RF Encoding via Non-linear, Iteratively determined Encoding Functions

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Introduction: Spatial signal encoding in MRI is usually performed via B_0-gradients. An alternative method is the use of B_1-gradients for RF encoding, which was already suggested in the early days of MR [1-3]. RF encoding offers the possibility to omit all B_0-gradients, allowing for MR scanning almost free of acoustic noise. This advantage might be compromised by long scan and reconstruction times, reduced image contrast, and/or enhanced SAR. This study investigates RF encoding using non-linear encoding functions using an eight-channel whole-body transmit system [4] for low-resolution imaging of phantoms. The encoding functions are determined iteratively by a randomized superposition of the spatial sensitivity distributions of the transmit array elements. Furthermore, the possibility of pure RF based phase encoding is investigated, which means to keep B_1 amplitudes for the individual encodings locally constant (within certain limits) to allow future steady state-like applications. Additionally, RF encoding was combined with a 1D Fourier encoding, using a frequency encoding readout, as an additional alternative for sequence acceleration.

Theory: In RF encoding, the encoding functions E_i are given by a superposition of the (previously determined) spatial sensitivity distributions T_n of the N transmit coils, multiplied with complex weighting coefficients W_{in} (Eq. (1)).The encoding functions are summarized to a matrix $\underline{\underline{E}}$. Its complex elements E_{ij} denote the value of the encoding function i at the spatial position j. Reconstruction of the image $\underline{M}_o$ is performed via (regularized) pseudo-inversion of this matrix (denoted by +) [5] with $\underline{S}$ the measured data summarized to a vector (Eq. (2)). Typically, RF encoding is performed via linear encoding functions, i.e., constant B_1 gradients [1-3,6-7]. This method has several drawbacks: (1) the optimum set of B_1 gradients has to be determined, (2) the superposition of the Tx sensitivities of the involved RF coils has to be fitted to the desired encoding functions, (3) this fit never yields perfectly linear distributions, (4) even in the case of a perfect fit, the obtained encoding functions are usually below the real maximum encoding potential of the RF system. To overcome these drawbacks, the following iterative scheme is proposed (Fig. 1). (a) A set of random amplitudes and phases for the Tx sensitivities is chosen, and the resulting encoding function is calculated. (b) It is checked, if the resulting encoding function fulfils the given boundary conditions, e.g., the maximum flip angle should be below a SAR-related limit, and/or the homogeneity of the encoding functions is high enough to enable steady state sequences. (c) It is checked, if the encoding function improves the encoding potential of the set of encoding functions determined previously. This can be done, e.g., by a Singular Value Decomposition of the encoding matrix [5], or a numerical solution of forward and inverse problem using a test image. (d) The set of encoding functions is complete if no new encoding function improving the existing set can be found, e.g., the number of tries to find an additional encoding function exceeds a predefined limit. The described procedure automatically determines the set of encoding functions with the highest encoding potential for a given set of Tx sensitivities. The resulting functions are usually non-linear. However, the described procedure guarantees that the system is able to transmit the desired encoding functions.

$$E_i(\vec{r}) = \sum_{n \le N} W_{in} T_n(\vec{r}) \qquad (1)$$

$$\underline{M}_o = \underline{\underline{E}}^{+} \underline{S} \qquad (2)$$

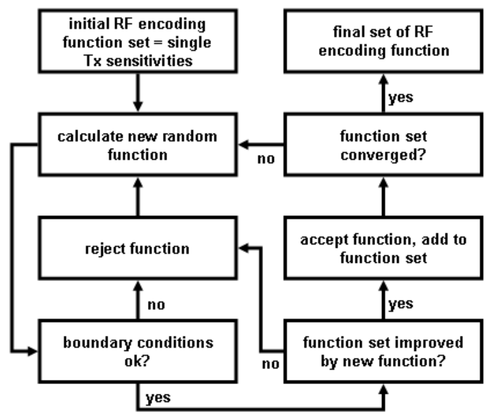
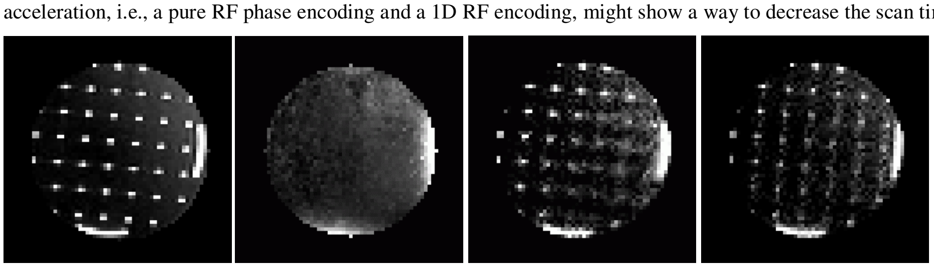


Fig: 1. Sketch of iterative determination of optimum set of non-linear RF encoding functions. Start is in the upper left box.

Methods: Tx sensitivities were determined on a 3T Philips Achieva (Philips Medical Systems, Best, The Netherlands) extended with eight independent transmit channels [4]. The Tx/Rx body coil consists of eight cylindrically arranged elements [8]. The feasibility of the above-described iterative procedure has been tested to find the optimum set of non-linear encoding functions including a restriction to maintain a certain spatial homogeneity level for the B_1 amplitude. This is considered as a step towards RF encoded steady state sequences. Additionally, RF encoding was combined with a standard B_0 frequency encoding. Thus, only one spatial dimension (corresponding to the standard "phase encoding direction") was B_1 encoded, which represents a compromise between RF encoding and acquisition speed.

Results / Discussion: Figure 2 compares images obtained using conventional B_0 Fourier encoding functions (Fig. 2(a)), linear B_1 encoding functions (Fig. 2(b)), iteratively determined, non-linear B_1 encoding functions (Fig. 2(c)), and iteratively determined, non-linear B_1 encoding functions combined with conventional B_0 Fourier encoding in the left-right direction. The linear B_1 encoding functions are not able to reconstruct the high-resolution structures of the phantom. The non-linear B_1 encoding functions yield a significant improvement of the reconstruction of the high-resolution structures. As expected, the introduction of B_0 Fourier encoding in one direction further improves the image quality. Table 1 shows the consequence on the encoding performance and the time to find appropriate encoding functions if the amplitude variation for B_1 encoding is restricted to a certain percentage. Basically, this approach forces towards pure phase encoding. This restriction influences the quality of the RF encoded image only marginally. However, the CPU time required to find the appropriate encoding functions increase considerably. This could lead to the effect, that less “useful” encoding functions formed by the superposed individual transmit sensitivities could be selected exhibiting a lower or insufficient encoding potential.

Conclusion: RF encoding benefits substantially from the introduction of non-linear, iteratively determined encoding functions. The two options tested for sequence acceleration, i.e., a pure RF phase encoding and a 1D RF encoding, might show a way to decrease the scan times of RF encoding techniques to an acceptable level.



a b c d

Fig. 2: Phantom reconstruction results. (a) Phantom image obtained with standard B_0 Fourier encoding (grid 64×64). (b) Reconstruction result using linear RF encoding functions (correlation with Fig 2(a) = 55.6%). (c) Reconstruction result using iteratively determined, non-linear RF encoding functions (correlation with Fig 2(a) = 82.1%). (d) Reconstruction result using iteratively determined, non-linear RF encoding functions and a Fourier encoding in left-right direction (correlation with Fig 2(a) = 83.9%).

maximum NRMSE of encoding function	normalized correlation with Fourier encoded image	normalized CPU time for iteration
35%	99.3%	306%
25%	97.7%	494%
15%	97.4%	1882%

Table 1: Influence of constraining the B_1 amplitude variations of the B_1 encoding function to a given normalized root mean square error (NRMSE). This limitation does not significantly influence the quality of the RF encoded image (2. column). However, the CPU time required to find the appropriate encoding functions increases (3. column). The 2. and 3. columns are normalized to the case without NRMSE limitation.

References: [1] D.I. Hoult, JMR 33 (1979) 183 [2] A.A. Maudsley, MRM 3 (1986) 768 [3] G.S. Karczmar et al., MRM 7 (1988) 111 [4] I. Graesslin et al., ISMRM 14 (2006) 129 [5] A. Tarantola, “Inverse Problem Theory”, Elsevier Amsterdam, 1987 [6] S.B. King et al., ISMRM 14 (2006) 2628 [7] U. Katscher et al., ISMRM 15 (2007) 679 [8] P. Vernickel et al., MRM 58 (2007) 381