Motion artifact correction in cardiac MRI as an irregularly sampled parallel imaging reconstruction

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INTRODUCTION

Generalized parallel MRI (pMRI) algorithms such as generalized SENSE (1), SPACE RIP (2), or PARS (3) allow irregularly sampled acquisition schemes. This feature can be advantageously used to correct some types of physiological motion artifacts, such as those induced by incorrect cardiac or respiratory triggering (4). It is possible to identify the k-space data which are corrupted by physiological motion with efficient patient monitoring (5). Then these corrupted data are eliminated by retrospective undersampling of the k-space, for any k-space trajectory. A generalized pMRI algorithm is then applied to reconstruct an artifact free image (see Fig.1). Here several implementations of generalized SENSE (G-SENSE) are used for the reconstruction, in the case of arbitrary cartesian sampling, by using different iterative methods. We compare the reconstruction time needed for each method.

METHODS

Downsampled MRI acquisitions can be reconstructed without aliasing by inverting the generalized encoding operator E relating the k-space signal s to the image ρ:

$$s = E\rho\,, \qquad [1]$$

Inversion of [1] is usually done by solving the least squares problem:

$$\min\left(\left\|s - E\rho\right\|^2 + \lambda\left\|\rho\right\|^2\right), \qquad [2]$$

where λ is a Tikhonov regularization tuning parameter. A necessary condition for solving [2] is given by:

$$\left(E^H E - \lambda Id\right)\rho = E^H s \qquad [3]$$

Generally, the Conjugate Gradient (CG) method is used to iteratively solve [3]. Methods based on Krylov spaces can also be used. In both cases, the reconstruction time is determined mainly by the computation of $E^H Ex$, for some vector x, which is repeated for each iteration of the chosen algorithm. We tested the Generalized Minimum RESidual (GMRES) algorithm as a Krylov space method, and also the Bi-Conjugate Gradient STABilized (BICG-STAB), which is a hybrid method.

Acquisitions were performed on a 1.5 T MR scanner (Signa, GEHC, WI), using an 8-element cardiac coil, with ECG triggered black-blood FSE pulse sequences. Physiological signals were acquired using a dedicated computer and electronics system presented in (5).

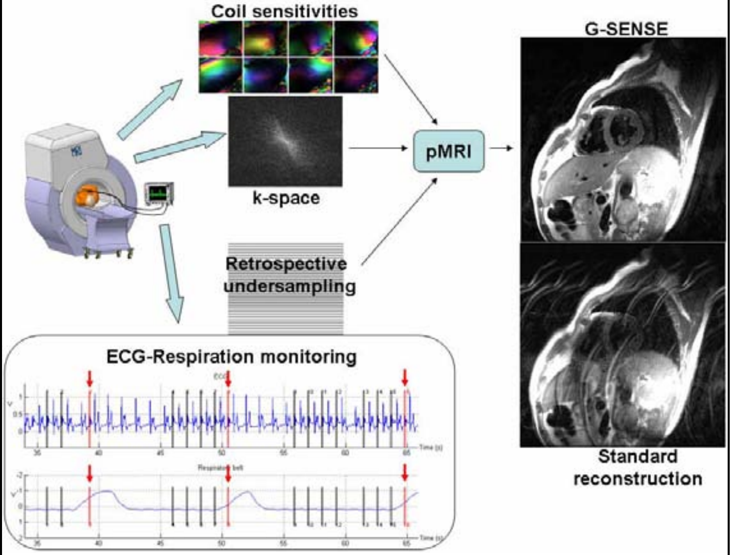

Fig.1: Reconstruction of a cardiac-respiratory triggered multi-shot sequence (black-blood FSE). Black lines drawn on the waveforms indicate correctly triggered shots, and red lines indicate corrupted acquisitions. This information is used to retrospectively undersample the k-space data (reduction factor=1.23 in this example). Images on the right show the resulting reconstruction with generalized SENSE (G-SENSE) and the standard reconstruction for comparison.

	Time (s)	# $E^H Ex$ calls
GMRES	21	12
CG	42	27
BICG-STAB	54	35

Table1: Time needed for the G-SENSE reconstruction of a 320x256 image (reduction factor=1.23, 8 coils), using Matlab code on a 1.5 GHz laptop, with 3 different iterative methods: Generalized Minimum RESidual (GMRES), Conjugate Gradient (CG), and Bi-Conjugate Gradient STABilized (BICG-STAB).

RESULTS

Results on 4 healthy subjects, in 10 image acquisitions, show that artifacts induced by incorrect triggering can be corrected with G-SENSE. A typical situation in which artifacts occur is when a trigger signal is detected at the end of an expiration plateau, and the diastole acquisition starts several hundreds of milliseconds after this trigger signal, during the inspiration phase (as in Fig.1). Reconstruction times obtained with the 3 different iterative methods are presented in Table1. In our tests, the GMRES should be the method of choice since it converges faster than other methods.

DISCUSSION

The proposed artifact correction method can be used alone or in combination with an already undersampled pMRI acquisition. The resulting pMRI reduction factor is then the combination of the standard pMRI acceleration factor and the artifact correction reduction factor. Hence an SNR loss is expected as for any pMRI technique but is the cost for obtaining an artifact-free image.

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