SVD based calibration of transmit arrays

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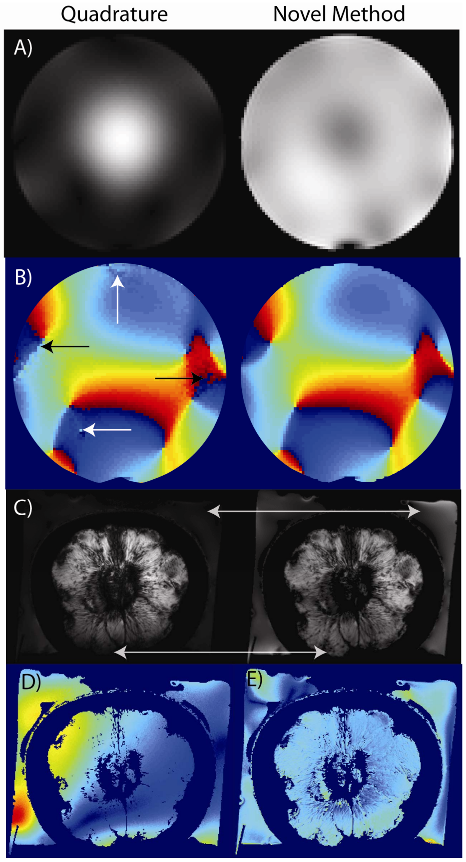

Figure 1: *Comparison between quadrature and SNR optimal combination: Magnitude image (A), resulting relative phase maps between two transmit channels (B), novel method used to obtain a more uniform image than with a single RF shim (C), single channel sensitivity map retrieved from 8 acquisition transmitting with alternating elements of the array in the presents of nonlinear saturation effects (D) which are visible in the transmit profiles (E).*

Introduction: In order to optimally combine signals received from an array coil, the sensitivities of each element have to be known. Acquiring these receive sensitivities is especially challenging at ultra high field conditions using transmit-receive arrays (TRA), since signal voids induced by destructive interferences of the transmit B_1 fields cause strong local noise amplification in the obtained sensitivity maps which propagates into the reconstructed images used e.g. as input for subsequent B_1^+ calculations, design of tailored RF pulses [1] or parallel imaging modalities. Magnitude based coil combination methods cannot be used in this context because the phase relation between the transmit channels have to be preserved by the reconstruction. When acquiring the transmit calibration data, this problem ends therefore in a tricky predicament: Signal voids in the transmit field corrupt the retrieved receive sensitivity profiles while the strong noise amplification arising thereof hampers the acquisition of the transmit sensitivities, which would be needed to shim the transmit field in order to get a reliable receive signal combination. In this work we describe a reconstruction, that finds concomitantly the optimum transmit and receive coil combinations from data typically retrieved in a transmit array calibration process and solves the before mentioned entangled problem in a single step. Furthermore we show that this approach can be used in order to calculate signal optimal global RF shim combinations for subsequent experiments.

Method: The signal retrieved from a TRA in a voxel ρ when sending with a coil combination vector **t** and combining the received signal linearly with weighting factors **w** is given in a linear small flip angle regime by:

$$s^{\rho}(\mathbf{w},\mathbf{t}) \propto \sum_{cc'} \mathbf{w}_{c'} B_{1,c'}^{-}(\vec{r}_{\rho}) \cdot B_{1,c}^{+}(\vec{r}_{\rho}) \mathbf{t}_{c} = \mathbf{w}^{T}\mathbf{S}^{\rho}\mathbf{t} \text{ with } \left(\mathbf{S}^{\rho}\right)_{c'c} := B_{1,c'}^{-}(\vec{r}_{\rho}) \cdot B_{1,c}^{+}(\vec{r}_{\rho})$$

which is a bilinear form with respect to the coil combination vectors (**w**,**t**) (T denotes the transpose). The goal is now to find one optimal receive coil combination simultaneously for all possible transmit combinations ensuring that the relative phase and amplitude relations between the transmit sensitivities are maintained. For this, the matrices $\mathbf{S}^{\rho}$ are measured by recording the signal received from each coil when sequentially exciting the TRA with different elements. A subsequent singular value decomposition of the matrix $\mathbf{S}^{\rho}$ in each voxel gives the combinations $\mathbf{w}_{opt}$ and $\mathbf{t}_{opt}$ yielding maximum SNR as the singular vectors corresponding to the maximum singular value σ_{11}, which is the maximum signal by itself. The calibration and reconstruction procedure works in the presence of noise correlation among receive channels and using generic transmit combinations for interferometric transmitter calibration [3,4] by first pre-whitening the signals from the receive-channels, second calculating the singular value decomposition of the resulting signal matrices $\mathbf{S}^{\rho}$ at each voxel, and third calculating the transmit field of each channel as in [3,4] using the calculated optimal pixelwise receive channel combination.

The global RF shims yielding the most signal power *P* over all pixels of an ROI can then be found by using the knowledge about the optimum local transmit combinations:

$$P = \sum_{\rho} \left(\mathbf{w}^{T}\mathbf{S}^{\rho}\mathbf{t}\right)\left(\mathbf{w}^{T}\mathbf{S}^{\rho}\mathbf{t}\right)^{*} = \mathbf{t}^{H}\boldsymbol{\Omega}\mathbf{t} \text{ with } \boldsymbol{\Omega} = \sum_{\rho\in ROI} \left|\sigma_{11}^{\rho}\right|^{2} \mathbf{t}_{opt}^{\rho} \otimes \mathbf{t}_{opt}^{\rho *}$$

using the Kronecker product of the optimum transmit combinations at each position ρ. The eigenvectors of **Ω** represent now the global RF shims with maximum signal yield which is given by its corresponding maximum eigenvalue. The signal strength in each pixel given by σ_{11} can be set to 1 weighting each pixel equally (normalized reconstruction). For single voxel applications, the measurement of $\mathbf{S}^{\rho}$ as shown here can already as such be used in order to set the signal optimal transmit and receive coil combinations.

Experiments & Results: An 8 channel array has been used loaded by a 15cm saline water sphere and a 13cm pomelo submerged in a water tank. Fig.1A shows a comparison between quadrature coil combination and the novel method in order to retrieve a reference image, retrieving the relative phase between two transmit channels (B) and in in-vivo like conditions reconstructing an image from 8 different RF shims (C). Remarkably, the algorithm yields the relative receive coil sensitivities even in the presents of nonlinear saturation effects during transmission and combines the information collected during all calibration measurements performed (Fig.1D&E) that fits the linear behavior of the receive signal combination. Therefore the receive sensitivity map stays uncorrupted even in the presents of strong nonlinear saturation effects.

Fig.2 shows the resulting global RF shims in descending order of efficiency. The plots below show the SNR efficiency of each mode and also the non-uniformity (ratio of standard deviation of the signal intensity and its mean) present in images reconstructed using only the first n modes.

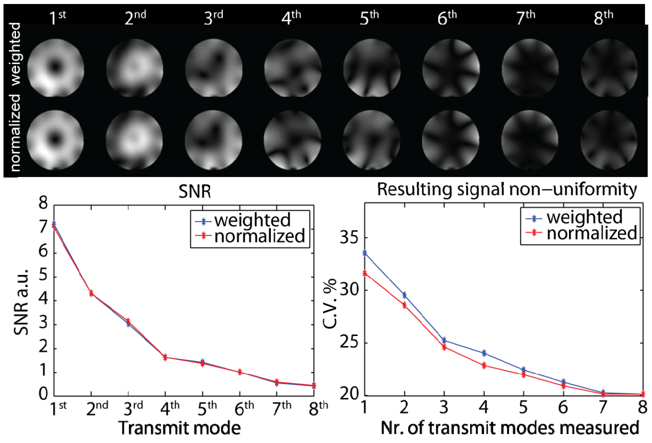

Figure 2: *Intensity patterns (top images, SNR efficiency of derived global RF shims (left plot), non-uniformity of reconstruction including reduced numbers of excitation settings (right plot).*

Conclusion: The presented reconstruction is shown to yield a more uniform reference image with higher SNR (Fig. 1.A) . It results in less noise corruption in TRA calibration data (see arrows in Fig.1B) that is problematic in calculation of RF shims and transmit SENSE pulses. Furthermore the reconstruction is able to combine acquisitions performed with different RF shims to provide high SNR over the entire FOV which drops the requirement of a single reference image with a uniform excitation for the calculation of the receive coil sensitivities (see Fig.1C-D). Additionally the reconstruction is capable to find the transmit modes yielding highest SNR over an extended ROI such that in a subsequent acquisition the number of excitations needed for a good reconstruction can be shorted (Fig.2B&C). Surprisingly the normalized method yields in this case similar signal efficiency but achieves a high uniformity with the same number of measured modes.

References: [1] Katscher MRM 2003; [3] Nehrke ISMRM 2008; [4] Brunner MRM 2009