Magnetic Resonance Imaging 33 (2015) 962–969

Contents lists available at ScienceDirect

Magnetic Resonance Imaging

journal homepage: www.mrijournal.com

High temporal resolution dynamic contrast-enhanced MRI using compressed sensing-combined sequence in quantitative renal perfusion measurement

Bin Chen [a], Kai Zhao [b], Bo Li [c], Wenchao Cai [b], Xiaoying Wang [a,b], Jue Zhang [a,c,*], Jing Fang [a,c]

[a] Academy for Advanced Interdisciplinary Studies, Peking University, 100871, Beijing, China
[b] Dept. of Radiology, Peking University First Hospital, 100034, Beijing, China
[c] College of Engineering, Peking University, 100871, Beijing, China

ARTICLE INFO

Article history:
Received 2 July 2014
Accepted 6 May 2015

Keywords:
Kidney
DCE-MRI
Perfusion
Compressed sensing
Temporal resolution

ABSTRACT

Purpose: To demonstrate the feasibility of the improved temporal resolution by using compressed sensing (CS) combined imaging sequence in dynamic contrast-enhanced MRI (DCE-MRI) of kidney, and investigate its quantitative effects on renal perfusion measurements.

Materials and Methods: Ten rabbits were included in the accelerated scans with a CS-combined 3D pulse sequence. To evaluate the image quality, the signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were compared between the proposed CS strategy and the conventional full sampling method. Moreover, renal perfusion was estimated by using the separable compartmental model in both CS simulation and realistic CS acquisitions.

Results: The CS method showed DCE-MRI images with improved temporal resolution and acceptable image contrast, while presenting significantly higher SNR than the fully sampled images ($p < .01$) at 2-, 3- and 4-X acceleration. In quantitative measurements, renal perfusion results were in good agreement with the fully sampled one (concordance correlation coefficient = 0.95, 0.91, 0.88) at 2-, 3- and 4-X acceleration in CS simulation. Moreover, in realistic acquisitions, the estimated perfusion by the separable compartmental model exhibited no significant differences ($p > .05$) between each CS-accelerated acquisition and the full sampling method.

Conclusion: The CS-combined 3D sequence could improve the temporal resolution for DCE-MRI in kidney while yielding diagnostically acceptable image quality, and it could provide effective measurements of renal perfusion.

1. Introduction

Dynamic contrast-enhanced MR imaging (DCE-MRI) has been established as a reliable method for diagnosis of renal diseases, enabling not only to differentiate between benign lesions and renal cancer but also to measure renal filtration and perfusion [1–5]. These accurate measurements considerably benefit from the improved temporal/spatial resolution and the elimination of artifacts. However, limited by conventional imaging methods, the spatial resolution is usually compromised to improve the temporal resolution for quantitative measurements [6].

To balance the tradeoff between spatial and temporal resolution, several algorithms with reduced k-space data have been explored, such as keyhole [7], Reduced-encoding Imaging by Generalized-series Reconstruction (RIGR) [8], k-t Broad-use Linear Acquisition Speed-up Technique (k-t BLAST) [9], k-t FOCal Underdetermined System Solver (k-t FOCUSS) [10] and Time-resolved angiography WIth Stochastic Trajectories (TWIST) [11]. However, a reference image has to be acquired to compensate the loss of information due to undersampling. Parallel imaging could also accelerate the acquisition [12] and had been used in kidney MR imaging [13,14]. Nevertheless, signal to noise ratio (SNR) is dramatically decreased when the acceleration factor increases in parallel imaging [12].

Compressed sensing (CS) is a recently emerging technique that may significantly accelerate data acquisition [15–19]. It allows images, which are intrinsically sparse in some domains, to be faithfully recovered from insufficient sampling data sets by using a nonlinear reconstruction method [20]. Furthermore, CS algorithm could provide image quality gains without the constraint of any reference images.

Principally, MRI images have long been found to be sparse in Fourier domain and can be reconstructed from incoherent undersampled k-space data [20–22]. Several retrospective CS simulations using the fully sampled DCE-MRI data set have been investigated, including the feasibility of temporal resolution improvement in breast

* Corresponding author at: 5 Yiheyuan Rd, Peking University, College of Engineering, Beijing, 100871, P.R.CHINA. Tel.: +86 10 62755036; fax: +86 10 62753562.
E-mail address: zhangjue@pku.edu.cn (J. Zhang).

http://dx.doi.org/10.1016/j.mri.2015.05.004
0730-725X/

DCE-MRI [23–25]. However, images of all those studies were reconstructed by the compressed k-space data, which were obtained from the fully sampled data set by only discarding it, rather than collecting it in acquisition. Recently, a CS-optimized 2D FLASH was proposed to shorten acquisition time and proved its feasibility in animal DCE-MRI [26], but analyses of kinetic parameters in realistic CS acquisitions were not performed. Those simulated undersampling would not have as high temporal resolution as realistic undersampled acquisitions. Thus, the effects on quantitative measurements in realistic CS acquisitions should be intensively investigated for in vivo DCE-MRI.

In this study, compressed sensing combined technique was implemented in 3D fast spoiled gradient-recalled echo sequence (FSPGR) to improve the temporal resolution in DCE-MRI of kidney. A longitudinal DCE-MRI study with different accelerated acquisitions was performed to verify the feasibility of each CS acceleration factor and the effects on quantitative renal perfusion measurements on ten rabbits. In order to assess the image quality in CS-accelerated kidney images, the signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) were tested between CS strategy and the conventional method. Furthermore, the effects on renal perfusion measurements due to the undersampling in realistic CS acquisitions were investigated.

2. Materials and methods

2.1. Animals and MR imaging

The Hospital Ethics Committee on Animal Care and Use approved the in vivo animal experiments. A total of ten healthy male New Zealand white rabbits (weighting 3.3–3.5 kg) underwent a longitudinal DCE-MRI study. All the rabbits were free fed with standard feed and tap water at room temperature, and stopped feeding 6 hours before experiments. The rabbits were anaesthetized by an administration of pentobarbital sodium (0.5 ml/kg body mass) through the marginal ear vein with a venous cannula (24G) and placed in a fixed device to avoid large respiratory motion in a supine position. Heart rate was continuously monitored by using a photopulse sensor of the MR scanner during acquisitions.

MRI scans were performed on a 3.0 T whole-body MR scanner (Signa Excite™; General Electric Medical Systems, Milwaukee, WI, USA) with 8-channel TORSOPA coil, and the coil could cover the abdomen of the rabbits. During the ten days' experiment, conventional full sampling (1-X) acquisition and the three CS acceleration scans (2-X, 3-X and 4-X) were randomly performed every three days for each animal by using a modified CS-combined 3D sequence.

In the first day of this experiment, a three-dimensional spoiled gradient-recalled echo sequence was scanned for baseline T1 measurement using variable flip angles method [27], with the following imaging parameters: TR = 6.3 msec, TE = 3.0 msec, flip angle = 3, 9, 20°, matrix = 256 × 228, NEX = 2, 180 × 180-mm field of view, 3.0 mm thickness and 16 slices. Subsequently, in each T1-weighted DCE-MRI scans, a CS-combined sequence was performed with the following imaging parameters: TR = 4.9 msec, TE = 1.6 msec, flip angle = 15°, matrix = 128 × 128, NEX = 1, 180 × 180-mm field of view, 3.0 mm thickness and 16 slices. During each acquisition, five pre-contrast frames were obtained, then, an administration of 0.1 mmol/kg of contrast agent (Omniscan; GE Healthcare Ireland, IDA Business Park, Carrigtohill, Co.Cork) was performed with a venous cannula, and 5 ml of saline was immediately flushed in. Totally 32, 65, 90, 125 frames were obtained for 1-, 2-, 3- and 4-X accelerated acquisitions during separate days for each animal, respectively. The temporal resolution is 5.0 s for 2-X, 3.5 s for 3-X and 2.5 s for 4-X acceleration. Total scan time is about 5 minutes for each DCE-MRI scan.

2.2. Compressed sensing combined MRI

In 3D MR imaging, both the phase encode and slice encode are practical to undersample the set of k-space lines. In our study, we modified a CS optimized slice-phase encode in the conventional 3D FSPGR sequence for DCE-MRI scan. First, the slice-phase encode of the conventional pulse sequence was modified in kz–ky plane for randomly undersampling (Fig. 1). The random sampling pattern was conducted with polynomial variable-density sampling [20]. According to this undersampling scheme, we randomly sampled 1/2, 1/3 and 1/4 set of k-space lines in realistic acquisitions, which resulted in 2-X, 3-X and 4-X acceleration for our CS acquisitions. By using this 3D k-space trajectory, the incoherent undersampled k-space data were acquired.

Compressed sensing recovers images from undersampled data by optimizing sparsity of reconstruction in the sparsifying transform. This can be faithfully achieved by solving the constrained optimization problem [20,22]. Furthermore, it is useful to perform a total-variation (TV) penalty as well [28,29]. Then, our compressed sensing reconstruction is as follows:

$$\begin{array}{ll} \textit{minimize} & \lambda_W \|\psi f\|_1 + \lambda_{TV} TV(f) \\ \textit{subject to} & \|Ff - d\|_2 \le \varepsilon \end{array} \quad (1)$$

where f is the image to be recovered, and ψ denotes the linear operator that transforms from pixel representation into a sparse representation, λ_W and λ_{TV} trade ψ sparsifying transform with finite-differences sparsity, and the initial values were set to be 0.02 and optimized according to a previous study [29]. F is the partial Fourier transform corresponding to a given undersampling scheme, d is the undersampled k-space raw data of each frame that were acquired by using our CS-combined sequence, ε controls the fidelity of the reconstruction which is usually set below the expected noise level [20].

The requirements of CS application to MRI were detailed previously [20] and summarized briefly in this study: a) transform sparsity, images exhibit a sparse representation in Fourier transform domain, b) artifacts due to the undersampling scheme in k-space are incoherent, c) a nonlinear reconstruction [22].

2.3. SNR/CNR measurements of the reconstructed images

From all of DCE-MRI reconstructions over approximately five minutes' acquisition after each bolus, totally 5 frames at 10 s, 30 s,

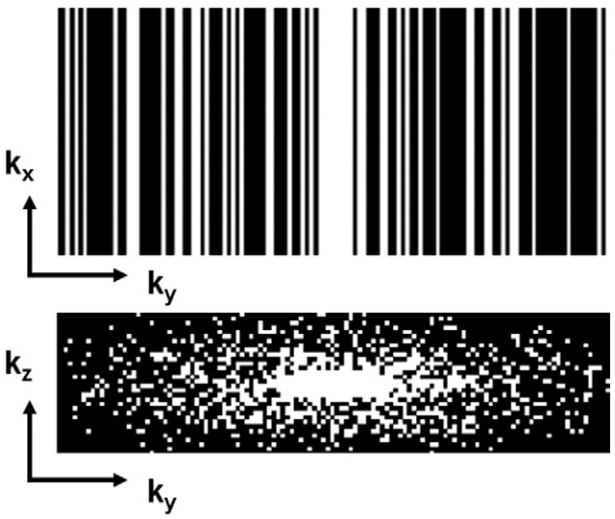

Fig. 1. The associated variable density undersampling scheme in kx–ky plane (top) and the cross-section of randomly undersampling in kz–ky plane (bottom) for CS-combined MRI.