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High Temporal Resolution DCE-MRI Using Partial K-Space Data for Imaging the Early Phase of Contrast Agent Uptake

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INTRODUCTION

The characterization of contrast uptake dynamics may provide important markers for identifying the invasiveness of breast tissue, increase specificity and diagnostic accuracy in breast dynamic contrast enhanced MRI (DCE-MRI). Standard high spatial-resolution clinical scans produce images at a low temporal resolution (approx. 60-120 seconds), leading to the loss of useful diagnostic information at early phase. While the use of ultrafast imaging (approx. 3.5 seconds) in recent studies[1, 2] shows capability to characterize the enhancement kinetics of arteries and veins, malignant and benign lesions, and background parenchymal tissue, it yields a lower spatial resolution and its temporal resolution is not sufficiently high to fully capture contrast uptake kinetics.

We propose a method to reconstruct images from small fraction of k-space to increase temporal resolution, so that the arterial input function (AIF), the propagation of the contrast media bolus and early media uptake by tissue can be more accurately measured. We test this reconstruction method using k-space produced by simulation phantom and mouse imaging.

AIM

We aim to increase the temporal resolution of DCE-MRI, by using small fraction of the total k-space dataset to reconstruct high temporal resolution images of the early phase of the contrast media uptake.

METHOD

Enhancement-constrained acceleration (ECA) reconstruction method

- The core of the ECA method is to solve a smoothness-constrained optimization problem (method pipeline is illustrated in Figure 1)
- High temporal resolution is achieved by partitioning k-space measurements into the desired temporal resolution and zero-padding the rest of k-space (unmeasured) to initialize the iteration (Figure 2)
- A positive smoothness penalty matrix penalizes the pre-voxel discretized second time derivation in the image-domain data
- Minimization is solved by projected conjugate gradient descent.
- Iteration stops when a pre-set tolerance is achieved

Simulation phantom

- Time-continuous phantom are created based on acquired breast DCE-MR images
- Spoiled gradient echo sequence
- Nominal temporal resolution: 3.5 sec
- High temporal resolution by ECA method: 0.25 sec (acceleration factor of 14)

Mouse imaging

- Images of femoral artery/vein of mice (Nude)
- 9.4 T MRI system (Bruker, Biospin)
- High dose contrast agent (Omniscan, 0.45 mmol Gd/kg) was injected into tail vein as a bolus
- Spoiled gradient echo sequence
- Nominal temporal resolution : 5 sec
- High temporal resolution by ECA method: 1 sec (acceleration factor of 5)

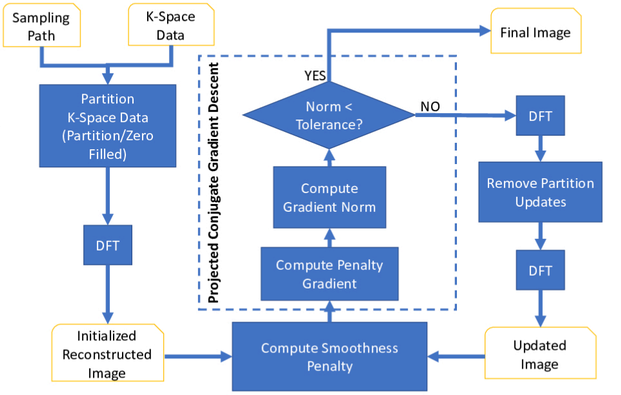

Figure 1. A flowchart illustrating pipeline of the Enhancement-Constrained Acceleration (ECA) method. In simulation, k-space is produced by a phantom created from ultrafast patient data and used a spoiled gradient-echo signal model. In mouse imaging, k-space data is exported from the 9.4 T MRI system (Bruker, Biospin). Sampling path contains time point of each k-space data been sampled. Reconstruction are produced via projected conjugate gradient descent over a quadratic smoothness penalty. Loss Function penalizes discontinuities in second discretized time derivative. Iterative updates is constrained to initially zero-filled k-space regions. Rectangles (yellow lined) represent data, while rectangles and diamond (blue filled) represent computational processes.

RESULTS

High temporal resolution images reconstructed by ECA method are accurate to the simulated phantom, as illustrated in Figure 3. While the peak of AIF is missed by standard IFT method due to the low temporal resolution, it is recovered by high temporal resolution images by ECA method. In addition, the ECA method offers a more accurate estimation on bolus arrival time (BAT), as indicated by a lower error standard deviation in Table 1.

In mouse imaging, ECA reconstructed images with high temporal resolution are able to recover a rapid enhancement at early phase. However, at high field, a significant drop in arterial magnitude signal is observed at early time points after injection of the contrast media. We reconstruct phase images as an alternative to magnitude imaging for recovering the AIF[3]. AIFs from phase imaging by ECA method show good agreement in shape compared with AIFs by standard IFT, as observed in Figure 5.

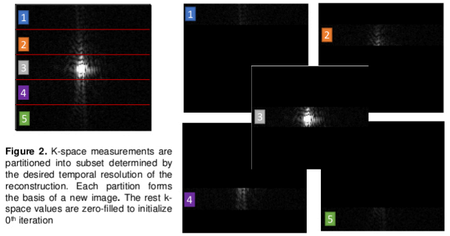

Figure 2. K-space measurements are partitioned into subset determined by the desired temporal resolution of the reconstruction. Each partition forms the basis of a new image. The rest k-space values are zero-filled to initialize 0th iteration

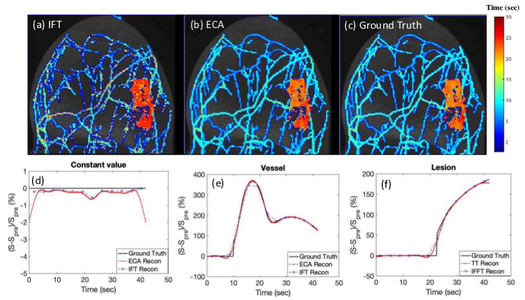

Figure 3. Evaluation of ECA method by simulation phantom from magnitude imaging. Upper figures: Bolus arrival time recovery map from: (a) a standard Fourier transform, (b) the ECA method, (c) the simulation phantom used as ground truth. Lower figures: Input function curve: standard Fourier transform (IFT) vs. the enhancement-constrained acceleration (ECA) method vs. ground truth of (d) Constant voxel, (e) Vessel voxel and (f) Lesion voxel. Using simulation phantom, ECA reconstructed curve is consistent with the ground truth curves and provides enhancement-fidelity and significant temporal resolution advantage over the standard IFT resolution.

Table 1. Bolus Arrival Time Error in Reconstructed Images of Simulation Phantom (Error Mean ± Error Std. Dev.)

	Lesion	Vessels
IFT	0.80 ± 3.8 sec	0.21 ± 6.0 sec
ECA	0.89 ± 0.81 sec	0.084 ± 0.097 sec

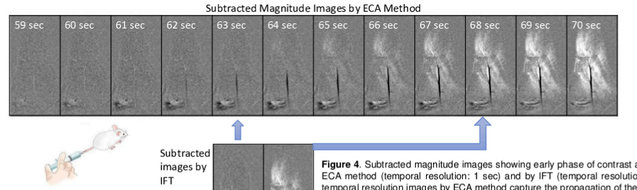

Figure 4. Subtracted magnitude images showing early phase of contrast agent uptake by ECA method (temporal resolution: 1 sec) and by IFT (temporal resolution: 5 sec). High temporal resolution images by ECA method capture the propagation of the contrast media bolus in artery and tissue. At high field, increased susceptibility effects and decreased longitudinal relaxivity of contrast agents lead to predominant T_2^* effect on arterial signal, causing a large undesirable dip in arterial magnitude signal at early time points. As a result, in subtracted magnitude images, artery is shown in black at early phase, indicating a negative change, while tissue (muscle) becomes brighter after few second after injection of contrast agent.

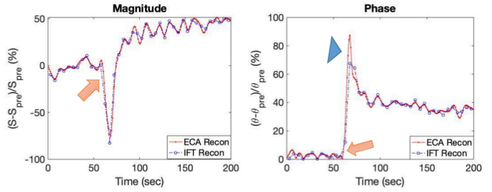

Figure 5. Normalized signal intensity change of a vessel voxel by standard IFT (temporal resolution: 5 sec) and ECA method (temporal resolution: 1 sec) from (a) magnitude imaging and (b) phase imaging. High dose of contrast agent was injected at 60 seconds for 10 seconds. This causes a rapid signal change, particularly in artery. Magnitude image shows a significant drop after injection due to T_2^* effect. Arterial input function curve is recovered by phase imaging. A clear bolus peak is observed in images by ECA method after injection of the contrast agent (blue arrow head), however, by standard IFT reconstruction, the peak is missing because of its low temporal resolution. In addition to the recovery of the peak in AIF, a sharper enhancement slope is observed in both magnitude and phase image (orange arrows) by ECA method, which indicates more accurate estimation of bolus time of arrival with high temporal resolution images by ECA method.

CONCLUSIONS

- ECA reconstruction method significantly increases temporal resolution during the initial phase of contrast media uptake, when enhancement is very sparse, at the same time, maintaining spatial resolution as well as SNR
- ECA method recovers temporal features, such as the peak in a sharp AIF in pre-clinical imaging, that are missed by standard Fourier method
- The early-enhancing features provide critical diagnostic information, e.g. K-trans, velocity of blood flow
- Future work will focus on:
  - Further study on pharmacokinetic characterization from high temporal resolution images produced by ECA method
  - further validating ECA method with mouse imaging
  - phase correction for reliable phase imaging in mouse experiment

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