3D dynamic contrast enhanced imaging of liver at 250ms temporal resolution

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Introduction: Multi-phase contrast enhanced 3D liver imaging is important for assessing liver disease and tumors [1-3]. Multiple phases are necessary to correctly characterize lesions which enhance during arterial versus portal or delayed phases. But timing the bolus for optimal arterial and portal phases can be challenging especially when different arterially enhancing lesions may be better seen at different points of the arterial phase. High spatial resolution is essential but high temporal resolution is also useful to resolve early, middle and late periods of the arterial phase. Here, we present a method which combines high spatial resolution data acquisition using spiral trajectories [4-5] incremented at the golden ratio angle [7] to achieve 250ms temporal update rate for 3D whole liver coverage at an SNR equivalent to typical 15s breath hold acquisition. The high temporal fidelity reduces sensitivity to slow motion of, for instance, shallow respiration and peristalsis. Optimal time points within the arterial and portal phases can be chosen retrospectively or individual lesions can be interrogated on cine loops with 250ms temporal update rate.

Theory: The signal equation is written as $y = F(x) = P_k F T P_{FOV}(\rho \cdot c)$, where y is k-space measurements, ρ is image content and c is coil sensitivity. x can be solved iteratively using Gaussian-Newton method by updating dx in a linearized equation $F'(x_N)dx = y - F(x_N)$ (1). $F'(x_N)$ is the searching direction in each iteration[6]. When y is undersampled, $F'(x_N)$ in equation (1) is low in rank and heavily affected by the sampling trajectory. Penalizing high frequency of the k-space of coil sensitivity effectively improves the conditioning of the underdetermined system. Accurate coil sensitivity also helps to confine the search direction $F'(x_N)$ to the true direction. In fact, if no coil sensitivity regularization is used, the nonlinear problem is equivalent to a linear problem. But the reconstruction error will increase due to the bad conditioning and lack of reasonable constraint. In dynamic imaging, the last time frame is used as initial guess of current frame. With high temporal resolution, $y - F(x_N)$ is small, making this underdetermined system more stable. So it is possible to update an image for a single spiral leaf (including all slice encodings for that leaf) because spiral sampling has higher acquisition efficiency and covers more k-space area than a single Cartesian or radial sampling readout.

Materials and Methods: ***1) Acquisition and reconstruction:*** k-space is sampled using golden-ratio variable density stack of spirals, where consecutive spiral leaves are rotated over $2\pi\varphi \approx 220°$. Cartesian partial slice encoding with spectrally selective inversion pulse ensures fat suppression. A fully sampled static image is acquired before dynamic imaging as a start image. Each dynamic frame is calculated using the previous frame as initial guess and a single spiral leaf for updating. Temporal resolution of 3D image is TR * Nslice. Reconstructed images are temporally filtered using median filter to eliminate residual spiral undersampling artifacts.

2) Moving phantom experiment: A periodically moving phantom with maximum displacement 25mm, speed 13mm/s and plateau time 1s was scanned twice using 2D echo-train fast gradient echo sequence (90ms/frame) as reference and 3D spiral sequence(16 slices, temporal resolution 108ms/frame). Displacement as a function of time was calculated using sub-pixel image registration algorithm. 2D and 3D displacement curves are compared to demonstrate temporal fidelity. Reconstruction results using different iteration number and coil sensitivity regularization are compared. ***3) Human study:*** Our method was evaluated on 3 healthy volunteers and 4 patients after informed consent was obtained. Scans were conducted at 1.5T (GE EXCITE) using an 8-channel cardiac coil. Typical scan parameters were: TR/TE=7.2/0.6ms, flip angle=12˚, BW=±125kHz, FOV=34cm, spatial resolution= 1.25*1.25*5mm, matrix size=256×256×36-40. 20ml of Gd-DTPA or 10 ml Gadoxetate (Bayer, Wayne, NJ) were the bolus was injected at the moment of scan initiation. Total scan time was 33 seconds when patient is under breath hold. Dynamic images with temporal resolution of 250ms were generated over the total scan time. Aorta enhancement curve was compared with sliding window reconstruction.

Results: ***1) Moving phantom:*** The 3D dynamic reconstruction results tracks the moving phantom very well. By using 3 iteration for each frame (Fig 1 red curve), the maximum delay time is only 0.3s and gets smaller as time goes on. After 20 seconds, there is only negligible delay. Comparison of different iteration number (Fig 1) shows 3 iterations are normally needed to converge. Comparison of with and without coil regularization demonstrates that this prior information helps in updating the current frame (Fig 2). ***2) Human study:*** In all normal volunteers and patients, multiple diagnostic 3D data sets were obtained for early, middle and late arterial phases as well as for the portal venous phase (Fig 3). In patients who had minor diaphragm motion, in spite of breath holding, the technique was able to resolve this motion without creating artifacts. In addition, peristalsis was visible on the cine without smearing phase artifacts onto the organs. Optimal arterial, portal and venous phases were retrospectively selected by looking at the single slice showing all phases in time. Comparison with sliding window is shown in Fig 4 with superior tracking of aorta enhancement by our proposed method due to a lagging and averaging effect found in sliding window reconstructions.

Discussion/Conclusion: Multiphase spiral acquisitions with small update reconstruction improves dynamic 3D contrast enhanced liver imaging by increasing temporal resolution by nearly two orders of magnitude while preserving spatial resolution and SNR. This allowed interrogating many arterial and portal phases optimized for identifying different types of lesions. In patients, this would allow to asses enhancement kinetics for each lesion separately. Resolving shallow respirations and peristalsis enhances quality in uncooperative patients and eliminates any possibility of bolus timing error. Cine loops through lesions are useful for diagnostic characterization.

References:

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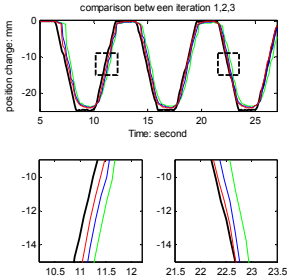

Fig 1. Moving phantom displacement curves show comparison of different iteration numbers. There is good temporal agreement between proposed method (red) and truth (black).

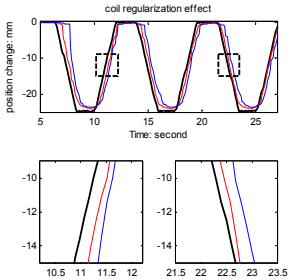

Fig 2. Comparison between with (red), without (blue) coil smoothness regularization and truth (black). Regularization effectively helps the method converge to the truth.

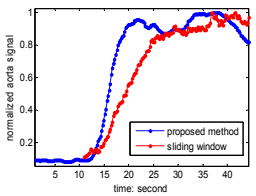

Fig 4. Comparison of aorta enhancement between proposed method and sliding window shows a superior response time for proposed method.

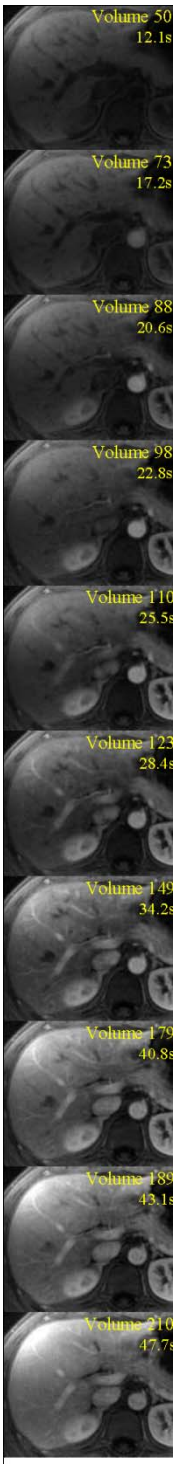

Fig 3. Arterial, portal and venous phases retrospectively chosen to characterize sub-second dynamic contrast enhancement process