Experimental verification of over- and underdetermined Transmit SENSE

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Introduction: A major goal of parallel transmission is to reduce the length of spatially selective RF pulses [1,2], which might be applied, e.g., for RF shimming or localized excitation [3]. The reduction of the pulse duration, however, is accompanied with a decreasing accuracy of the excited spatial pattern. In this study, the trade-off between RF pulse duration and excitation accuracy is investigated with an experimental MR system capable of parallel transmission.

Theory: The central equation of parallel transmission is [1,2]

$$P_{des}(\mathbf{x}) = \sum_{i=1}^{N} S_i(\mathbf{x}) P_i(\mathbf{x}) \quad . \tag{1}$$

Eq. (1) states, that the undersampled spatial patterns $P_i(\mathbf{x})$ have to be excited by the N transmit coils, each exhibiting a characteristic sensitivity profile $S_i(\mathbf{x})$, to obtain the desired excitation pattern $P_{des}(\mathbf{x})$. Here, $P_{des}(\mathbf{x})$ is defined within the Field of Excitation (FOX), assumed to be discretized on M spatial pixels. To facilitate the calculation of the unknown $P_i(\mathbf{x})$, Eq, (1) is rewritten [1]

$$p_{des}(\mathbf{k}) = s_{full}(\mathbf{k} - \mathbf{k}')\, p_{full}(\mathbf{k}') \quad . \tag{2}$$

Here, s_{full} contains the sensitivities of all N transmit elements transformed into k-space, and, correspondingly, the N individual p_i are combined to the vector p_{full} [1]. Compared with the "original" k-space trajectory $\mathbf{k}(t)$, fulfilling the sampling theorem, the length of the k-space trajectory $\mathbf{k'}(t)$ is reduced by a factor R. Now, the pseudo-inverse solution of Eq. (2) depends on R and N. For the case $R < N$, the system of equations is underdetermined, and the solution of Eq. (2) reads

$$p_{full} = s_{full}^{H}\left(s_{full} s_{full}^{H} + \lambda\right)^{-1} p_{des} \quad . \tag{3}$$

For the case $R > N$, the system of equations is overdetermined, and the solution of Eq. (3) reads

$$p_{full} = \left(s_{full}^{H} s_{full} + \lambda\right)^{-1} s_{full}^{H} p_{des} \quad . \tag{4}$$

Please note, that this mathematical scenario is opposite to SENSE in the receive case [4], where $R < N$ yields an overdetermined and $R > N$ an underdetermined scenario [5].

Methods: A 3T MR system (Philips Achieva, Philips Medical System, Best, The Netherlands) was equipped with an 8-channel body coil and the corresponding RF channels capable for parallel transmission. To test the stability of the excitation accuracy, 8, 4, and 2 transmit elements were controlled individually. Reduction factors between 0.8 and 8.9 have been applied, corresponding to spiral k-space trajectories between 16 and 2 revolutions, exciting FOX of 32×32 pixel. A modified spin echo with a non-selective refocusing pulse has been used. The sensitivities have been acquired with a non-selective sequence for each array element separately. Two types of experiments have been performed: local excitation of a circular pattern (radius 6 pixels) and RF shimming (constant excitation pattern). Furthermore, for N=2, the influence of the sensitivity distribution on the accuracy excitation was tested. Therefore, two transmit elements in an angular distance of dφ=45°, 90°, and 180° were investigated. Additionally, the 8 elements were combined in two different ways to two groups of four elements. In the "neighbor" mode, adjacent elements have been combined to a single transmit element. In the "interleave" mode, every second element was combined to a single transmit element.

Results: The normalized root mean square error (NRMSE) is shown in Fig. 1 for the local excitation and in Fig. 2 for RF shimming. NRMSE increases with increasing reduction factor and with decreasing number of transmit elements. NRMSE is larger for local excitation than for RF shimming. The experimental results agree well with the expected values obtained by simulations. The accuracy was fairly independent of the used sensitivity tested for the example N=2. Only the "interleave" mode deteriorates the results significantly. A large angular distance is beneficial only for high reduction factors.

Discussion/Conclusion: Parallel transmission was tested with a large variety of transmit elements and reduction factors. Simulations as well as experiments confirmed the feasibility for both underdetermined and overdetermined cases. The excitation accuracy is in an acceptable range for both types of experiments performed in this study, local excitation and RF shimming.

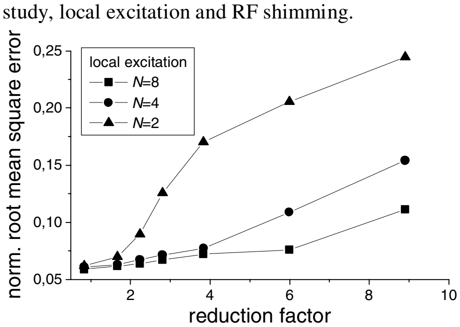

Fig. 1: Normalized root mean square error (NRMSE) for local excitation. NRMSE increases with increasing reduction factor and with decreasing number of transmit elements.

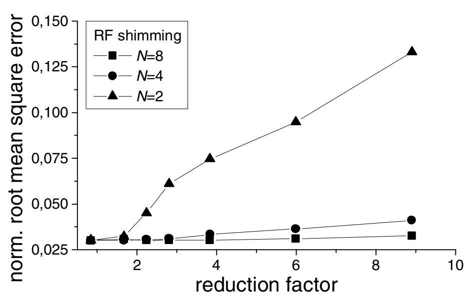

Fig. 2: Normalized root mean square (NRMSE) error for RF shimming. NRMSE increases with increasing reduction factor and with decreasing number of transmit elements. NRMSE is larger for local excitation (Fig. 1) than for RF shimming.

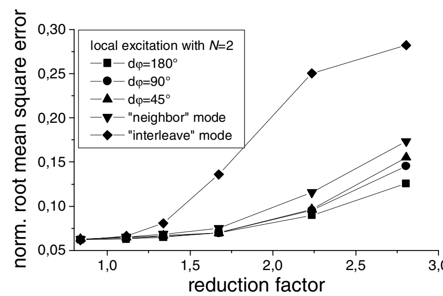

Fig. 3: Normalized root mean square error (NRMSE) for local excitation for different coil sensitivities (N=2). NRMSE is fairly independent of the used sensitivity. Only the "interleave" mode deteriorates the results significantly. A large angular distance is beneficial only for high reduction factors.

References: [1] Katscher U, Börnert P, Leussler C, van den Brink J, Transmit SENSE, *Magn, Reson, Med,* 2003; **49**: 144-150, [2] Zhu Y, Parallel excitation with an array of transmit coils, *Magn, Reson, Med,* 2004; **51**: 775-784, [3] Ullmann P, Junge S, Wick M, Seifert F, Ruhm W, Hennig J, Experimental analysis of parallel excitation using dedicated coil setups and simultaneous RF transmission on multiple channels, *Magn, Reson, Med,* 2005; **54**: 994-1001, [4] Pruessmann KP, Weiger M, Scheidegger MB, Boesiger P, SENSE: sensitivity encoding for fast MRI, *Magn, Reson, Med,* 1999; **42**: 952-962, [5] Katscher U, Manke D, Underdetermined SENSE using a-priori knowledge, *Proc, Int, Soc, Magn, Reson, Med,* 2002; **10**: 2396