Generalized Reconstruction by Inversion of Coupled Systems (GRICS) applied to free-breathing MRI

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INTRODUCTION

The reconstruction technique in (1) allows correction for artifacts caused by arbitrary motion (spatial encoding errors). Practical implementation is very difficult as the algorithm requires prior knowledge about motion at each MR acquisition time. The proposed framework involves building an optimal motion model for motion compensated reconstruction, by solving both problems simultaneously (coupled systems formulation).

METHODS

Motion compensated reconstruction is an inverse problem, described by an encoding operator E modeling the acquisition pipeline (see Fig.1):

$$s = E\rho_0 \text{, or } E^H s = E^H E\rho_0 \text{, with } E^H E = \sum_{n=1}^{N} T_{t_n}^H \left(\sum_{\gamma=1}^{N_\gamma} F^H \sigma_\gamma^H \xi_{t_n}^H \xi_{t_n} \sigma_\gamma F \right) T_{t_n} \quad . \qquad [1]$$

Inversion of [1] requires knowledge of spatial transformation operators T_{t_n} at each acquisition time t_n. T_{t_n} may be given by a motion predictive model. Let δu be the displacement error fields at each acquisition time. Assuming that MR signal is conserved during the acquisition process (which is expressed locally by the optical flow equation), it can be shown that these motion prediction errors propagate linearly in the algorithm [1], that is, they induce a reconstruction residue of the form:

$\varepsilon = R\delta u$ (see Fig.2), [2]

It is possible to invert Eq. [2] in order to find better displacement field estimates, minimizing the reconstruction residue ε. However Eq. [2] contains too many unknowns for practical implementation. To overcome this problem, a motion model is introduced to reduce the number of parameters, although allowing locally free deformations (non rigid or affine motion). This model involves constraining the time dimension by linear combinations of certain input signals $[S_1(t)...S_K(t)]$ provided by external sensors (bellows, ECG…) or navigator echoes. The model is described by K coefficient maps $[\alpha_1(r)...\alpha_K(r)]$, such that displacement fields are estimated by :

$$u(r,t) = \sum_{k=1}^{K} S_k(t)\alpha_k(r) \text{, with } r = [x,y,z] \qquad [3]$$

Then, using [1], [2], [3], reconstruction can be reformulated as 2 coupled inverse problems (see Fig. 2):

$$\begin{cases} s = E(\alpha)\rho_0 & \text{(motion compensated reconstruction)} \\ \varepsilon(\rho_0,\alpha,\delta\alpha) = R(\rho_0,\alpha)\delta\alpha & \text{(motion model optimization)} \end{cases} \qquad [4]$$

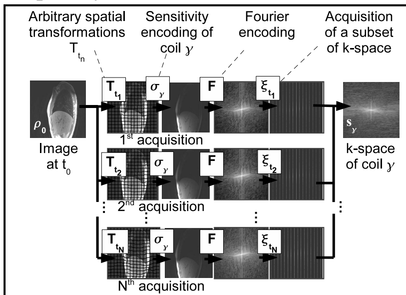

Fig.1: Encoding operator used for generalized reconstruction including arbitrary motion and sensitivity encoding, generalizing (1) and (2).

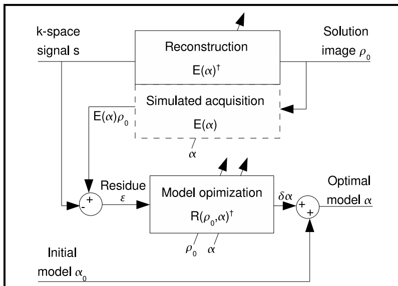

Fig.2: GRICS framework for coupled resolution of two inverse problems: motion compensated reconstruction and motion model optimization.

A multiresolution fixed point method is proposed for solving system [4], with an initial model comprised of zero coefficients. The algorithm was validated on real data acquired with a 1.5 T MR scanner (Signa, GEHC, WI). Physiological signals (pneumatic belts and ECG) were acquired with a dedicated system presented in (3). We used 4 input signals in 2D reconstructions (2 respiratory belts + their derivatives), and 1 input in 3D (1 belt).

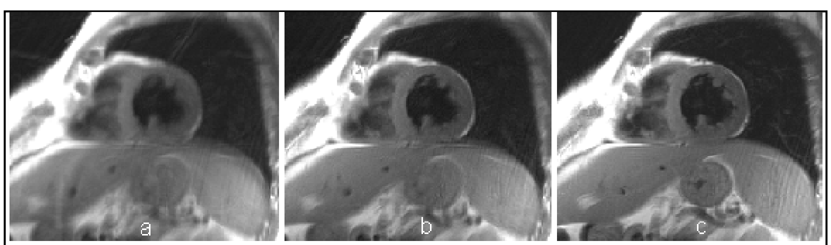

Fig.3: Free-breathing: standard reconstruction (a), GRICS (b) ; breathhold (c) (ECG triggered black blood RARE).

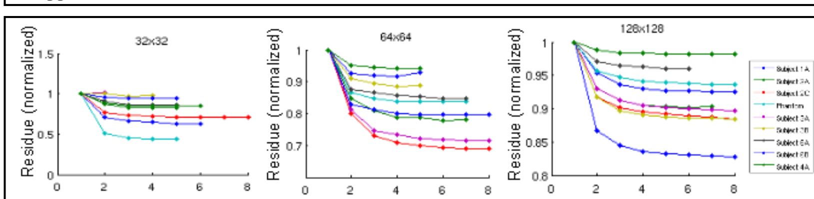

Fig.4: Evolution of the reconstruction residue over iterations, at each resolution level, in 9 reconstructions (2D , 256x256 matrix experiments).

RESULTS

Results have been demonstrated in data from a moving phantom and 6 volunteers, acquired in free breathing (17 pulse sequences in total), including 2D and 3D cardiac/abdominal scans. Reconstructed image quality was close to that obtained in breath hold (see example in Fig.3). Practical convergence was assessed by monitoring residue evolution (decrease) over iterations (see Fig.4). Time needed for reconstruction ranged from 3 min (256x256 image) to 210 min (256x256x32 volume) with Matlab® single-threaded code.

CONCLUSION

The GRICS framework overcomes many limitations of existing methods, as it allows correction for artifacts caused by elastic motion, which makes it suitable for cardiac or abdominal imaging. The multiresolution scheme allows accounting for large displacements. The method is completely autocalibrated, with regard to multiple coil acquisition (determination of coil sensitivities) and to motion correction (determination of model coefficients).

REFERENCES
1.Batchelor *et al.* [2005] MRM. 54:1273-1280 **2.**Pruessmann *et al.* [2001] MRM. 46:638-651 **3.**Odille *et al.* [2007] IEEE TBME. 54:630-640