Free breathing abdominal imaging via self-navigation and subvolume registration

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Target Audience: Clinicians interested in free-breathing abdominal imaging and physicists interested in self-navigated 3D non-Cartesian imaging.

Purpose: To develop a method to collect abdominal exams in a free-breathing fashion, and retrospectively correct for non-rigid motion.

Introduction: The acquisition of dynamic contrast enhanced (DCE) abdominal images remains challenging due to the high spatiotemporal resolutions needed, and typically requires multiple breath held acquisitions during contrast uptake. This makes completion of such scans highly dependent on patient cooperation and technologist performance. A free-breathing DCE exam would remove the need for breath holds and should help lower the rate of failed or repeated studies. Recently, a method for ordering the projections of a multi-echo 3D radial acquisition to produce relatively equidistant samples regardless of timescale was developed [1]. This approach has been successfully applied in time-resolved 4D contrast-enhanced MR angiography [2]. In that application, reconstruction at a long time scale (~ 2 minutes) allowed computation of sensitivity maps and field maps, while reconstructions at a much shorter time scale (~1-2 s) allowed dynamic imaging of the vasculature. Adapting this type of multi-echo 3D radial acquisition to a free-breathing DCE liver exam requires correction of respiratory motion. Unfortunately this motion is non-rigid and thus cannot be compensated for by simple corrections to the raw k-space data. For this reason, an image-domain based self-navigation and subvolume registration approach was developed to take advantage of the flexible sampling provided by this type of 3D radial acquisition.

Methods: Two human subjects were scanned in compliance with HIPAA and a local IRB protocol. Images were acquired on a 3T Siemens Verio scanner using a multi-echo 3D radial FLASH pulse sequence (TR=8.4 ms, resolution = 1.8 mm isotropic, FOV=380 mm, 9 radial lines per shot). 4096 unique shots were repeated 8 times (total imaging time: 4 min 36 s). Contrast (Gadobenate Dimeglumine, Bracco Diagnostics, Princeton NJ, 0.1 mmol/kg) was injected approximately 70 s into the scan.

Based on prior comparisons of abdominal images reconstructed at various respiratory phases, the primary component of respiration-related liver motion was known to be in the superior/inferior (S/I) direction. Volumes using a 1 s data window were reconstructed every 0.5 s maintaining full resolution in the S/I direction, but a much lower 10.8 mm resolution in-plane to reduce aliasing artifacts. From this low resolution data, a pencil-beam navigator through the dome of the liver can be extracted by choosing an appropriate in-plane voxel (or averaging several adjacent voxels) and plotting the signal intensity along the S/I direction as a function of time. A motion timecourse was extracted from the navigator data and the motion waveform was divided into a series of twelve motion bins. Each timepoint of the acquisition was assigned to the bin containing the motion interval corresponding to its navigator. All projections corresponding to a given bin throughout the full acquisition were then combined to reconstruct a full resolution image (1.8 mm isotropic) corresponding to each respiratory position/bin. Nonlinear registration with FNIRT [3] was then used to coregister each motion bin to a reference volume (corresponding to the central bin). The warp fields produced by the nonlinear registration algorithm were stored for later reuse.

Dynamic motion-corrected volumes at 4 second temporal resolution were then reconstructed as follows: 1.) For each volume to be reconstructed, separate gridding reconstructions were performed for all projections corresponding to a given respiratory bin. 2.) The previously stored nonrigid registration parameters were then applied to warp each of these highly subsampled subvolumes to the reference position. 3.) The registered subvolumes from each bin were summed to form a motion corrected image. Gridding operations were performed using NUFFT algorithms with table-based interpolation [4]. A kernel size of 4x4x4 and grid oversampling factor of ~1.4 were chosen to minimize computation time while maintaining acceptable accuracy. To reduce susceptibility artifacts, field-map correction via time-segmented reconstruction was used. The fieldmap itself was determined from the same 3D radial dataset by reconstructing images corresponding to individual echo times within the multi-echo readout as described further in [2].

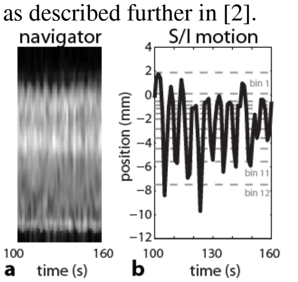

Fig. 1: a) pencil beam self-navigator. b) extracted motion timecourse with dashed lines indicating the motion bins.

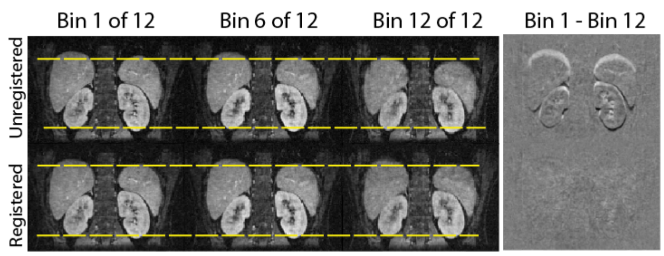

Fig. 2: top) Images corresponding to different respiratory bins before motion correction. bottom) corresponding motion corrected images. The rightmost column shows difference images between the most distant bins.

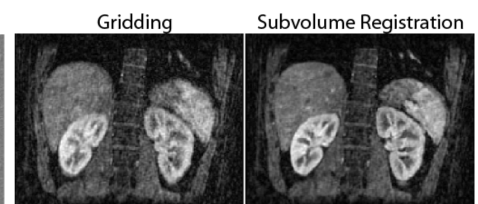

Fig. 3: (left) An early timepoint during contrast uptake reconstructed with four seconds of data, neglecting motion. (right) the simetimepoint reconstructed with registration of the temporal subvolumes. This is a separate subject than in Figs 1-2 (only 9 respiratory bins were used).

Results and Discussion: Fig. 1 shows a subset of the extracted pencil beam navigator timecourse and the corresponding motion estimates. Fig. 2 shows the images formed when using all projections for motion bins 1, 6 or 12 (top row). Motion corrected volumes are shown in the bottom row. The residual intensity differences are at the level of the noise in the subtraction of the registered images (Fig. 2, right). Registration of an individual subvolume is demonstrated in Fig. 3. Motion-related blurring is reduced in the image with subvolume registration. The results imply that a patient could be allowed to freely breathe throughout the contrast enhancement phases of the abdominal exam, and then the images retrospectively binned and registered to one another, allowing the retrieval of "motion free" images. In such an acquisition scheme, breath-hold requirements could be eliminated, with a major impact on patient comfort and compliance, and potentially extension of abdominal MR to patient groups currently excluded because they cannot provide the requisite breath-holds.

Conclusion The unique multi-resolution sampling properties of the 3D radial acquisition enable self-navigation and subvolume registration of free-breathing abdominal images. This could help reduce or eliminate respiratory motion corruption of abdominal MR exams.

References: 1. Lee et al. Proc. ISMRM 2012, p. 3012. 2. Lee et al. MRM 2012 (In Press: doi: 10.1002/mrm.24256). 3. Andersson et. al. FMRIB Technical Report TR07JA2, 2007. http://www.fmrib.ox.ac.uk/fsl. 4. Fessler et. al. IEEE Trans. Signal Processing 51(2):560-74, 2003

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