Synthetic CT Generation for the Pelvic Region Based on Dixon-MR Sequences: Workflow, Dosimetric Quality and Daily Patient Positioning

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Introduction

Over the past couple of decades, the adoption of MR imaging in support of Radiation Therapy treatment planning has increased dramatically. 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 contributed in part to the superior soft tissue contrast of MRI compared to CT imaging. This can allow to potentially have much more precise delineation of not only a patient's tumor, but also of surrounding organs at risk (OAR). Additionally, MR offers functional imaging to derive more information on tumor activity and therapy response.

However, the inherent limitation of MRI for RT planning compared to CT is that it has not been able to provide the electron density information which is needed for dose calculation in a treatment planning system (TPS). For this reason, and because CT provides good delineation of bony structures and the highest geometric accuracy in its imaging, CT remains utilized in almost 100% of RT planning [1].

1 Patient positioning example for MR sim for pelvis imaging including flat couch top overlay and dedicated coil holder (Qfix, Avondale, PA, USA) for body coil.

As such, more and more institutions are adopting a workflow which includes both traditional CT simulation for dose calculation but also MR simulation for superior and more precise delineation of tumors and surrounding OAR.

A combined MR and CT workflow has the potential to provide higher accuracy in both target volume and OAR definition. From CT we obtain accurate dose calculations from attenuation tissue properties and generation of reference images (DRR) used for patient positioning and beam placement, and from MR, good soft tissue contrast as well as functional imaging. However, challenges of such a combined MR and CT workflow are also introduced. These challenges may include, for example, accurate image registration between MR and CT, patient scheduling, and financial issues such as reimbursement.

Because of these challenges, institutions have been searching for ways to implement an MR-only workflow for their patient's treatment planning. While research has been ongoing for a few years, commercially available features enabling an MR-only workflow have only recently become available. We describe a method that allows us to adopt an MR-only workflow. Synthetic CT is commercially available as part of the *syngo*.via RT Image Suite[1] and is available for both brain as well as male and female pelvis.

MR-only radiotherapy workflow

Patient preparation and MR imaging

Pelvic patients scheduled for MR simulation need to be examined in RT treatment position, i.e. a flat table top for the MR scanner is required in addition to a dedicated coil holder to fix the flexible radiofrequency (RF) body coil without deforming the patient contour, as depicted in Figure 1 Furthermore, all necessary positioning devices,

[1]*For 3T MAGNETOM Vida and 1.5T MAGNETOM Sola with software version syngo MR NXA11A or later.*

such as knee fix, feet holder, etc. need to be available in MR-compatible fashion in order to position the patient accurately. Reference point markings need to be done using MR-visible markers and a MR-compatible laser bridge.

For the generation of a Synthetic CT (sCT), Siemens Healthineers offers dedicated Dixon sequences resulting in water, fat, in- and out-of-phase images which can then later be used to calculate Synthetic CT. To acquire the Dixon scans, the transversal field of view should encompass the entire patient outline and needs to be centered right above the hips in z-direction in order to cover lumbar vertebra L3. Furthermore, additional scans in diagnostic quality should be acquired in order to allow accurate target volume delineation, such as e.g. T2-weighted 3D turbo spin echo (TSE), diffusion weighted (DW) MRI and eventually T1-weighted or other MR sequences, depending on the patient case.

Generation of Synthetic CT data

After successful acquisition of the Dixon scans, the four different data sets are imported into the *syngo*.via RT Image Suite (RTiS). Here, a dedicated tool for data management is foreseen to calculate the CT based on the four Dixon-MR data sets. The resulting sCT data set is available in CT-dicom format and contains four different density compartments: fatty tissue, water-equivalent tissue, air and bone / dense bone (Fig.6). The data set is directly fused to the anatomical MR-data which have been acquired during the same session, i.e. contours generated on the anatomical MR can directly be saved on the sCT for later dose planning and calculation.

Clinical Synthetic CT images for pelvis

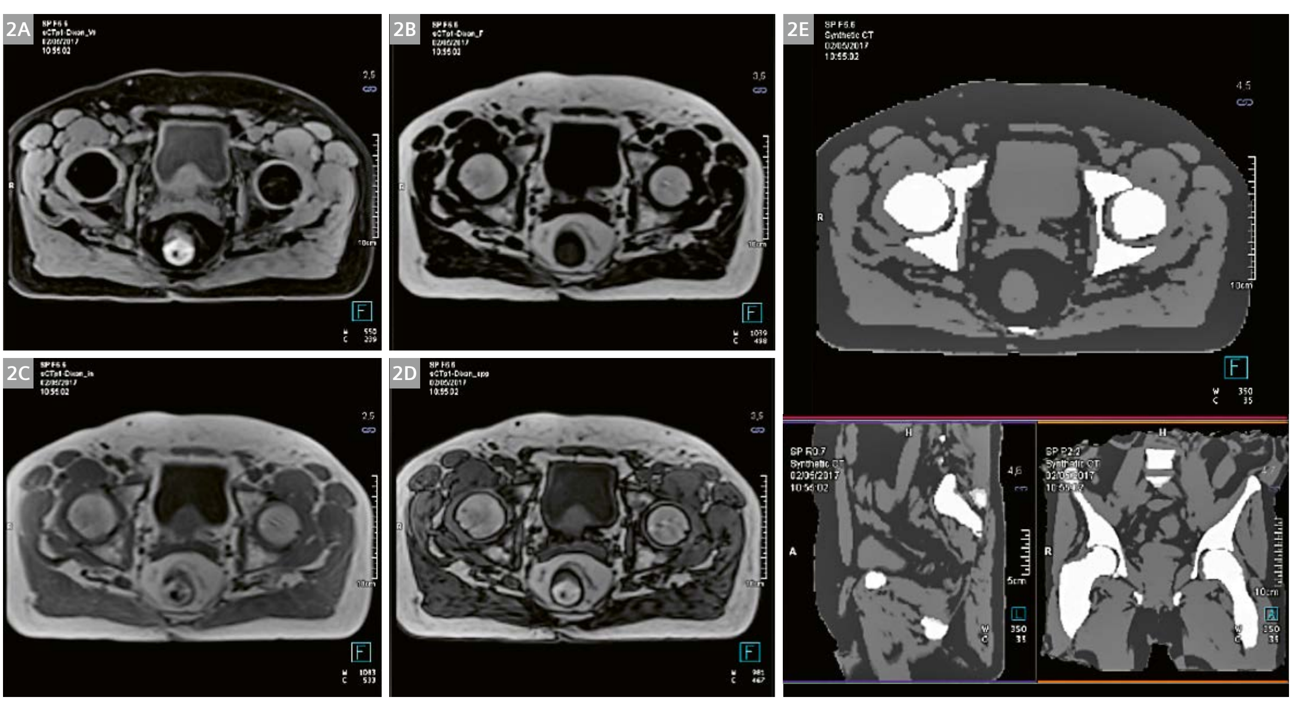
In a testing phase a total of n = 13 prostate cancer patients were asked to undergo MR simulation in addition to conventional CT simulation in order to evaluate sCT image quality, to investigate the dosimetric effects of using sCT data for RT dose calculation and to evaluate the usability of sCT data for daily positioning verification of the patient at a RT machine equipped with cone beam CT (CBCT). Three patients were imaged with the MAGNETOM Skyra[2] 3T scanner, five patients were imaged with the MAGNETOM Aera[2] 1.5T scanner, and five patients were imaged with the MAGNETOM Vida 3T scanner.

Figure 2 displays the four different Dixon-MR sequences from which the respective sCT is derived for an exemplary patient case.

In Figure 3, the Synthetic CT is compared to the real planning CT taken for this patient on the same day.

Contouring of tumor regions and organs at risk is done based on the anatomical T2w MRI data set after MR sim. The RT structure set is saved together with the sCT which facilitates transfer of the data to the RT planning system and subsequent treatment planning.

[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.*



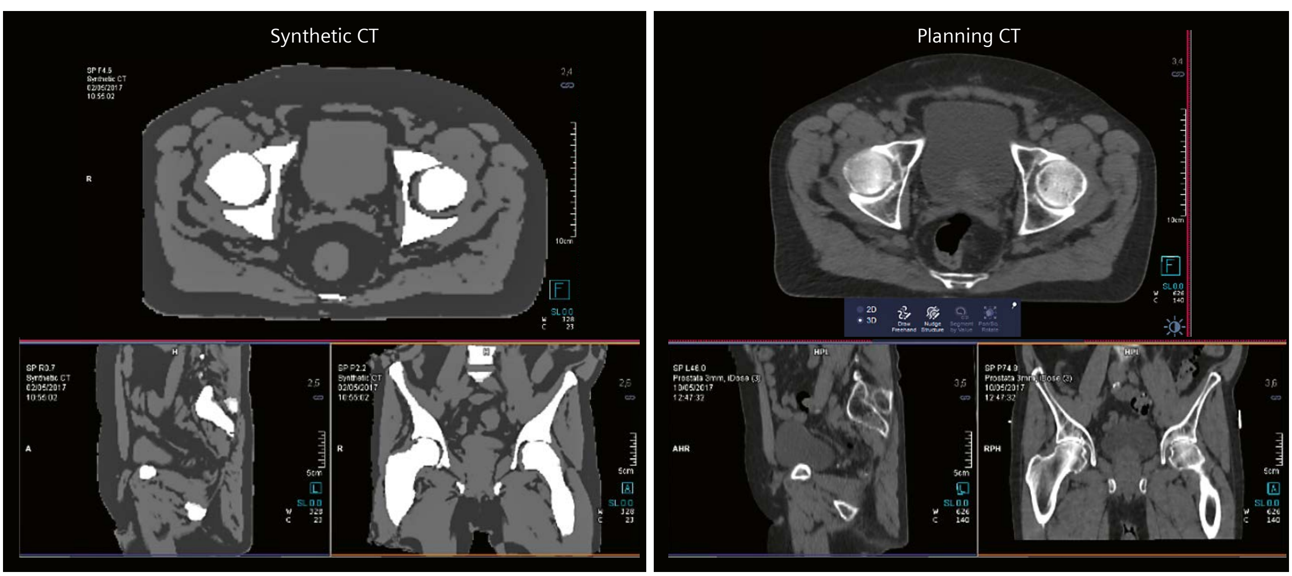
2 Four reference MR images acquired with the Dixon scan protocol **(2A)** water, **(2B)** fat, **(2C)** in-phase and **(2D)** out-of-phase Dixon data. **(2E)** Displays the Synthetic CT data set reconstructed from data sets (2A-D).

Evaluation of Synthetic CT dose calculation accuracy

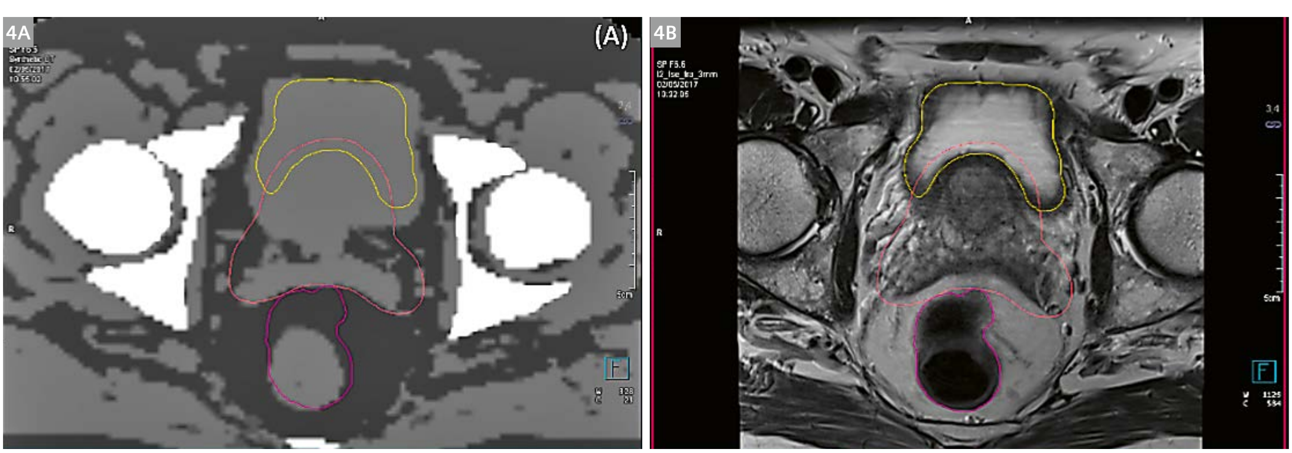
For all patients included into this study, the accuracy of dose calculation based on the sCT was evaluated by comparing the 3D dose distribution to the planning CT. For treatment planning, the Tübingen in-house planning system for intensity modulated radiotherapy (IMRT) was used. For all patients, planning CT data including planning target volume (PTV_{pCT}) and organ at risk (OAR_{pCT}) contours were available. After dedicated planning MR (pMR) examinations, sCT were calculated and a second set of PTV_{pMR} and OAR_{pMR} contours were created based on the anatomical T2w MRI. Then, an IMRT plan was optimized for the planning CT. The final plan was then recalculated on the sCT using Monte Carlo dose calculation with a maximum uncertainty of 1%. Dose volume histograms (DVH) were compared for PTV_{pCT}/PTV_{pMR} and OAR_{pCT}/OAR_{pMR}, respectively. Furthermore, the 3D dose distributions which were obtained using the planning CT and the sCT were compared using a gamma analysis with a gamma criterion of Γ = 3%/3 mm. In a last step of this analysis, the sCTs were exported to the treatment machine (Elekta AB, Sweden equipped with CBCT) in order to evaluate the accuracy of using sCT data for daily positioning verification.

Figure 5 shows dose distributions for the same plan calculated on the original planning CT and the MR-based sCT. Depending on the actual patient positioning during planning CT and subsequent MR simulation, overall very good agreement between the original dose distribution and the dose recalculated on the sCT was observed in this study.

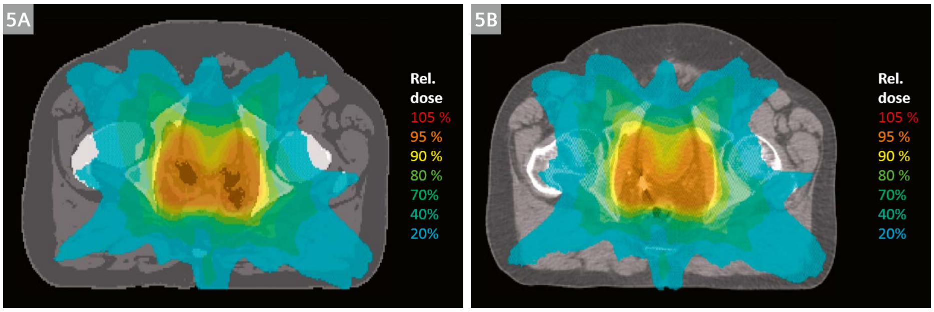
Figure 6 displays the DVH analysis for one patient, comparing for DVHs for the contours defined on the



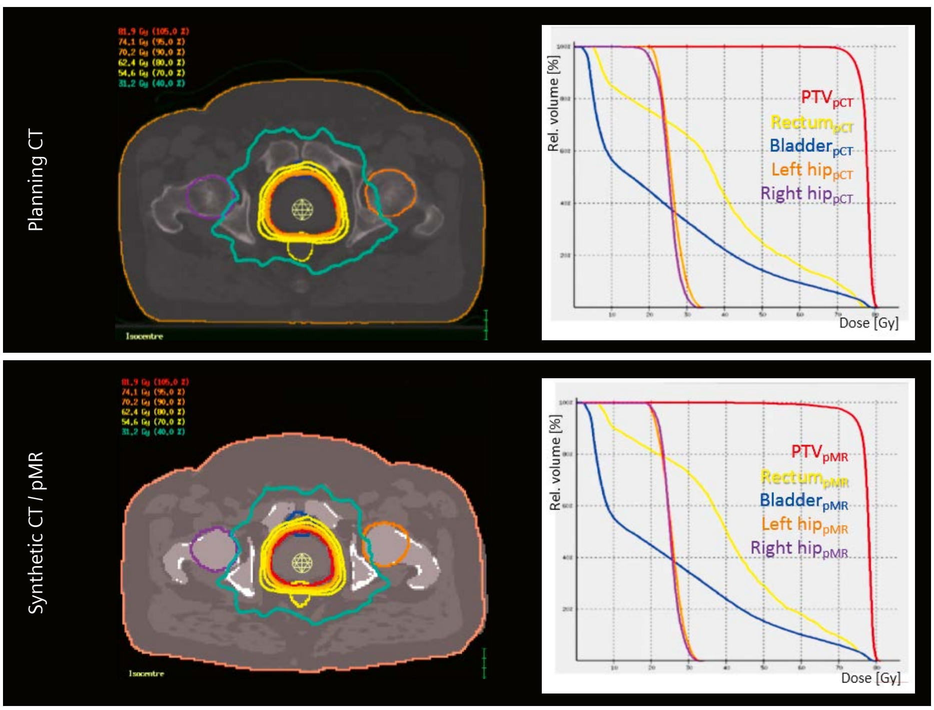
3 Synthetic CT (left) compared to conventional planning CT (right) of the same patient.



4 Synthetic CT **(4A)** with radiotherapy contours for planning target volume (PTV) in orange, rectum in pink and bladder in yellow which were created using an anatomical T2w TSE MRI **(4B)**.



5 Relative dose distribution recalculated on the sCT **(5A)**, compared to the original dose distribution calculated on the planning CT **(5B)**.



6 Planning CT with original dose distribution and DVHs for volumes created on the pCT (upper row). Synthetic CT with contours defined on the planning MR and corresponding DVHs for recalculated dose based on sCT (lower row).

planning CT (pCT) and the original dose distribution with the DVHs of volumes defined on the planning MR (pMR) and the dose recalculated with the sCT.

The gamma analysis shown in Figure 7 nicely shows the high level of agreement when comparing the original dose distribution with the dose recalculated on the sCT. Overall, a mean agreement of 98.7 % (range: 98.0 – 99.9 %) was found in this study.

In a last analysis step, the accuracy of using sCT for daily CBCT position verification was checked for this patient population by comparing sCT-CBCT registration results to pCT-CBCT registrations. Daily positioning accuracy was calculated to six degrees of freedom (three translational and three rotational axes). Each translation/rotation vector was calculated using either the pCT or the sCT as a reference scan. In total, mean differences of 3.4 mm / 1.5 mm / 4.8 mm in x-, y- and z-direction respectively (range: 0 – 10.6 mm) were observed as well as mean differences in the rotational degrees of freedom of 1.8° (range: 0 – 5.18°).

Figure 8 shows a comparison of using the original planning CT vs. the sCT as a reference image to be matched with the daily CBCT in the XVI matching tool (Elekta AB, Sweden).

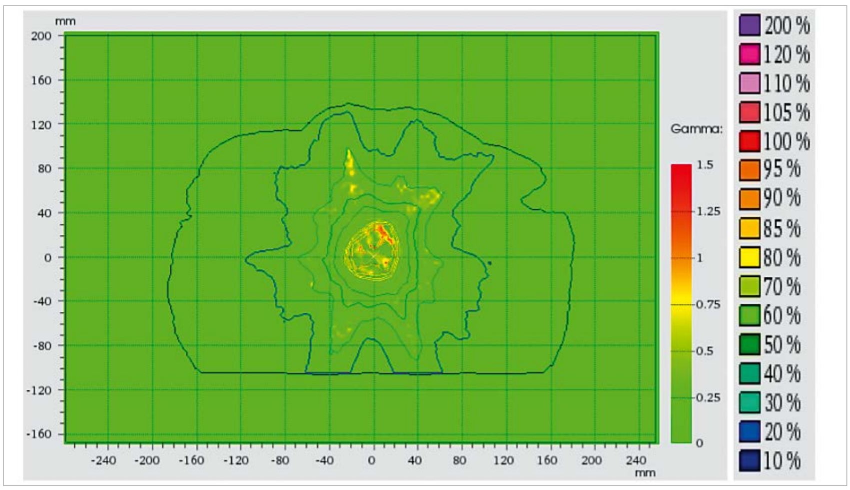
Discussion

In this study involving 13 patients with cancer treatments planned in the pelvic region, the sCT workflow proposed by Siemens Healthineers was tested and evaluated in terms of dosimetric accuracy, image quality and suitability of sCT to be used for daily positioning verification at the RT treatment machine.

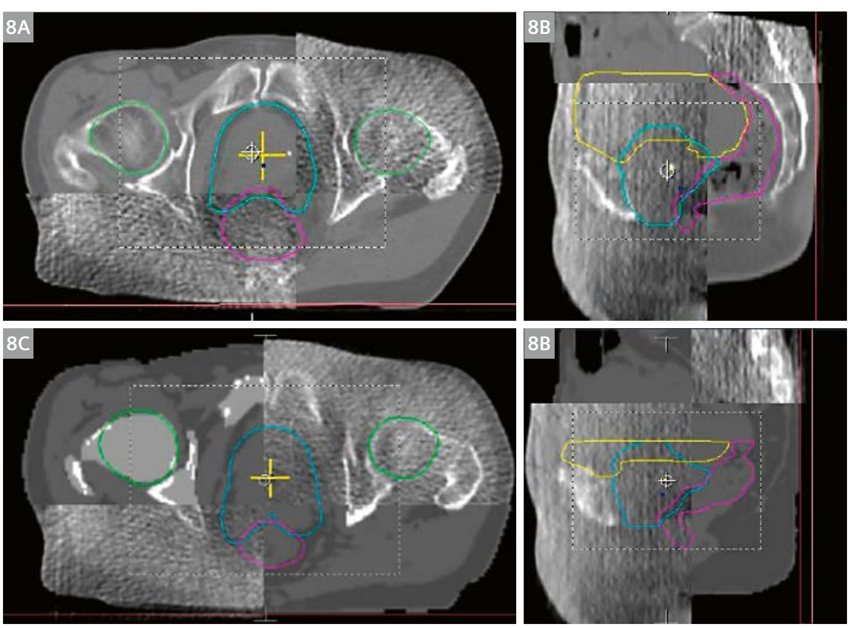
Overall, the MR simulation workflow is straight forward and ready to be used in academic departments as well as for clinical routine. Dedicated sequences are available to be applied during the MR examination. An essential prerequisite for accurate reconstruction of the Synthetic CT is the selection of a correct field of view for the Dixon sequences. The sCT data consist of four different density compartments, which results in a dosimetric accuracy of 1 – 2%. However, the evaluation of the dosimetric accuracy depends strongly on the positioning of the patient. If small discrepancies exist between patient positioning during pCT and pMR, this will result in dosimetric differences. However, in the pelvic region, sCT seems to present accurate dose calculation accuracy for clinical radiotherapy treatments. Furthermore, MR simulation which comes together with sCT reconstruction is providing excellent soft tissue contrast and thus allows for more accurate target volume delineation.

Reference

1 Lorna Young et al., IMV Radiation Therapy Market Summary Report. Oct 2018.



7 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%/3 mm is reached in 99.6 % of all voxels.



8 Comparison of using original planning CT data for daily position verification with respect to the CBCT **(8A, B)** vs. using the sCT data set as a reference image for daily position verification **(8C, D)**.

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