

First experience of 4D-MRI for abdominal radiotherapy planning

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Introduction

Four-dimensional (4D) computed tomography (CT) is widely used in radiation therapy (RT) and remains the current standard for motion evaluation during RT planning. The use of 4D-CT allows the delineation of an internal target volume (ITV) [ICRU RPT62]. Unfortunately, 4D-CT uses additional radiation exposure to the 3D planning CT, and has limitations in soft tissue contrast. Magnetic resonance imaging (MRI) offers superior soft tissue definition to CT and therefore has potential significant advantages when implemented during the radiotherapy process. The integration of MRI into the radiotherapy planning and treatment pathway has been rapid with developments in MRI-simulation [1] and real-time MR guidance [2].

Attempts to replace 4D-CT with an MRI counterpart have been made for over a decade. Until recently, imaging physiological motion using MRI has involved unacceptable trade-offs between spatial and temporal resolution [3]. The majority of published literature has utilized 2D cine [4] sequences, which have been acquired in two orthogonal planes or in combination with a 3D volume as a surrogate for real-time 3D acquisition. Nonetheless efforts have been made utilizing 2D cine for adaptive

radiotherapy planning [5]. Respiratory based sorting is another method with variable success [6]. Poor respiratory correlation can be problematic and incomplete binning can lead to gaps in data, which can be overcome by increasing scan time or utilizing a two-pass method [4, 7]. A combination of 2D-MRI and phase binning has yielded conflicting results [8] with noticeable phase mismatch and significant cycle-to-cycle motion variation. Both tumor deformation and motion out of plane is problematic with these methods. A much better approach is to acquire time-resolved 3D volume acquisitions, and this is now possible with sufficient resolution and image quality to be of clinical interest.

Here we present our initial findings using a prototype 4D-MRI technique based on a T1-weighted (T1w) 3D gradient echo (VIBE) sequence¹. This uses a continuous radial acquisition and retrospective binning of respiratory phases, to generate 3D high-resolution images from different parts of the respiratory cycle (Siemens Healthcare, Erlangen, Germany). 4D-MRI combined with the recent interest in replicating dosimetry calculations in MRI may further abrogate the need for CT-simulation.

¹ WIP, the product is currently under development and is not for sale in the US and in other countries. Its future availability cannot be ensured.

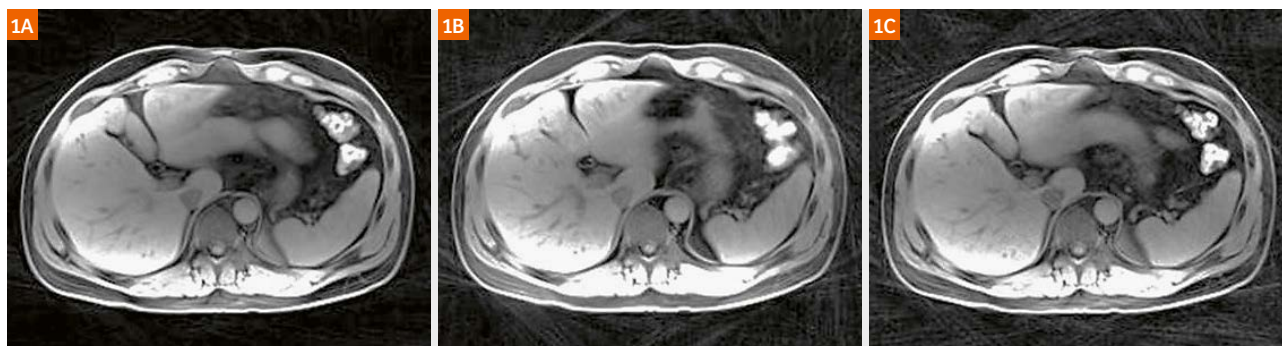


Figure 1: The radial streak artifact seen with three (1A), five (1B) and ten (1C) bins. All images using 2000 radial views.

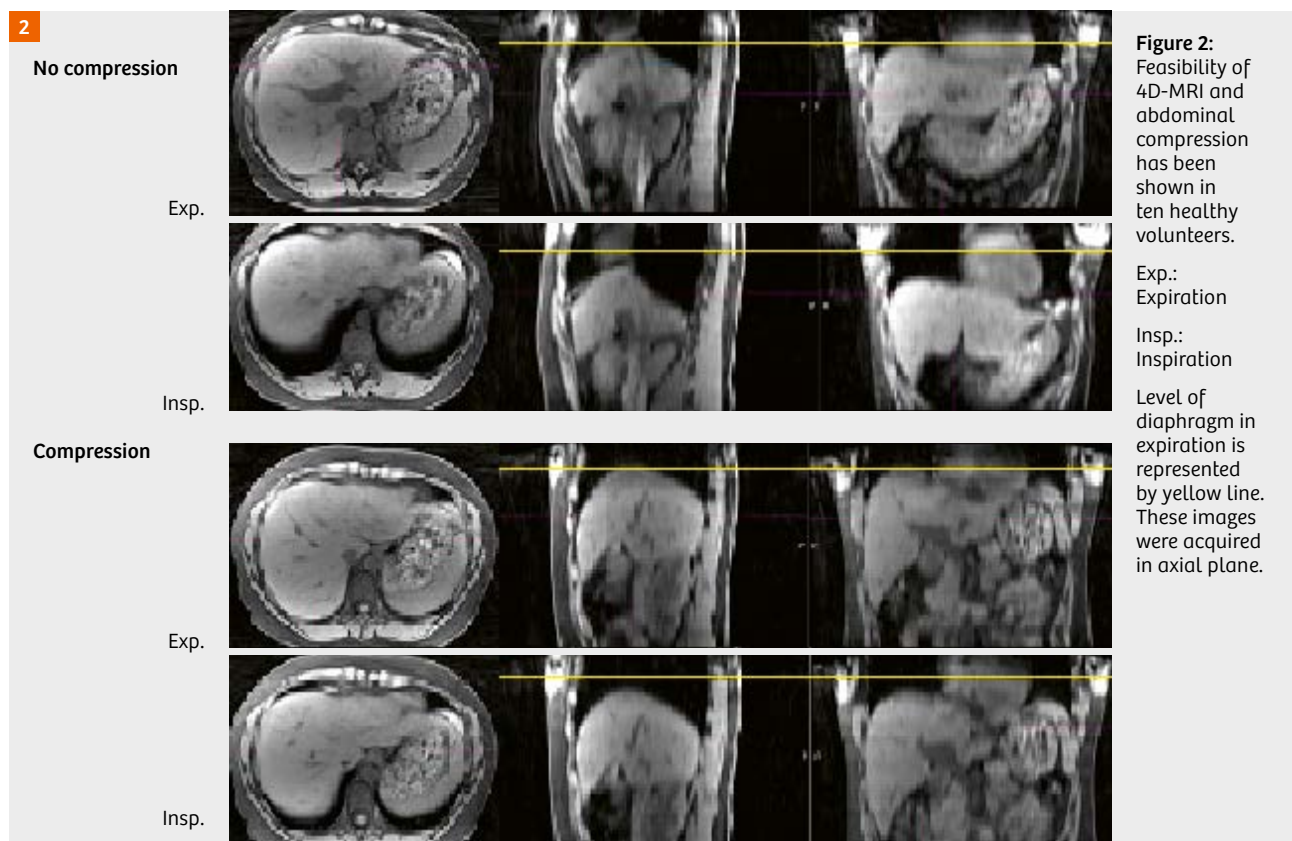
Initial experience

MRI was performed utilizing a customized vacuum bag (BlueBAG, Elekta, Stockholm, Sweden) for immobilization and a flat wing board (MTWB09 Wingboard, CIVCO Medical Solutions, Orange City, IA, USA) with arms above the head. All MR imaging was performed on the departmental radiotherapy dedicated 3T wide-bore MRI (MAGNETOM Skyra, Siemens Healthcare, Erlangen, Germany) on a flat-bed insert (CIVCO Medical Solutions, Orange City, IA, USA) with a 32-channel posterior in-table coil and 18-channel flexible array coil. Sequences included T2 HASTE gated with phase navigation, breath-hold T1 VIBE and multiphasic (arterial, venous and transitional phases) breath-hold T1 VIBE enhanced with 0.1 ml/kg Gadobutrol (Gadovist, Bayer, Leverkusen, Germany). Additionally all volunteers and patients underwent the prototype T1-3D gradient echo with radial self-gating (Siemens Healthcare, Erlangen, Germany) 4D-MRI sequence. *k*-space sampling is performed using a stack-of-stars trajectory with golden angle increment [9]. The sequence uses data from the centre of *k*-space to extract a surrogate respiration trace, which permits self-gating.

The sequence was first optimized on two healthy volunteers to qualitatively compare image quality of the liver and evaluate the trade-off between acquisition

time and artifacts. Changes in protocol were investigated to examine the effects on image quality including number of radial views (1500, 2000 and 3300) and uniform bins (3, 5 and 10). Image quality was assessed by two radiation oncologists and an experienced MRI radiographer (ML, AO, RR). When comparing the number of uniform bins, it was observed that for three bins there were fewer radial streak artefacts with overall good image quality, however the degree of motion of the liver was not completely captured. In contrast, ten bins captured a greater degree of motion but suffered from a greater degree of radial streak artefacts that impacted the ability to delineate organ borders for RT planning (see Fig. 1). However, five respiratory bins reproduced the liver motion whilst maintaining optimal image quality for contouring, and therefore five bins was selected for patient image acquisition. Two thousand radial views provided the best trade-off between time and radial streak artifacts. The acquisition time using these parameters was approximately five minutes. Increasing the number of radial views beyond this increased the acquisition time, which is not ideal for this patient cohort, without demonstrable benefits in image quality.

The efficacy of 4D-MRI with and without abdominal compression has been tested in ten volunteers (see Fig. 2).



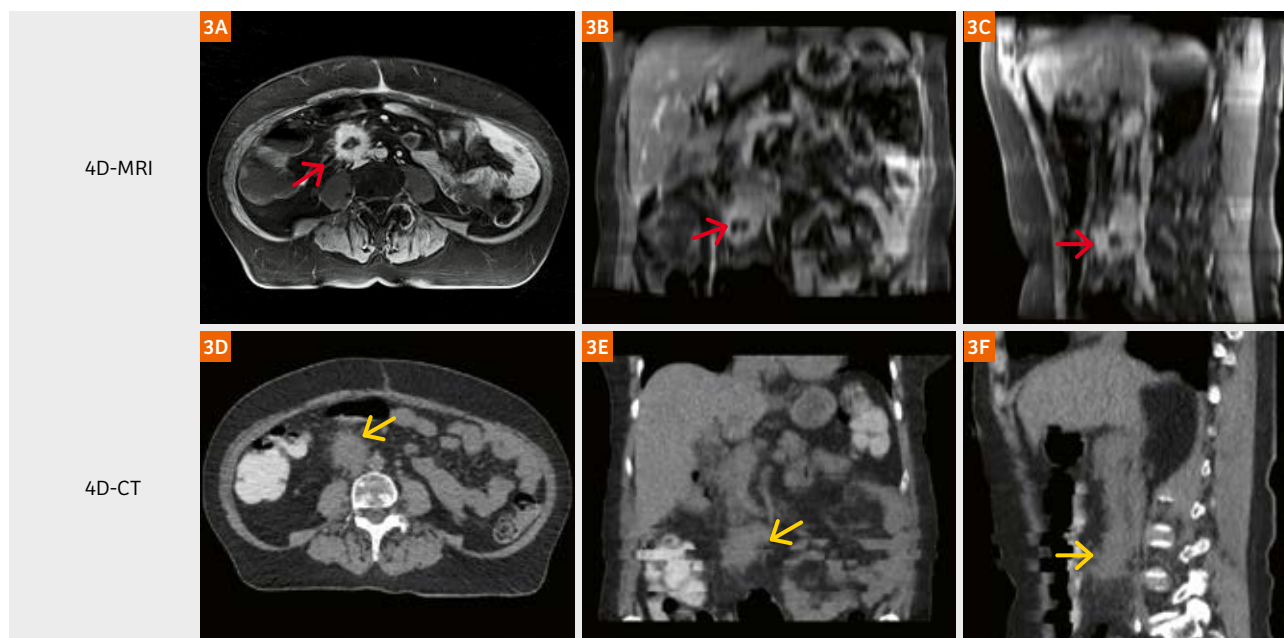


Figure 3: Comparison of 4D-MRI and 4D-CT in a patient with solitary nodal recurrence of colorectal cancer receiving high dose radiotherapy. In this case 4D-CT failed due to step artifacts (yellow arrows) over the area of interest. Gadolinium enhanced 4D-MRI provided excellent soft tissue delineation (red arrows) and accurate motion visualization.

Figure 2 demonstrates that a high image quality can be maintained whilst obtaining physiological motion information both with and without abdominal compression. For the volunteer study, the amplitude of movement of liver and volume of lung below the T10 vertebral level has been recorded for both compression and no compression. Volunteer study results are pending for publication.

This prototype 4D-MRI sequence has demonstrated encouraging results and as a self-gating technique it is very promising. Superior soft tissue delineation and reduced radiation exposure may mean 4D-MRI is a suitable replacement for 4D-CT. Figure 3 demonstrates a sample case where 4D-CT suffered from artifacts due to inconsistent breathing rate throughout image acquisition and poor signal from the respiratory trace. In this case the step artifacts impacted the delineation of the tumor volume, introducing uncertainty for treatment. 4D-MRI in comparison provided greater soft tissue contrast (Fig. 3A) with minimal artifacts allowing greater confidence in contouring the tumor volume. The clinical outcome of the first ten patients is pending for presentation and publication.

Future direction

Local area health research and ethics board approval has been obtained for direct comparison of 4D-CT to 4D-MRI in patients receiving upper abdominal radiotherapy. Recruitment to this study is ongoing with ten patients recruited to date. 4D-CT will be directly compared to 4D-MRI in parameters such as amplitude of movement and image quality. Artifact, noise, and tumor edge detection will be graded on a four-point scale as seen in Table 1 for both 4D-CT and 4D-MRI. This scoring system has been utilized previously [10]. Tumors will be contoured on maximal inspiratory and expiratory images and directly compared to 4D-CT. Clinical data from this research project will be presented in April 2018 at ESTRO 37.

Gadoxetate sodium (Primovist, Bayer, Leverkusen, Germany) has shown exceptional diagnostic potential in patients with both primary and metastatic liver tumors [11, 12]. The slow excretion of Primovist by hepatocytes is likely to facilitate superior contrast information during 4D-MRI scanning. We intend to explore Primovist in patients with primary and secondary liver tumors during 4D-MRI and we hypothesise that despite the longer acquisition time of 4D-MRI, the benefits of contrast can be maintained.

Score	1	2	3	4
Tumor edge detection	Tumor edge clearly defined	Tumor edge slightly blurred, not impairing definition of tumor boundary	Considerable blurring of tumor edge impacting on accurate definition of tumor boundary	Significant blurring of tumor edge, definition of tumor boundary not achievable
Artifacts	No artifacts	Little artifact not impairing image quality	Considerable artifact impacting evaluation of anatomical structures	Extreme artifacts obscuring delineation of anatomical structures
Image noise	Minimal noise	Little noise not impairing diagnostic image quality	Considerable noise impacts the evaluation of anatomical structures	Extreme noise obscuring delineation of anatomical structures.
Overall image quality	Very good image quality	Fair image quality not impairing the delineation of structures	Impaired image quality that may lead to incorrect delineation	Structures not definable

Table 1: Scoring system for tumor edge detection, artifact, image noise and overall image quality.

MRI linear accelerators are likely to play an increasing role within the radiotherapy treatment paradigm. Adaptive 4D-MR guidance is now clinically achievable [5, 13]. As the quality of 4D-MR imaging improves, and the integration of MR into radiotherapy delivery systems is refined, clinician’s confidence regarding real-time tumor position and movement may be further enhanced. Those patients where volumetric acquired 4D-MRI at simulation is seen to accurately represent movement of the region of interest may be the greatest beneficiaries of an MRI linear accelerator. With further refinement and rapidly growing MRI linear accelerator interest, online volumetric acquired 4D-MRI is clinically feasible. Volumetric 4D-MRI will significantly alter radiotherapy treatment delivery in liver, bowel, pancreas, heart, lymph node and prostate where real-time accuracy of soft tissues is pivotal.

Acknowledgements

The authors wish to thank Dr. Benjamin Schmitt at Siemens Healthineers for the development of this volumetric acquired 4D-MRI sequence (Siemens Healthcare, Erlangen, Germany) and ongoing input into this research project.

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 The statements by Siemens’ customers presented here are based on results that were achieved in the customer’s unique setting. Since there is no ‘typical’ hospital and many variables exist (e.g., hospital size, case mix, level of IT adoption), there can be no guarantee that other customers will achieve the same results.

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