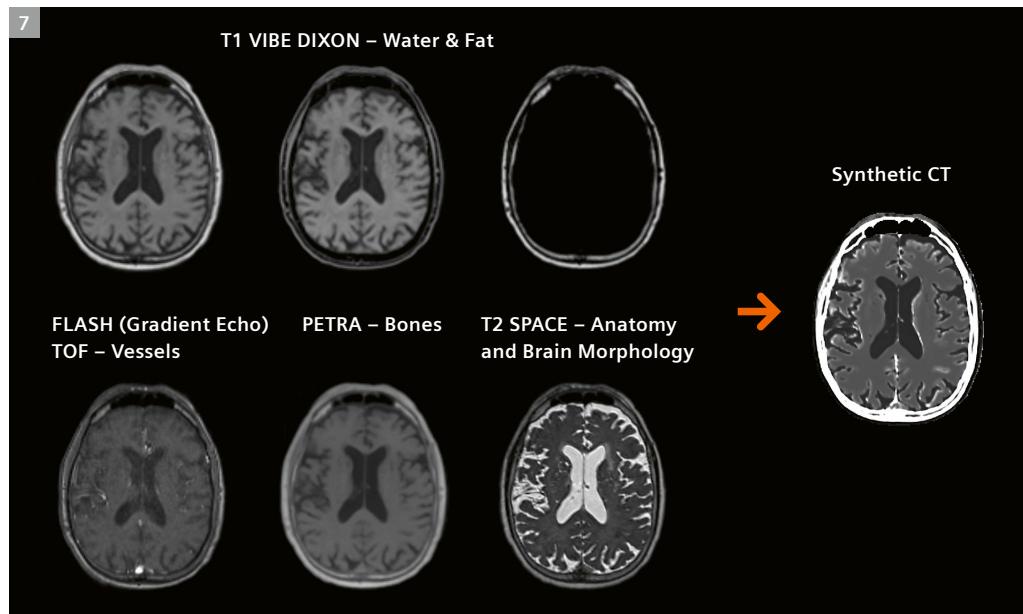
The brain RT Dot Engine includes the following sequences for generating Synthetic CT images of the brain: T1 VIBE Dixon, T2 SPACE, PETRA, FLASH Gradient Echo with "Time of Flight generated contrast" [2]. As Figure 6 illustrates, the four sequences are run and the different tissues are assigned to a class property leading to the generation of the Synthetic CT image. The acquisition of the four sequences takes around 14 minutes with the MAGNETOM Sola (1.5T) and around 9 minutes with the MAGNETOM Vida (3T). Figure 7 shows representations of the clinical images and how the information from the individual sequences contributes to the resulting Synthetic CT image. The T1 VIBE Dixon sequence produces the water and fat images

and the T2 SPACE sequence (with an isotropic voxel size of 1 mm) is run to visualize the brain anatomy and morphology. Furthermore, the T2 SPACE sequence defines the resolution of the Synthetic CT output. The FLASH sequence is used to make sure that a vessel is not misclassified as bone and PETRA (an ultra-short echo-time sequence sensitive to bone), is used as an override mask to correct voxels incorrectly identified as air.

These sequences are necessary to generate the Synthetic CT of the brain but are also sufficient for contouring of the targets and OARs. Nevertheless, additional sequences to generate even more specific clinical information such as Diffusion-Weighted Imaging (DWI) or T1 post-contrast agent injection can be performed additionally on the patient depending on individual clinical imaging needs.



6 Visualization of the Synthetic CT algorithm for the brain from image acquisition to Synthetic CT image generation



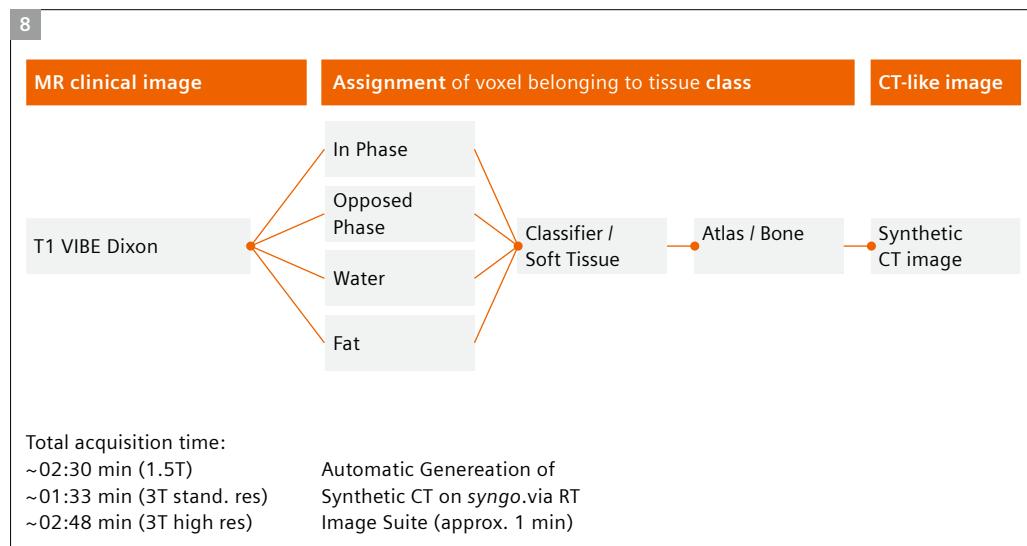
7 Image examples of MR sequences required to generate the Synthetic CT image for the brain
Image courtesy of Centre Hospitalier de l'Université de Montréal – CHUM, Montreal, Canada

Synthetic CT generation for the pelvis

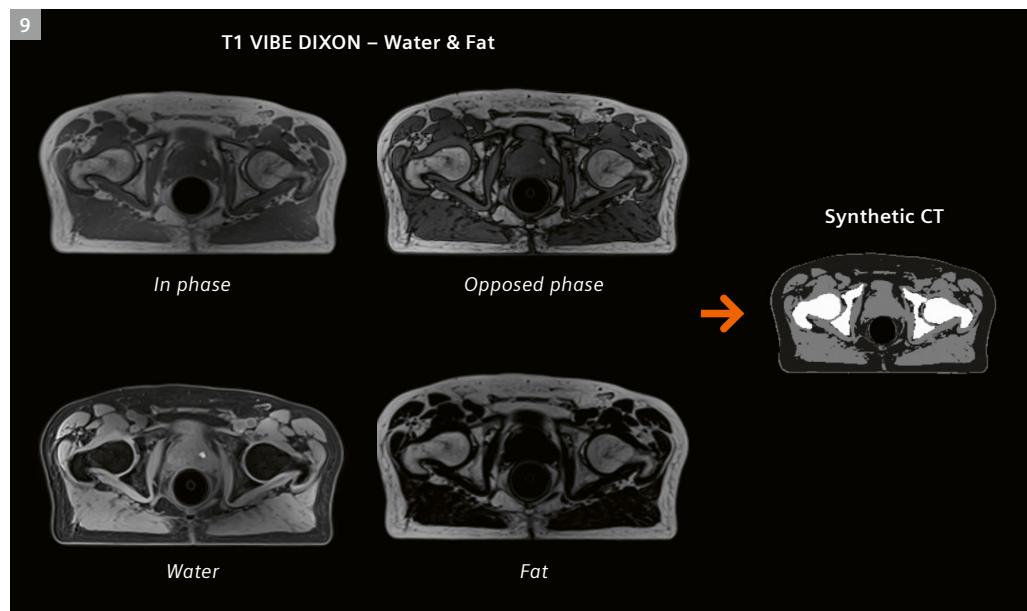
The pelvis RT Dot Engine workflow, includes amongst other sequences, the VIBE Dixon protocol, which is the only sequence needed for Synthetic CT generation for the pelvis. It produces in-phase, opposed-phase, water, and fat images in one acquisition. The tissue is classified as water and fat by using spectral information, and air using thresholding. The bone structures are rendered using a multi-atlas-based model. Using this information, the Synthetic CT image is automatically generated and

displayed at the MR console. Alternatively, a high-resolution (HR) VIBE Dixon sequence, also available in the pelvis RT Dot Engine, could potentially be used for more accurate contouring of bone and organs and for the visualization of small markers. The acquisition time is 2:30 minutes at 1.5T and at 3T ranges between 1:33 minutes for standard resolution and up to 2:48 minutes for high resolution.

The sequences for Synthetic CT acquisition of the pelvis are illustrated in Figures 8 and 9.



8 Visualization of the Synthetic CT algorithm for the pelvis from image acquisition to Synthetic CT image generation



9 Examples of MR images needed to generate the Synthetic CT image of the pelvis. The different tissues are classified, allowing differentiation between the tissue and the air in the body. The bones are included using an atlas-based model

Images courtesy of the University of Tübingen, Tübingen, Germany

Simulation and contouring with the syngo.via RT Image Suite

After the sequences have been scanned and the images acquired using the RT Dot Engine, the resulting Synthetic CT images are derived and automatically displayed in the *syngo.via* RT Image Suite that runs directly on the scanner console. The *syngo.via* RT Image Suite has been developed for radiation therapy to make simulation, image visualization, and contouring more intuitive [5].

Once the MR images have been acquired in the treatment planning position, the patient is marked using an external laser bridge, as depicted in Figure 10, to facilitate subsequent positioning of the patient in the treatment room. The *syngo.via* RT Image Suite provides an integrated workflow in which the lasers are moved (Direct Laser Steering)¹, the laser lines are displayed on a virtual 3D patient model (Virtual Laser View), and tools to help define and mark the isocenter or other points of interest are provided directly at the scanner immediately after image acquisition.

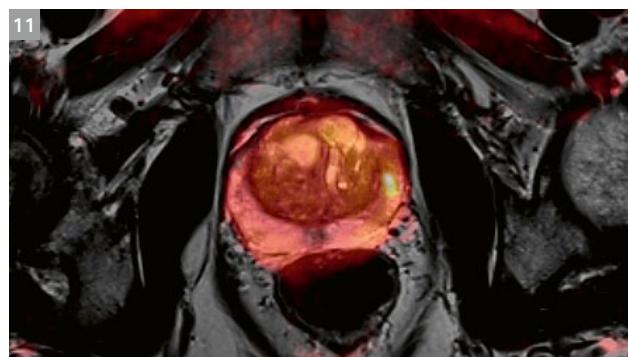
The sequences scanned for Synthetic CT generation are generally suitable for contouring. However, in some cases, other types of images, for example with increased contrast, are desired. In the RT Dot Engine for pelvis, for instance, sequences such as T2 TSE and T2 SPACE sequences are included. For prostate exams, the T2 TSE and T2 SPACE are used for delineating the prostate, the seminal vesicles, extracapsular lesions, the localization of the urethra and the lymph nodes, as well as the organs at risk, such as the rectum, bladder, and femoral heads. An isotropic 3D T2 SPACE would be the protocol of choice for the segmentation and the estimation of the target/tumor volume and the OAR in a female pelvis workflow.

DWI with the RESOLVE sequence is also included in the pelvis RT Dot Engine². It is used for the detection and

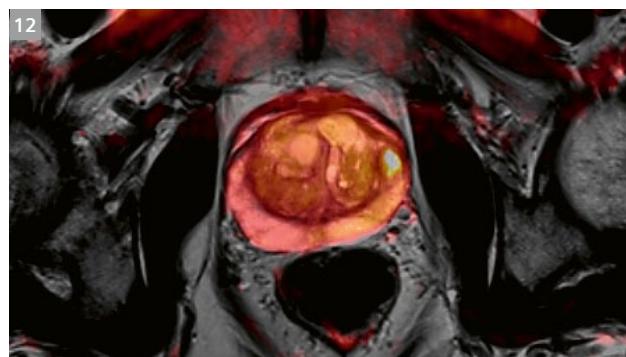


10 MAGNETOM RT Pro edition with external laser bridge from LAP, showing the laser markings on the patient

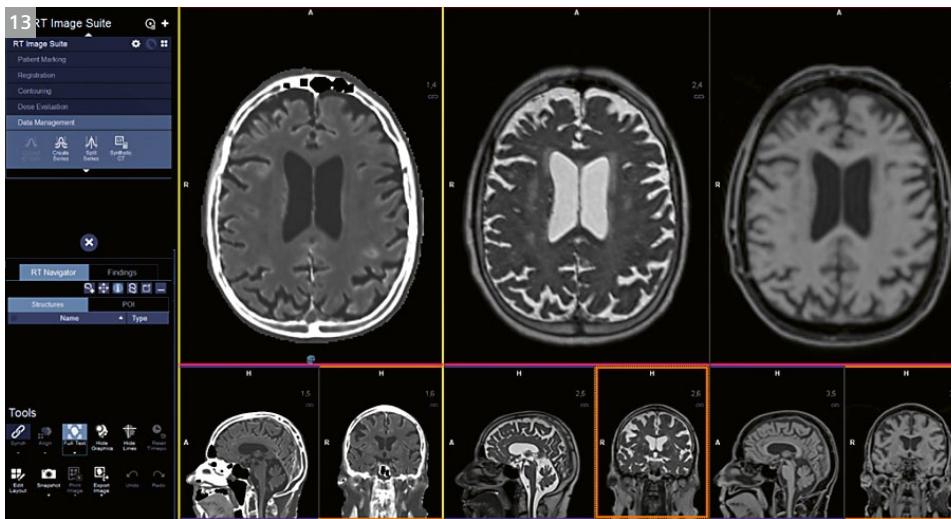
characterization of lesions according to their cellular density. DWI is generally subject to high distortions due to, for example, air in the rectum. RESOLVE provides an efficient approach for obtaining high-quality, high-resolution DWI images even in body regions strongly affected by susceptibility artifacts. It is largely free of distortions and delivers sharp images at a high spatial resolution. RESOLVE is especially useful for the evaluation of smaller lesions, typically of those within the prostate, and can provide "significantly better lesion conspicuity" [6] as shown in Figures 11 and 12. This helps to ensure high geometric accuracy and a good correlation with T2 anatomical scans. For a more extensive collection of RT-dedicated protocols, visit MAGNETOM World RT [7] and download our guide, "MR integrated workflows in RT".



11 Conventional DWI showing spatial mismatch between T2 image and overlaid DWI image (in color)



12 DWI image with RESOLVE showing reduced distortions and much better correlation with the anatomical T2 image

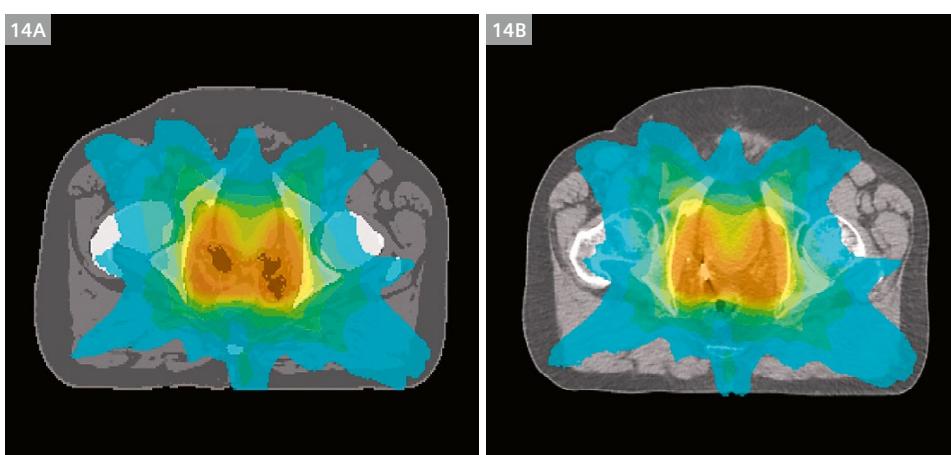


13 syngo.via RT Image Suite displaying T1 Dixon Vibe (right) and T2 SPACE (center) images side by side with the resulting Synthetic CT image (left). Contouring performed on the MR images is mirrored onto the Synthetic CT image, which can be exported to TPS
Image courtesy of Centre Hospitalier de l'Université de Montréal – CHUM, Montreal, Canada

With the multi-modality view feature of the syngo.via RT image Suite (shown in Figure 13), concurrent image series from any modality can be displayed on four panels. This allows for easy visualization and precise contouring of the target volume and the OAR on the MR image of choice. The contours are displayed on all the images and can be adjusted in any view. These contours are automatically mirrored on the corresponding Synthetic CT image. Finally, the contours and the Synthetic CT can be exported to the TPS for dose calculation. The Synthetic CT dataset is DICOM-file labeled as CT, allowing import by the TPS and linear accelerators. Therefore, the standard workflow using a planning CT for dose calculations can also be implemented using Synthetic CT.

Clinical evaluation by our partners

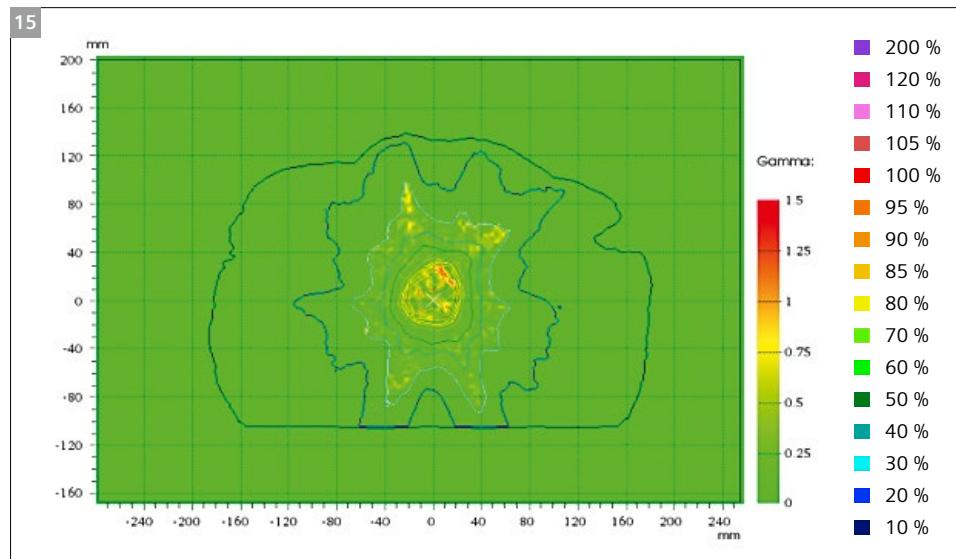
Several clinical departments have carried out evaluation studies to validate the MR-only workflow for the integration of Synthetic CT in clinical routine. A short summary of one of these studies, which was conducted by the University of Tübingen for the MAGNETOM Aera, Sola, and Vida, is described here [8]. For n=13 patients, MR images were taken for Synthetic CT (sCT) generation and planning CT (pCT) images. The calculated dose was compared on both datasets using the gamma-index criteria [9] with a gamma criterion of 3 % / 3 mm. Overall, a mean agreement of 98.7 % (range: 98.0 – 99.9 %) was found in this study. In Figure 14, an example of dose distributions on the sCT and pCT for one patient is shown.



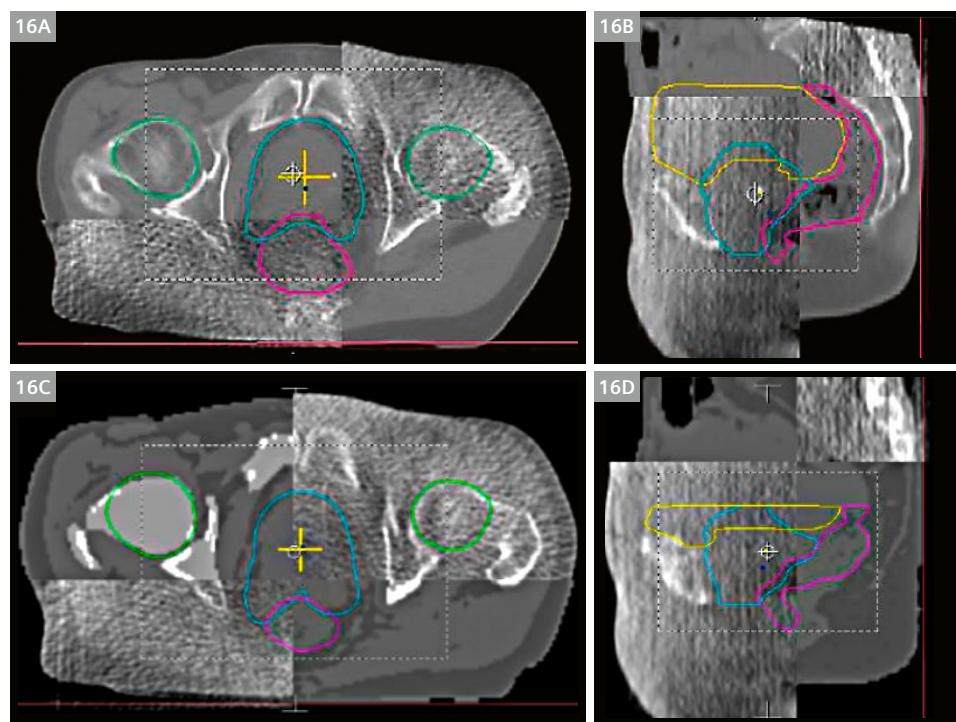
14 Relative dose distribution recalculated on the sCT (14A) compared with the original dose distribution calculated on the planning CT (14B)
Image courtesy of University of Tübingen, Germany

In Figure 15, the obtained gamma index distribution that compares the dose distributions calculated on the sCT and the pCT for one patient is shown. In addition to the dose comparison, the accuracy of using sCT for daily Cone Beam CT (CBCT) position verification was checked by comparing sCT-CBCT registration results with pCT-CBCT registrations. Figure 16 illustrates one such comparison, which shows an excellent agreement. It was concluded that, overall, the MR simulation is straight forward and ready to be used in academic departments as well as for clinical routine.

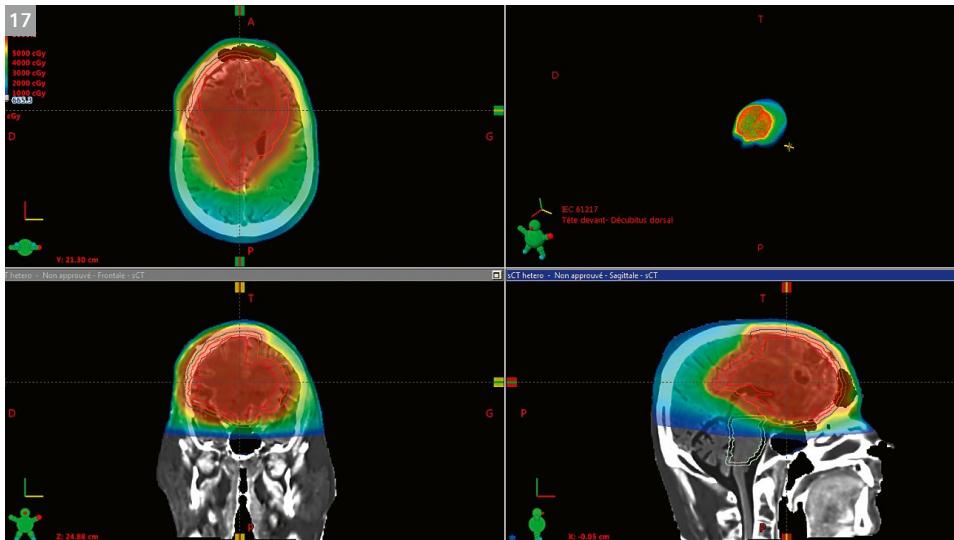
The Centre Hospitalier de l'Université de Montréal – CHUM has carried out similar studies for the brain and for the prostate. In Figure 17, the calculated dose distribution of a VMAT (volumetric modulated arc therapy) plan on an sCT for a brain tumor patient is shown. A publication with the results of these studies is in preparation.



15 Gamma map of a representative section of one patient case, generated with the software tool VeriSoft (PTW Freiburg, Germany). Here, an agreement according to the gamma criterion 3%/3mm is reached in 99.6% of all voxels
Image courtesy of University of Tübingen, Germany



16 Comparison of using original planning CT data for daily position verification with respect to the CBCT (**16A,B**) compared with using the sCT dataset as a reference image for daily position verification (**16C,D**)
Image courtesy of University of Tübingen, Germany



17 sCT dose map for 6MV VMAT treatment. Prescribed dose is 60 Gy
Image courtesy of Centre Hospitalier de l'Université de Montréal – CHUM, Montreal, Canada

Summary

Due to its soft-tissue contrast and functional imaging capabilities being superior to those of CT imaging, MR imaging can be an effective tool for radiotherapy treatment planning. With the challenges of a combined MR and CT RT planning workflow presented in this paper, interest and demand for an MR-only radiotherapy planning workflow is increasing.

The Synthetic CT feature as part of the *syngo.via* RT Image Suite enables MR-only radiotherapy planning. The sequences needed for Synthetic CT generation, patient marking, contouring, and data export are explained in detail in this white paper. The RT Dot engine includes not only the necessary sequences and protocols for Synthetic CT generation and additional sequences useful to gain more contrast in the images for contouring, but also a smart workflow guidance, making the patient MR scan an intuitive and efficient task. Several clinical validations have already provided successful results. An MR-only workflow using Synthetic CT for RT planning has been validated and is available for adoption in RO departments for routine clinical use.

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The data acquisition protocols for Synthetic CT are available on Numaris X software with MAGNETOM RT Pro edition for MAGNETOM Sola and MAGNETOM Vida.

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¹ Optional, compatible LAP laser system required for Direct Laser Steering

² With software version XA11B, and cannot be guaranteed with other software versions

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