Experimental Verification of Transmit SENSE with Simultaneous RF-Transmission on Multiple Channels

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Introduction: Parallel RF-transmission has recently been proposed by Katscher et al. [1] and Zhu [2] as a method that allows to reduce the k-space trajectories used in multidimensional spatially-selective excitation which results in shorter RF-pulse durations or increased spatial resolution. This is achieved by transmitting with a coil array in which every element is driven with an individual RF-waveform. By analogy to parallel acquisition the non-uniform transmit sensitivities of the array elements provide an additional encoding effect which compensates for a certain degree of undersampling in k-space. Up to now the practical feasibility of Transmit SENSE has only been shown partially, since all previous studies were limited by the lack of suitable hardware to perform real simultaneous transmission with individual waveforms on multiple channels. For this reason it has only been shown that the successive transmission with different coils on a single channel and the subsequent numerical combination of the excited patterns approximately leads to the excitation pattern predicted by theory for a joint transmission experiment. With the present study these hardware limitations have been overcome and the feasibility of Transmit SENSE is demonstrated in experiments with simultaneous transmission on up to three channels.

Theory: When using an array of transmit coils for spatially-selective excitation the generated transverse magnetization pattern $M(\mathbf{x})$ can be expressed as a linear, sensitivity-weighted combination of virtual single-element patterns $M_n(\mathbf{x})$:

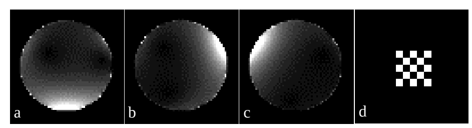
$$M(\mathbf{x}) = \sum_n S_n(\mathbf{x}) M_n(\mathbf{x}), \quad \text{where} \quad M_n(\mathbf{x}) = i\gamma M_0 \int_0^T B_{1,n}(t) e^{-i\mathbf{x}\cdot\mathbf{k}(t)} dt \qquad (1)$$

(S_n is the sensitivity of the n-th array-element in which the RF-waveform $B_{1,n}$ is played; $\mathbf{k}(t)$ is the (reduced) k-space trajectory traversed during RF-transmission).
Several methods have been proposed to determine the RF-waveforms $B_{1,n}$ necessary to excite a given pattern $M(\mathbf{x})$ ([1],[2],[3]). In this study the approach proposed in [3] has been used which is the direct temporal and spatial discretization of the equations (1) that leads to the following linear system (u and v are the spatial and temporal indices respectively):

$$\mathbf{m} = \mathbf{Ab}, \quad \text{where} \quad A_{u,(n,v)} = i\gamma M_0 S_n(\mathbf{x}_u) B_{1,n}(t_v) e^{-i\mathbf{x}_u\cdot\mathbf{k}(t_v)} \Delta t \qquad (2)$$

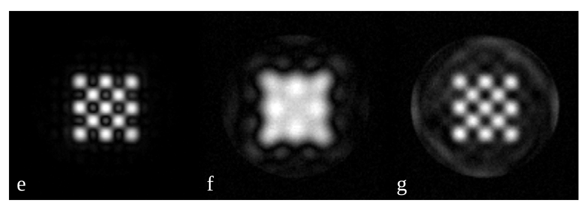
For a given magnetization vector $\mathbf{m}$ the waveforms $\mathbf{b}$ can be calculated by formulating the linear system (2) as a minimization problem and by solving it using a suitable direct or iterative method in combination with a regularization technique, if necessary.

Materials and Methods: A 4.7 T, 40 cm bore, *BioSpec*® system (Bruker BioSpin MRI GmbH, Ettlingen, Germany) equipped with four independent transmit channels was used in combination with a novel coil setup specially designed for multiple channel transmit applications. This coil configuration consists of a three element current-sheet-antenna (CSA)-array [4] integrated into an actively decoupled birdcage-type resonator. This experimental setup permits simultaneous transmission of independent waveforms on three channels using the CSA-elements with spatially varying transmit profiles. Alternatively the resonator can be used for single-channel transmission with a homogeneous transmit profile. As sample a homogeneous, spherical water-phantom, doped with copper sulfate and sodium chloride, was used.
All experiments in this study were performed using a modified spin-echo sequence with a 2D spatially selective excitation module and a slice selective refocusing module in the orthogonal direction. The excitation module consists of a constant angular velocity spiral k-space trajectory, designed for a maximum gradient slew rate of 274 T/m/s and a peak gradient strength of 98.6 mT/m, and simultaneous RF transmission either with the resonator or with up to three array elements in parallel.
The transmit sensitivity profiles required for RF-pulse calculation were determined by acquiring spin-echo images (64x64 matrix) with non-selective excitation. The transmission was successively done with the resonator and each array element, while the reception was always done with the resonator. Division of the obtained element images by the resonator image yielded raw sensitivity maps which where refined by thresholding and local polynomial fitting as described in [5]. The maps obtained in this way (figures (a)-(c)) represent the transmit sensitivities of the array elements relative to the resonator transmit profile. For a sufficiently homogeneous resonator profile it is adequate to use such relative maps for calculating the RF-pulses, which was the case in this study.

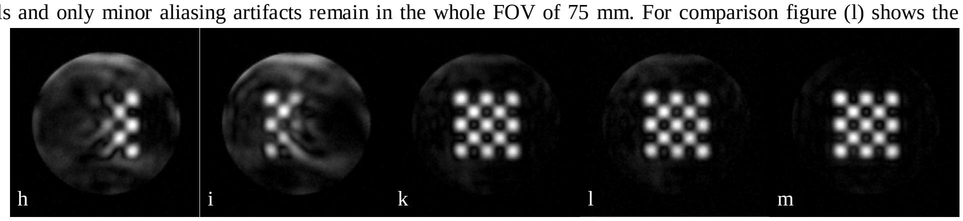


The calculation of the RF pulses was done in MATLAB (The MathWorks Inc., Natick, MA, USA) using the least squares approach described above together with a direct Tikhonov regularization technique [6]. As target structure for excitation the chequerboard pattern displayed in figure (d) was used in all experiments. All images were acquired with the modified spin-echo sequence (TE=13.6 ms, TR=1500 ms) and have a FOV of 75x75 mm and a 128x128 image matrix. The refocusing pulse was adjusted to select a slice of 5 mm thickness.

Results: Figure (e) shows the chequerboard pattern as generated by excitation with a standard one-channel 2D RF-pulse applied by the resonator in combination with a 16-revolutions spiral k-space trajectory (duration 13.6 ms) determining a field of excitation (FOX) of 75 mm (this corresponds to a 32x32 resolution in the FOX). For pulse calculations the chequerboard (as well as the sensitivities for the following Transmit SENSE experiments) had been given with the double resolution of 64x64 to increase the quality of the calculated shapes. In figures (f) and (g) the pattern is shown as excited by the resonator with a spiral of only 8 revolutions. In figure (f) the FOX is maintained (i. e. the resolution is divided by 2), whereas in figure (g) the resolution is kept constant and the FOX is reduced accordingly which results in strong radial undersampling artifacts.



In figures (h)-(k) the images generated in a first Transmit SENSE experiment with only two of the array elements (no. 2 and 3) are displayed. The k-space trajectory features 8 revolutions and the FOX is reduced to 37.5 mm (i. e. a radial reduction factor of 2 that decreases the pulse duration to 6.8 ms). Figures (h) and (i) show the patterns generated by element 2 and 3 respectively when operating them separately with the calculated Transmit SENSE waveforms. The pattern shown in figure (k) is achieved by simultaneous transmission on both channels and only minor aliasing artifacts remain in the whole FOV of 75 mm. For comparison figure (l) shows the numerical combination of the single element images: there is almost no visual difference to the real Transmit SENSE experiment. The residual artifacts of the two-element experiment can once again be considerably reduced, as shown in figure (m), when increasing the number of transmit channels to 3 while maintaining the FOX and the number of revolutions of the k-space trajectory.



Conclusion: This study presents a first implementation of Transmit SENSE with real simultaneous transmission of different RF-waveforms on multiple channels. The Transmit SENSE images with two elements and a reduction factor of 2 show only minor artifacts which are also partially due to the fact that the array geometry is optimized for three-channel transmit. In this latter case almost no artifacts remain and the spatial definition of the excitation pattern is even better than the one achieved with the resonator in single-channel mode and with full sampling of the trajectory due to the considerable shortening of the spatially-selective excitation pulses.

References: [1] U. Katscher et al., Magn. Reson. Med. 2003, 49:144-150; [2] Y. Zhu, Magn. Reson. Med. 2004, 51:775-764; [3] W. Grissom et al., Proc. 2nd Int. Workshop on Parallel Imaging, Zürich, 2004, p. 95; [4] S. Junge et al., Proc. ISMRM 2004, p. 41; [5] K. Pruessmann et al., Magn. Reson. Med. 1999; 42:952-962; [6] P. C. Hansen, Numer. Algorithms 1994, 6:1-35