4D-MRI sequence for radiotherapy application: validation of a retrospective method on a motion phantom

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Introduction

Abdominal motion imaging is challenging due to breathing artifacts. A widely used technique for organ motion management in radiotherapy (RT) is 4D-CT. It consists of acquiring a breathing signal thanks to an external surrogate at the same time as repeated acquisitions of images and the sorting of the images according to the respiratory cycle obtained from the breathing signal. However, CT scans present poor contrast for soft tissue, such that the lesions are difficult to observe even when a contrast agent is used. To overcome this limitation, MR images are acquired for precise tumor delineation and in our institute, motion is managed with acquisitions triggered on exhale phase [1]. Both CT and MR images are registered on exhale phase, as these are more reproducible [2]. In this configuration, only the exhale phase of the respiratory cycle is registered, and therefore the dynamic behavior and the organ deformation during free breathing are not captured.

Figure 1:
The Quasar™ MRI^{4D} motion phantom placed in the 1.5T MAGNETOM Aera bore.

4D-MRI is a promising method for imaging respiratory movements. Besides excellent soft tissue contrast, the method exhibits great flexibility in selecting image plane orientations. Different strategies have been developed for organ movement consideration [3–5]. These methods are limited by the temporal resolution, as well as image quality. A novel retrospective gating approach for dynamic MR imaging during free breathing was developed by von Siebenthal et al. [3] and further improved by Celicanin et al. [6]. In this work, the innovative 4D-MRI approach has been evaluated and validated for RT application using a motion phantom.

Motion phantom

The Quasar™ MRI^{4D} motion phantom[1] (Modus QA, London, ON, Canada) consists of an oval hollow body, in which two cylindrical inserts may be positioned (Fig. 1). The MRI contrast gel used in this study, which is a prototype based on a gellan gum gel, containing manganese chloride as a contrast agent (0.3 mM for the high-contrast tumor sphere and 0.15 mM for the surrounding medium) was supplied by Modus QA. Different motion waveforms were tested. The sinusoidal mode allows the adjustment of the frequency and the amplitude of the motion. On Figure 2A, an example of a 5 s respiratory cycle (12 breaths/min) with 20 mm peak-to-peak amplitude is presented. In addition, MRI measurements were realized for respiratory cycles with duration of 4 s and 6 s with 10 and 30 mm amplitude peak-to-peak (not shown). Real respiratory cycle from patient data was also acquired (Fig. 2B).

[1] The information shown herein refers to products of 3rd party manufacturer's and thus are in their regulatory responsibility. Please contact the 3rd party manufacturer for further information.

2A 2B

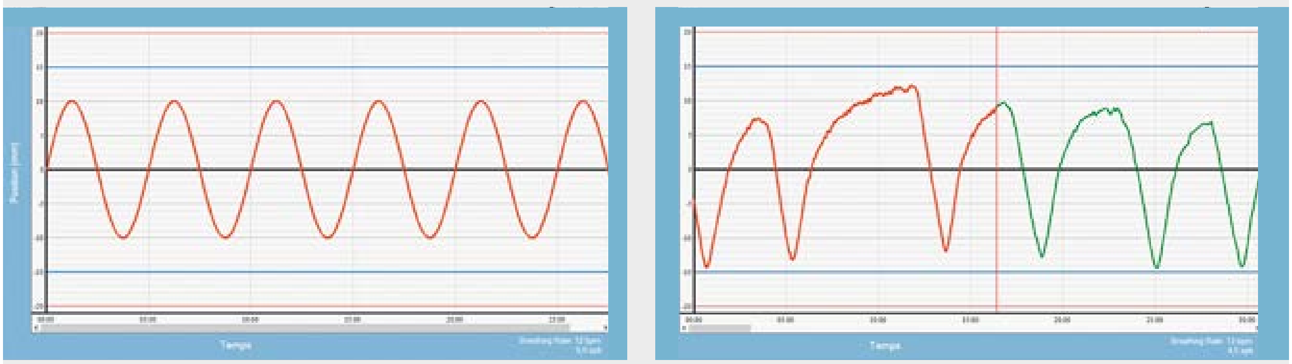


Figure 2:
Examples of 5 s respiratory cycles with 20 mm peak-to-peak amplitude **(2A)** and real respiratory signal from patient recording **(2B)** are given as motion waveforms to the phantom.

3

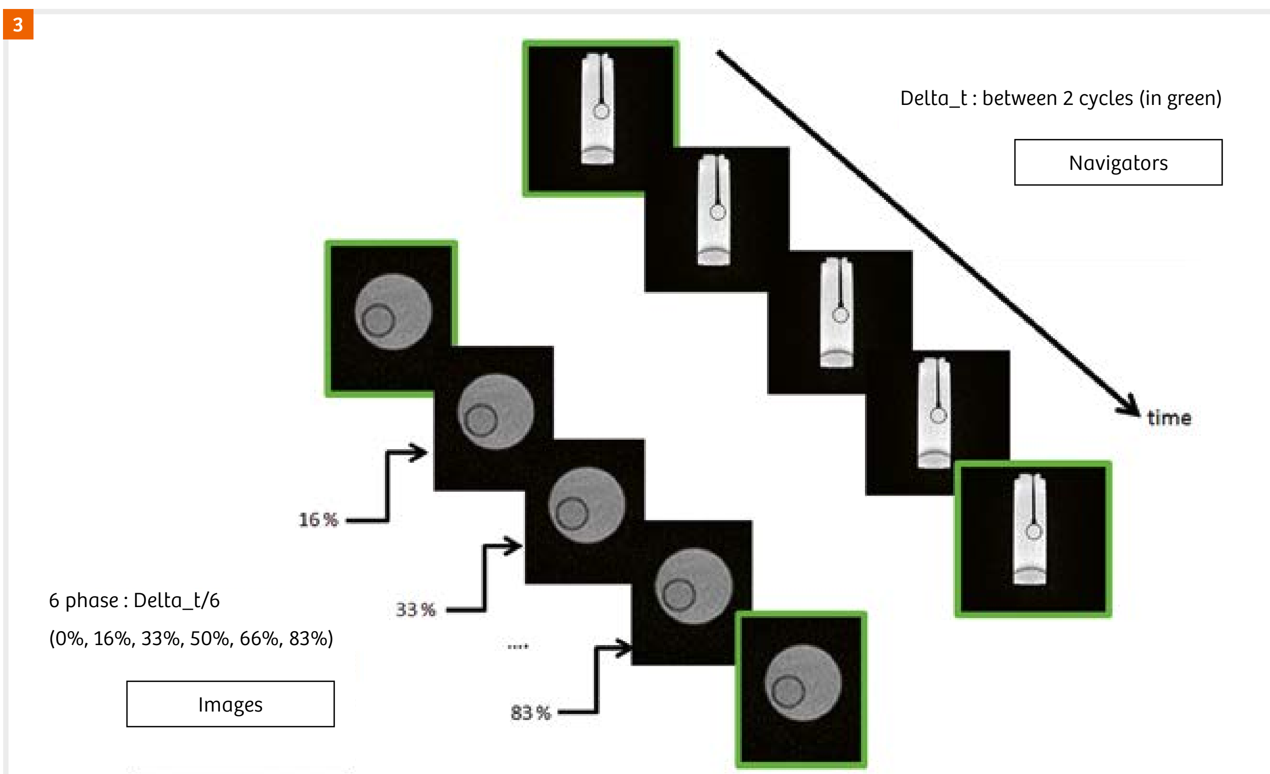
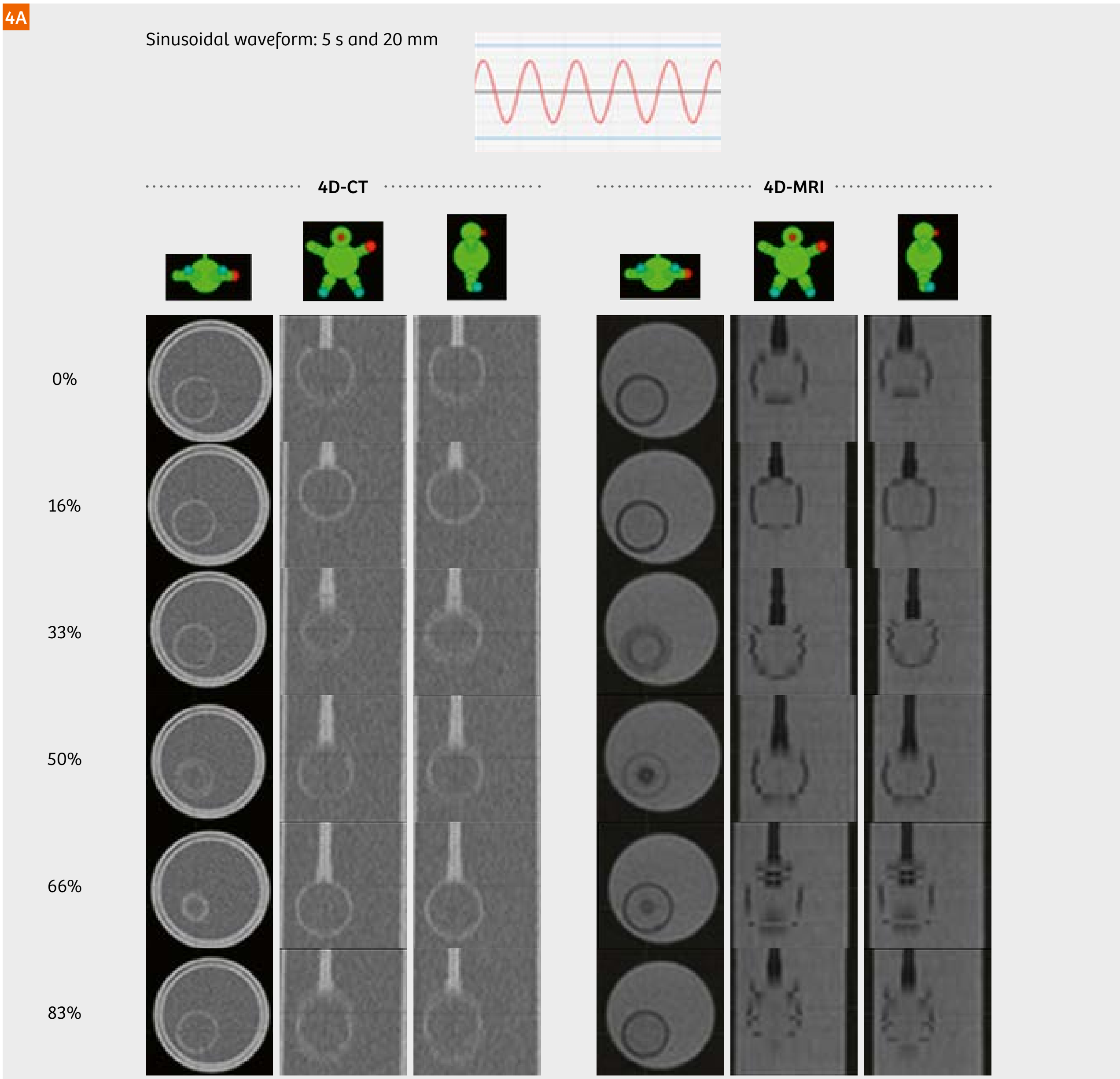


Figure 3:
Representation of 4D-MR images sorting according to 6 respiratory phases. Respiratory phases are defined identically as for the 4D-CT by the time interval between two navigators acquired at the same position.



4B

Real patient waveform:

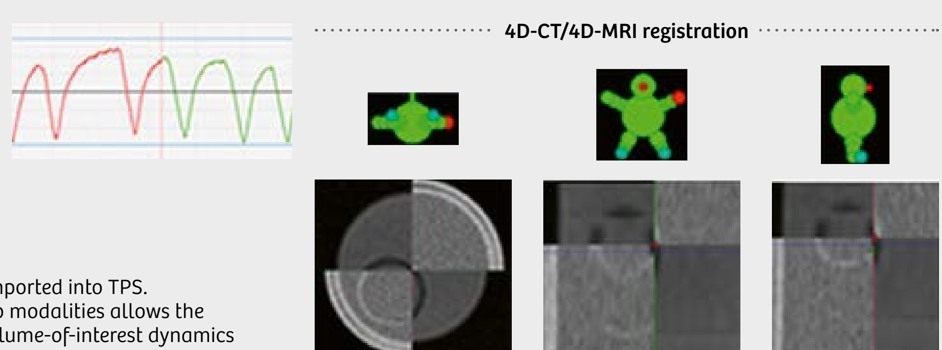


Figure 4:
4D-CT and 4D-MR images imported into TPS. Registration between the two modalities allows the visualization of the entire volume-of-interest dynamics at different respiratory phases **(4A)**. For the motion obtained from real patient breathing signal, the registration is shown with fragmented window **(4B)**.

MRI acquisitions

The data were acquired using a MAGNETOM Aera 1.5T whole body scanner (Siemens Healthcare, Erlangen, Germany), using an 18-channel design body flex coil. The 4D-MRI sequence is based on a modified balanced Steady State Free Precession (bSSFP) sequence [6] and consists of an interleaved acquisition of 2D data slices and navigators. The navigators were acquired at a fixed position in sagittal orientation and were used to determine the motion position during breathing. Contrary to navigators, the image slice position changed in order to cover the entire volume-of-interest in axial direction. 4D-MR images were acquired over 40 slices with a thickness of 2.5 mm, acquisition matrix of 272 x 288, FOV 299 x 299 mm^2 and with the following parameters Flip Angle (FA) = 70°, TE/TR = 2.43 ms / 440.75 ms, slice-time-resolution 0.44 ms. The sequence was repeated 10 times to cover the entire respiratory cycle. Total acquisition time for 10 repetitions was less than 6 min.

4D-MRI data reconstruction

The period of the respiratory cycle was divided in 6 bins, similarly to 4D-CT, which corresponds to 0%, 16%, 33%, 50%, 66% and 83% of the respiratory phase. The 2D-MR image slices where arranged by the respiratory phases and stacked in 3D-volumes thanks to the position and acquisition time of the navigators (Fig. 3). The data slices with the same slice location were grouped, offering the visualization of the entire volume-of-interest.

4D-CT/4D-MRI registration

4D-CT images of the Quasar™ MRI^{4D} motion phantom with the same motion waveforms as for the 4D-MRI were acquired and integrated in our Treatment Planning System (Eclipse Aria v13.7; Varian Medical Systems, Palo Alto, CA, USA). On Figure 4A, 4D-MR and 4D-CT scan registration for the sinusoidal waveform with 12 breaths/min and 20 mm peak-to-peak amplitude is shown. All respiratory phases were successfully reconstructed. The movement amplitude is well captured. 0%, 16%, 50% and 66% phases of the sinusoidal waveform are well defined both on 4D-MRI and 4D-CT images. Movement artifacts are clearly visible on both modalities on 33% and 83% phases during which the movement is the fastest. Registration of 4D-CT and 4D-MRI acquired from waveform of patient real respiratory signal is shown on Figure 4B.

Conclusion

4D-MRI sequence for RT application was validated on motion phantom with several evaluations of different motion signals. Acquisition time is compatible with clinical routine. Future work will consist of performing measurements on patients to assess whether the sequence is optimized to visualize the gold fiducials and the lesion for liver stereotactic body RT application.

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