Respiratory phase-resolved 3D MRI with isotropic high spatial resolution: Determination of the average breathing motion pattern for abdominal radiotherapy planning

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Introduction: Four-dimensional CT is currently a standard in radiotherapy planning to assess the impact of breathing on tumor motion and determine appropriate treatment margins. However, this modality has poor soft-tissue contrast, particularly for abdominal tumors, and involves high radiation dose. Likely, the motion pattern derived from a brief scan may not translate to the radiotherapy context. These limitations can be overcome by using 4D MRI. Two major approaches previously proposed include real-time 3D volume acquisition and retrospectively sorted 2D multislice acquisition. The first approach often faces a trade-off between the frame rate and spatial resolution/signal-to-noise ratio (SNR), whereas the second one is usually subject to poor slice resolution and sometimes an unpredictable scan time [1-4]. **The present work developed a retrospective 4D MRI technique (respiratory phase-resolved 3D MRI) that features: a) isotropic high spatial resolution (1.56 mm), b) a fixed scan time (8 minutes or less), c) an estimate of average respiratory phase resolved motion pattern with, and d) minimal intra-phase motion artifact.**

Methods: Sequence Design A spoiled gradient echo-based 3D projection reconstruction (PR) sequence with self-gating (SG) was developed for 4D MRI at 3T. Briefly, radial projections in the *k*-space are successively collected with 2D golden means ordering that allows for flexibility in both the scan length and data inclusion/exclusion and sorting [5]. The respiration-induced shift of the imaging target is recorded by an SG *k*-space line acquired in the superior-inferior (S-I) direction every 15 radial projections (i.e. 98 msec). A total of 73000 radial projections were obtained in 8 min in this initial study.
Data Post-Processing The S-I projections of the entire imaging volume were derived by Fourier transforming each SG line. The relative S-I translation of the imaging target throughout the 8 min was calculated by a cross-correlation based method [6]. Thus, each SG line serves as a motion stamp for a group of 15 *k*-space radial projections that follow. Following the detection of expiratory peaks on the S-I amplitude vs. time curve, exclusion of the projection group outliers (i.e. those involved in a breathing cycle with either an abnormal time period or inconsistent expiratory peak) and sorting of the valid projection groups were performed. More specifically, each valid breathing cycle was evenly divided into 10 temporal bins and each projection group was assigned a nominal respiratory phase among 1 to 10. Averaged over all valid cycles, each respiratory phase had a range in S-I amplitude, i.e. mean ± standard deviation. All projection groups were again successively reviewed for their S-I amplitudes to finalize the phase number; a group can be rebinned into an immmediately adjacent phase if its S-I amplitude is beyond the range of its nominal phase. After sorting *K*-space data, ten respiratory phase-resolved 3D image sets were eventually reconstructed using a self-calibrating CG-SENSE method [7].
Human Study The feasibility of the 4D MRI technique for abdominal imaging was tested on **four healthy subjects** and **three patients with liver or pancreas tumors**. All subjects were scanned in a head-first-supine position at 3.0T (MAGNETOM Verio; Siemens) using a 32-channel surface coil. An 8-min 4D MRI scan was followed by two 1-min 2D real-time (498 ms/frame) scans with a sagittal and a coronal slice traversing the liver parenchyma, respectively. Imaging parameters for the 4D MRI scan were: FOV (400 mm)^3, isotropic resolution 1.56 mm, flip angle 10^o, TR/TE 5.8/2.6 ms, bandwidth 399 Hz/pixel, water excitation to suppress fat signal. In-plane spatial resolution of the 2D scans was matched to those in the 4D MRI.

Results: The cycled S-I movement of the imaging target secondary to respiration were well extracted from SN signals as shown in **Fig. 1** (curve in blue). The proposed retrospective projection sorting strategy was capable of detecting occasional global drift (dashed box in black), abnormal time period (dashed box in purple), or inconsistent expiratory peaks (arrows). About 15-20% data were discarded owing to these reasons, resulting in ~6000 projections remained in each phase for image reconstruction. The technique yielded multi-phase 3D image sets with isotropic spatial resolution, permitting flexible image reformatting and visualization. No image artifacts, including intra-phase motion-induced blurring or undersampling-induced streaking, were observed. **Fig 2a** shows typical phase-resolved coronal and sagittal images reconstructed from the 4D MRI scan in a healthy subject; compared to the corresponding 2D real-time scan, the 4D scan revealed a similar S-I motion trajectory at the dome of the liver (not shown here). The movements of tumors were clearly identified by 4D MRI in patients. In one patient, for example, the gold fiducials as well as radiotherapy treated tumor were well depicted in all 10 phases (**Fig. 2b**); the motion trajectories of the lesion coincide with each other between the 4D and 2D scans.

Discussion: Our preliminary study has demonstrated that the retrospective 4D MRI technique can provide high-quality respiratory phase-resolved 3D images. Several factors that contribute to the success include using SG signals to directly detect the respiratory motion of the imaging target, using 3D radial sampling with golden-ratio ordering to obtain isotropic data, and using CG-SENSE to reduce required projection number while maintaining image quality. The scan time could be further reduced if employing a more advanced reconstruction method. Mobil phantom studies are currently underway to validate the accuracy of the technique. Further patient studies to compare it with 4D CT and assess its value in radiotherapy planning are warranted.

References: 1. Tokuda J et al. MRM 2008;59:1051. 2. Cai J et al Med. Phys.2011;38:6384. 3. Hu Y et al. Int J Radiat Oncol Biol Phys 2013;86:198. 4. Tryggestad et al. Med. Phys. 2013;40:051909. 5. Chan R.W. et al. MRM 2009 61:354–363. 6. Pang J. Et al. ISMRM 2013 (1314). 7. Pang J. et al. ISMRM 2013 (1295).

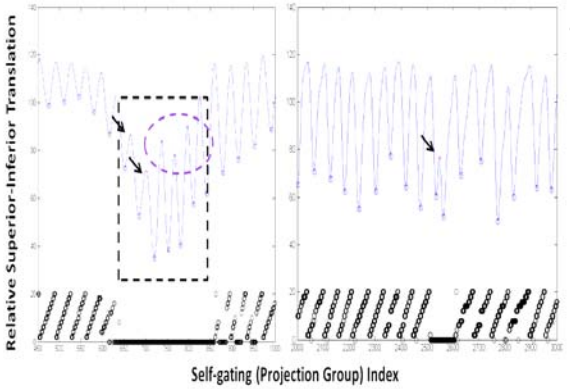

Fig. 1. *Two representative motion time-series (trimmed). Projection group outliers are discarded if involved in occasional global drift (dashed box in black), abnormal time period (dashed box in purple), or inconsistent expiratory peaks (arrows). Valid projection groups were binned to 10 phases (circles on the bottom)*

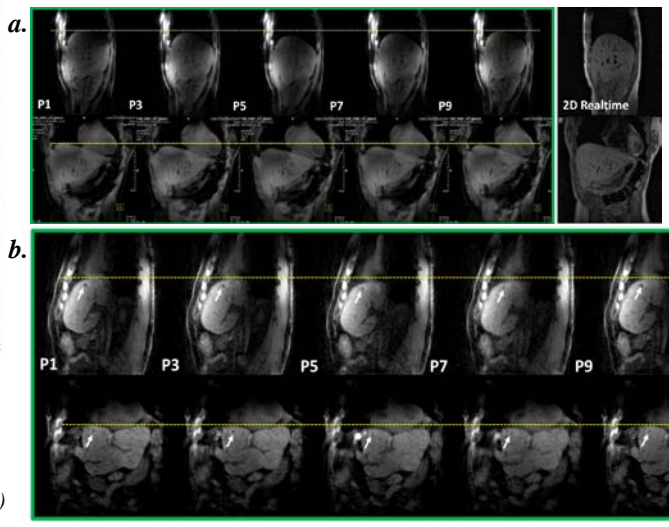

Fig. 2. *Phase-resolved sagittal and coronal images (phase 1, 3, …, 9) reformatted from 4D MRI in a healthy volunteer (a.) and a patient with gold fiducials (b. arrows).*