4D-MRI: Future of Radiotherapy of Moving Targets?

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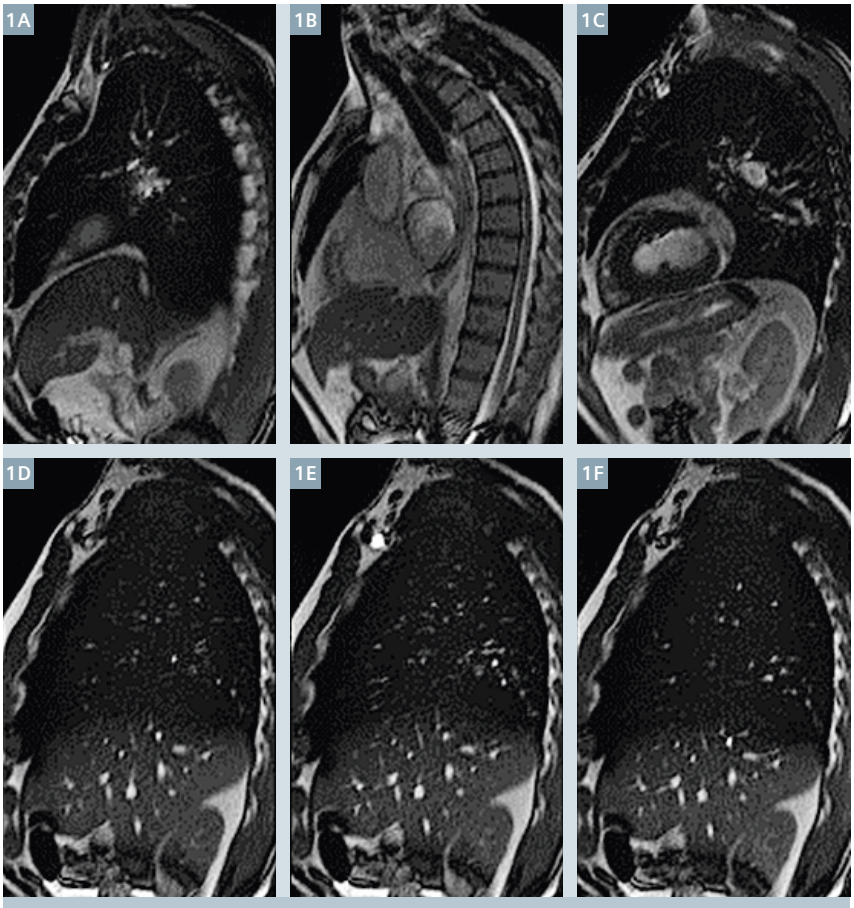
Background

4D-CT imaging is widely used in radiotherapy planning of moving tumors to account for motion, and to provide the physical properties of tissue for dose calculations, e.g. electron density for conventional radiation therapy or proton stopping power for proton therapy. However, it is limited to representing only a single, averaged breathing cycle, often contains imaging artifacts, and contributes a substantial dose exposure for the patient. To overcome these issues, a 4D-MRI imaging protocol applied to evaluating respiratory motion of the liver was proposed by von Siebenthal et al. [1].

This approach is capable of resolving irregular respiratory motion, with the added benefit of delivering no imaging dose to the patient. Unfortunately, whilst being a promising technique, MR imaging alone does not provide the physical properties of tissue required for accurate dose calculations. However, by combining the motion information provided by 4D-MRI, with the density data provided by single phase CT data, the advantages of motion imaging with 4D-MRI can now be applied to radiotherapy applications.



1 Sagittal slices through the thorax and upper abdomen, showing image slices **(1A–C)** and navigator slices **(1D–F)** acquired with the experimental 4D-MRI protocol*.

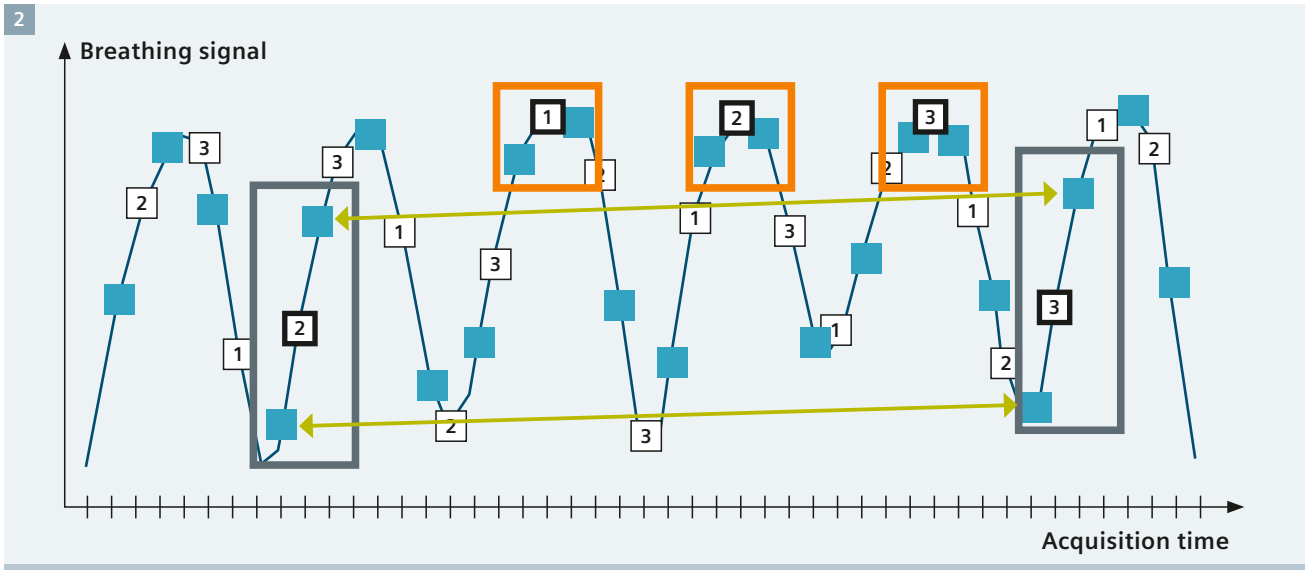
4D-MRI acquisition

The 4D-MRI protocol relies on the interleaved acquisition of a 'navigator' and different image slices in the sagittal plane (Fig. 1). The navigator is fixed at a single position throughout the acquisition time, and describes the motion state of the volume of interest at any instant during the acquisition. The actual 2D image slice is then scanned through the planned field-of-view (FOV).

This experimental sequence* does not make any assumptions about the breathing amplitude, its regularity, or the number of reconstructed phases. In contrast, commonly used methods for 4D imaging use a one-dimensional respiratory signal for sorting the 2D images, whereas 4D-MRI images can be retrospectively sorted based directly on the acquired navigator frames. The correspondence of the imaging slices is then established by comparing the two temporally embracing navigator frames (see Fig. 2). If these navigator frames are similar, the image slices can be stacked into a (3D) volume with the same time stamp and therefore, a complete 4D image data set with the same temporal resolution as the navigator frames can be reconstructed.

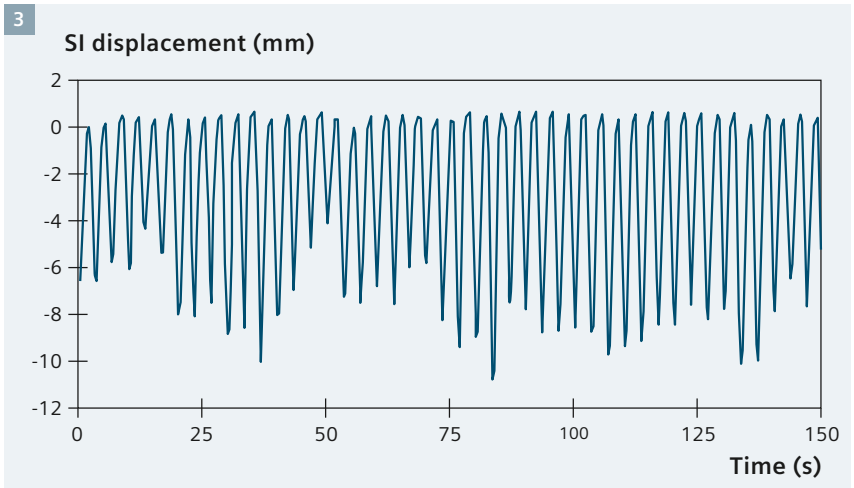
This approach has now been implemented on a 1.5T MAGNETOM Aera MR system (Siemens Healthcare, Erlan-

* Work in progress, the product is currently under development and is not for sale in the US and in other countries. Its future availability cannot be ensured. The product is not yet licensed for sale in Canada, in accordance with Canadian Law. Performance claims have not been reviewed by Health Canada, and are subject to change. Its future availability cannot be guaranteed.



2 Acquisition of slices (white boxes) and embracing navigator frames (blue boxes). Slices associated with the same volume are matched by comparing navigator pairs (green arrows) [2].

gen, Germany) using an experimental version of the balanced steady state free precession sequence (TrueFISP)*. Images are acquired in batches of 3-5 minute duration, with up to one hour of total acquisition time and with image slice thicknesses of 4 to 6 mm. Recent advances in the field are now looking at the simultaneous acquisition of navigator and data slices, with use of other advanced sequences, for example CAIPIRINHA [3].



3 Example of extracted 2.5 minute trace of the average liver SI motion [2].

Applications

- **Intra- and inter-fraction motion studies**
  Since MRI involves no radiation dose to patients or volunteers, 4D-MRI protocols allow for repeated studies on the same subject and/or for longer time period acquisitions in order to capture breathing variability (Fig. 3). Motion deformation fields can also be extracted using deformable image registration.
- **Mapping motion from MRI-CT**
  The 4D-CT (MRI) method has now been developed within our group for simulating many 4D-CT data sets from a single, static reference CT and a data-base of motion deformation fields extracted from 4D-MRI studies [4]. The mapping of motion information from 4D-MRI onto CT images is thereby achieved using subject-specific or population-based models, based on the establishment of mechanical correspondences between structures of interest (e.g. the liver). The resulting 4D-CT (MRI) images are of good quality when compared to 4D-CT (Fig. 4), and now represent the tissue properties necessary for dose calculations, whilst incorporating the motion information provided by 4D-MRI.
- **4D dose calculations in radiotherapy**
  Including the realistic, variable respiratory motion in provided by 4D-CT (MRI) data into 4D dose calculations, opens the door to novel future applications. Based on such data sets, advanced imaging and delivery methods, such as beam tracking (Fig. 5), can now be evaluated and comprehensive 4D planning studies and robustness evaluations performed.

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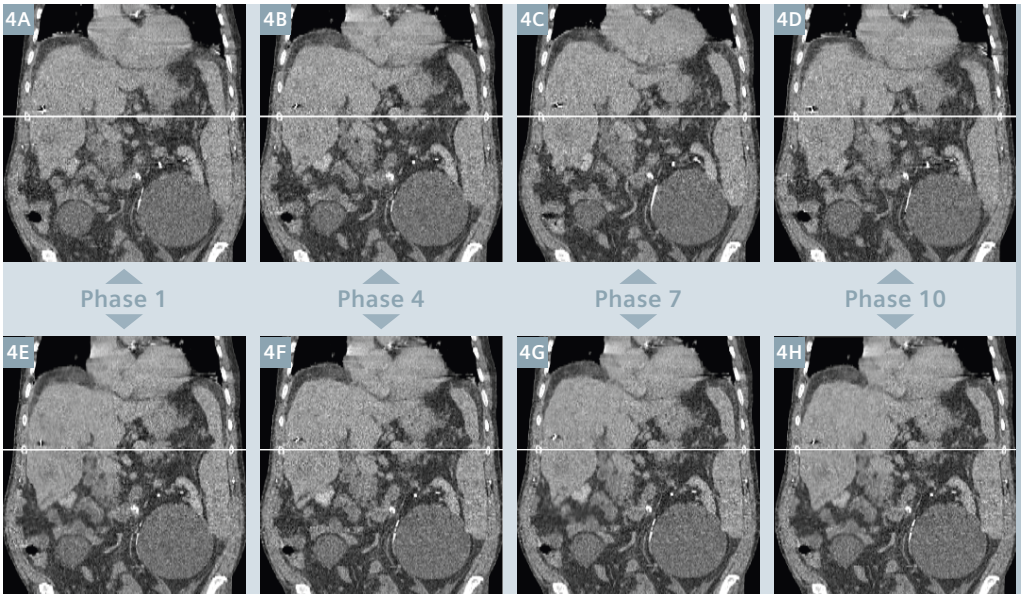
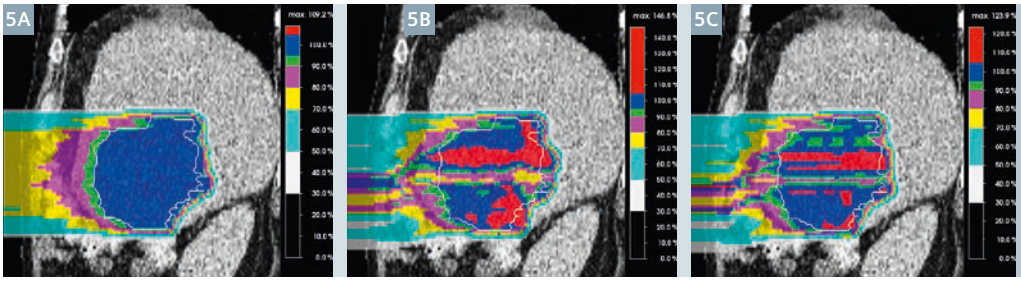


4 Comparison of different breathing phases of 4D-CT **(4A–D)** and 4D-CT (MRI) image sets **(4E–H)** simulated from the 4D-MRI motion library and a reference CT [4].



5 4D dose calculation results for different scanned proton tracking techniques based on 4D-CT (MRI) [5, 6].

Summary

4D-MRI, combined with CT data to produce 4D-CT (MRI) data sets, is a powerful new technique for imaging and modeling motion for radiotherapy applications. It allows for accurate modeling of motion variability, an important limitation of current 4D-CT techniques, and will allow in the future for the acquisition of patient specific motion libraries for advanced motion mitigation techniques such as tracking and re-tracking [5, 6].

References

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