Coil Sensitivity Encoding for Fast MRI

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INTRODUCTION

As suggested earlier by various authors [1-5] the sensitivity of a receiver coil may be regarded as a modification of the harmonic encoding functions in Fourier imaging. According to this view parallel acquisition with an array of receiver coils yields distinct spatial information in each channel. However, special image reconstruction methods are required in order to take advantage of sensitivity encoding for faster imaging.

The techniques described in [1-4] are based on the image domain formulation of Fourier aliasing. *In vivo* feasibility has been reported for the SMASH method [5] which uses the k-space formalism for image reconstruction.

Taking the image domain approach, in this work we introduce a scheme of acquisition and reconstruction steps called 'SENSE', short for SENSitivity Encoding. Given a receiver array it enables the reduction of scan time in any standard Fourier imaging mode. As compared to previously proposed image domain techniques [1-4], SENSE exhibits crucially improved *in vivo* practicability due to a generalized approach to the inversion problem and to an advanced *in vivo* reference strategy. Together with the method an SNR analysis is presented as well as a selection of phantom and *in vivo* results.

METHODS

Using an array of M receiver coils the duration of a standard Fourier scan is reduced by increasing the distance of readout lines in k-space by a real number $L \leq M$. Reconstruction of single coil images by FFT yields a reduced FOV with each pixel representing the superposition of N equidistant voxels in the object, where $N < L+1$. Foldover in corresponding pixels of the M single coil images is described by

$$\vec{a} = S\vec{b} \qquad (1)$$

where a_i is the pixel value in the i-th coil image, S_{ij} is the complex sensitivity of the i-th coil at the position of the j-th out of N voxels, and b_j is the tissue contrast function at the j-th position. The vector b is determined according to

$$\left|S\vec{b} - \vec{a}\right| = min \quad \Rightarrow \quad \vec{b} = S^{+}\vec{a} \qquad (2)$$

where S^+ denotes the pseudoinverse of the M×N matrix S. This inversion is performed for each pixel in the reduced field of view, yielding a representation of the tissue contrast function in the full FOV at preserved resolution.

Good knowledge of the matrix S is essential. In addition to actual imaging, low-resolution full-FOV single coil images of arbitrary contrast are acquired simultaneously as references. Raw sensitivity maps are obtained through division by either the 'sum-of-squares' of the single coil references or by an optional body coil reference. In the latter case reconstructed images will automatically be intensity corrected. Refinement of raw maps is crucial for image quality. It is achieved by a local polynomial fit procedure including thresholding, smoothing and extrapolation.

Compared to an array image obtained with full phase encoding the SNR of a reconstructed image is reduced approximately by

$$\frac{SNR_{full}}{SNR_L} = G\sqrt{L} \qquad (3)$$

where $G \geq 1$ is a local geometry factor reflecting the degree of linear dependence of the coil sensitivities at superimposed positions. The G factor is calculated from the matrix S only, thus enabling a priori estimates of SNR and optimal choice of L. G is minimized by excluding those voxels from inversion which lie outside of the object according to the reference images. Thereby, local SNR is significantly improved and sensitivity extrapolation may be restricted to a short, reliable range.

RESULTS

The proposed methods were evaluated experimentally on a 1.5 T Philips Gyroscan NT system. Fig. 1 demonstrates unfolding and intensity correction in a quality phantom using five surface coils positioned around the object. Fig.2 shows a brain image acquired with a reduction factor of L=2.0 using only two coils, and a short axis heart image acquired with five coils and L=2.9. Using the same setup single-shot EPI data were collected from a transverse heart slice in 31 ms per image (L=2.5) yielding images of acceptable quality with a resolution of 2.3×2.9mm.

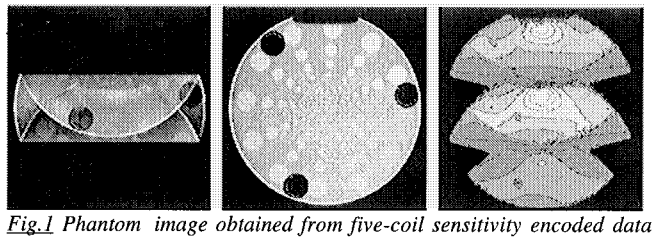

Fig.1 Phantom image obtained from five-coil sensitivity encoded data 2.9-fold undersampled in phase encoding direction.
Left: 'sum-of-squares' from single coil images. Middle: Reconstruction.
Right: map of G-factor reflecting local noise enhancement.

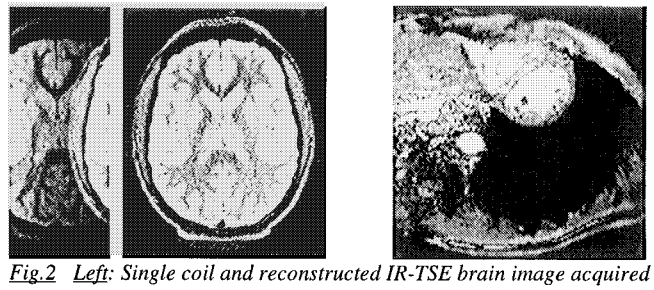

Fig.2 Left: Single coil and reconstructed IR-TSE brain image acquired with a two coil array in 85 s instead of 170 s for full Fourier encoding.
Right: Short axis half Fourier EPI heart image from a multi-phase series acquired with a five coil array in 7 instead of 17 heart beats.

DISCUSSION

It has been demonstrated that the discussed method is feasible *in vivo* and enables considerable reduction of scan time. No residual foldover artifacts are observed. Optimized non-integer reductions are possible and no particularly shaped coil sensitivities are required. Nevertheless, the coil arrangement is a major determinant of SNR and will be subject to further studies.

The sensitivity encoding concept is naturally impaired by the need for fairly good sensitivity maps. However, practicability is improved considerably by the use of low resolution references and automated map refinement. Extrapolation allows sensitivity maps to be applied also to slightly changing tissue configurations as encountered in cardiac imaging. Thus, successive imaging is enabled with only one initial reference scan. 3D sensitivity maps may be a major future improvement.

Clearly, SENSE is only appropriate if the need for scan speed outweighs SNR concerns. Therefore, it appears most promising for real-time and rapid imaging, especially using single-shot strategies which strongly benefit from shorter echo trains.

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