Noise in Transmit SENSE

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"Transmit SENSE" adapts ideas of parallel imaging to RF transmission. Using multiple independent transmit coils, the duration of spatially-selective multidimensional RF pulses can be reduced, while the spatial definition of the pulse profile is maintained. This study discusses possible noise sources within Transmit SENSE and its influence on the resulting excitation pattern. The understanding of this subject can help in the design of optimized transmit coils and in improving the performance of Transmit SENSE. It is shown that the freedom in designing coil arrays is much larger in Transmit SENSE than in conventional "receive" SENSE.

Introduction

Recently, parallel imaging techniques have been developed to accelerate MR image acquisition (1,2). The physics of spatially-selective RF pulses shows strong similarities to the principles underlying MRI, and the application of the principles of parallel imaging to RF pulse design has been proposed recently (3,4). Using multiple transmit coils, the path to be traversed in excitation *k*-space can be reduced, thereby shortening the RF pulses without sacrificing spatial definition. On the other hand, parallel imaging techniques provoke specific noise (5,2). Once the origin and propagation of this noise is understood, the design of the used receive coil array can be optimized minimizing this noise. The present study discusses basic features of noise origin and propagation in Transmit SENSE. The understanding of this subject can help in developing specific transmit coils yielding improved results for Transmit SENSE.

Theory

The central equation of Transmit SENSE for an arbitrarily shaped, desired magnetization pattern $P_{des}(\mathbf{x})$ is

$$P_{des}(\mathbf{x}) = \sum\nolimits_{r=1}^{R} S_r(\mathbf{x}) P_r(\mathbf{x}) \quad . \qquad [1]$$

Here, R is the number of transmit coils with the (complex) sensitivity profiles $S_r(\mathbf{x})$, each having an individual pulse profile $P_r(\mathbf{x})$ within the excitation FOV. These pulse profiles, corresponding to the reduced *k*-space trajectory, are affected by subsampling artifacts. However, these artifacts are cancelled out by the superposition described by Eq. [1], and the desired magnetization pattern $P_{des}(\mathbf{x})$ is obtained, which corresponds to the full *k*-space trajectory. According to ref. (3), one solution of Eq. [1] is

$$\mathbf{p}_{full} = \mathbf{s}_{full}^{H} (\mathbf{s}_{full} \mathbf{s}_{full}^{H} + q^2)^{-1} \mathbf{p}_{des} \quad . \qquad [2]$$

In Eq. [2], q represents the regularization parameter, and H denotes the transposed complex conjugate. The Fourier transform of $P_{des}(\mathbf{x})$ is denoted with $\mathbf{p}_{des}$, $\mathbf{s}_{full}$ contains the coil sensitivity profiles, and $\mathbf{p}_{full}$ contains the desired individual waveforms, which in the experiment have to be transmitted simultaneously via the different transmit coils (for details cf. ref. (3)).

Noise in Transmit SENSE might originate from, e.g., the D/A converting process and RF amplifier imperfections. This system noise affects the individual pulse profiles $P_r(\mathbf{x})$, and, thus, influences the final result in a linear way as a superposition in the spatial domain (cf. Eq. [1]). Noise or measurement errors in the coil sensitivity profiles also influence the final result linearly via Eq. [1]. It is important to note, that the system noise does not interact with the central matrix inversion (Eq. [2]). This is a crucial difference with respect to conventional SENSE, where the system noise generated in the receive chain is enhanced, if the matrix inversion is ill-conditioned. The difference is caused, since, in conventional SENSE, the inverted matrix is multiplied with the measured data bearing noise. In Transmit SENSE, the inverted matrix is multiplied with the desired excitation pattern, which is free of noise (cf. Fig. 1a). In that respect, the concept of the geometry factor as deduced for conventional SENSE (2) cannot be adapted directly to Transmit SENSE. If the inverse problem of Transmit SENSE (cf. Eq. [2]) is ill-posed, the superposition of Eq. [1] does not lead to a complete cancellation of the subsampling artifacts, and noise-like structures appear in the final result. The problem becomes ill-posed, if the spatial frequency components of the actual coil sensitivity profiles are not able to compensate the missing parts of the reduced *k*-space trajectory. Thus, a proper interplay between the coil sensitivity profiles and the involved trajectories has to be found. In the following, this interplay is investigated in some detail in the framework of a numerical simulation.

Methods and Results

A homogeneous, circular, desired magnetization pattern $P_{des}(\mathbf{x})$, two transmit coils, and a reduction factor $R = 2$ were assumed. Both transmit coils had a constant modulus sensitivity profile. Additionally, one transmit coil had a linear phase distribution of 20° across the excitation FOV. The orientation α of this linear phase relative to the excitation FOV was varied. The corresponding waveforms were calculated via Eq. [2], which should be applied using the corresponding transmit coils, while the gradient system generates the reduced trajectory. This experiment was simulated solving the Bloch equations assuming small flip angles. To benchmark the result, the correlation between the numerical result and the desired magnetization pattern was calculated. Fig. 1b shows the result of this simulation. The correlation does not depend on α for a spiral trajectory. However, for a Cartesian trajectory, the correlation is significantly reduced for $\alpha \approx 90° \pm 0.001°$, i.e., if the coil sensitivity does not differ significantly in preparation direction. On the other hand, radial symmetric coil sensitivities did not lead to a significantly reduced correlation for spiral (as well as Cartesian) trajectories: all investigated scenarios with radial symmetric coil sensitivities resulted in correlations larger 99%.

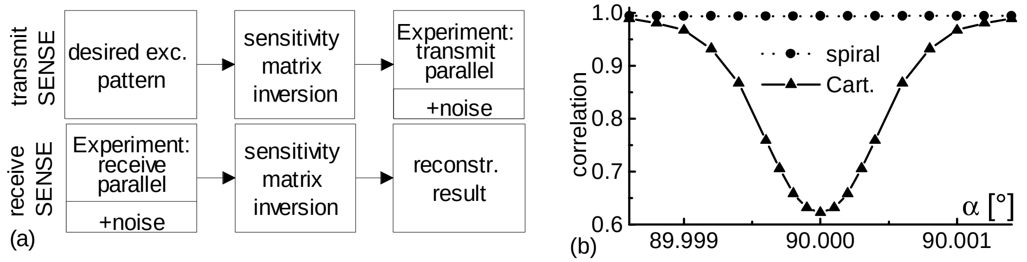

Fig. 1: (a): Comparison of Transmit / receive SENSE demonstrating the occurrence of experimental noise after / before the inversion of the sensitivity matrix. (b): Influence of ill-conditioned sensitivity matrix in Transmit SENSE. The correlation between desired excitation pattern and simulation is shown for a linear coil sensitivity. The orientation α of the coil sensitivity influences the correlation only for a Cartesian trajectory and only for a very small angular range.

Discussion and Conclusion

The results show, that an ill-posed matrix and, thus, significant image quality deterioration in Transmit SENSE can be found only for coil sensitivities varying only perpendicularly to the preparation direction of a Cartesian *k*-space trajectory. It is very unlikely to find such a pathologic situation in real experiments. Thus, the problem of an ill-posed inverse problem does not seem to play a major role in Transmit SENSE. Consequently, the freedom in designing coil arrays seems to be much larger in Transmit SENSE than in SENSE in the receive mode. Noise in Transmit SENSE is caused predominantly by system imperfections and is assumed to propagate linearly according to the underlying theory.

References

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