Original Article

Precompensation for mutual coupling between array elements in parallel excitation

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Abstract: Parallel transmission or excitation has been suggested to perform multi-dimensional spatial selective excitation to shorten the pulse width using a coil array and the sensitivity information. The mutual coupling between array elements has been a critical technical issue in RF array designs, which can cause artifacts on the excitation profile, leading to degraded excitation performance and image quality. In this work, a precompensation method is proposed to address the mutual coupling effect in parallel transmission by introducing the mutual coupling coefficient matrix into the RF pulses design procedure of the parallel transmission. 90° RF pulses have been designed using both the original transmit SENSE method and the proposed precompensation method for RF arrays with non-negligible mutual coupling, and their excitation profiles are generated by simulating the Bloch equation. The results show that the mutual coupling effect can be effectively compensated by using the proposed method, yielding enhanced tolerance to insufficient mutual decoupling of RF arrays in parallel excitation, ultimately, providing improved performance and accuracy of parallel excitation.

Key Words: Parallel transmission; mutual coupling; transmit SENSE; transceiver array; Bloch equation

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Introduction

Multidimensional spatially selective RF pulses have been used in MRI to limit the electromagnetic signal emitted from the imaging object within arbitrarily shaped and spatially restricted areas (1-6). This approach requires homogeneous radiofrequency (RF) field to ensure the accuracy of the excitation profile, especially for spin echo imaging. This requirement has impeded the further development and application of multidimensional spatial RF pulses to ultrahigh field MRI (7 Tesla and beyond) (7-13) in which homogeneous RF field is difficult to be achieved (8,14-18) due to the high frequency wave effect in the conductive and high dielectric imaging object such as human body (19). To achieve homogeneous RF field distribution and shorten the pulse width, parallel transmission (20-28) is suggested to perform spatial selective excitation using a coil array and the sensitivity information of each element. The amplitude and phase of each element are independently controlled to manipulate the RF field distribution within imaging object to ultimately achieve B1 homogeneity (29,30). The parallel transmission can be used not only in small-tip-angle excitation, but also in large-tip-angle excitation and refocusing pulses at ultrahigh fields (31-33). Although the average and local specific absorption ratio (SAR) increase with the acceleration factor in parallel transmission (34), the SAR can be optimized using different strategies such as variable sampling rate or optimized k-space trajectories (21,35-38), providing feasible ways to make tradeoffs between the acceleration factor and the power deposition.

The mutual coupling has been a critical problem in RF coil array design (39,40), especially at ultrahigh fields where the imaging sample mediates the mutual coupling among the array elements (9,11,12,29,41-43). Comparing with the situation in parallel reception, this decoupling problem becomes more critical in parallel transmission, deteriorating the excitation accuracy and degrading the image quality. Although a variety of decoupling schemes have been developed to address the issue (12,14,29,40,42-46), insufficient decoupling among array elements is still a major problem hindering the development and application of parallel transmission.

In this work, a precompensation method is proposed to address the mutual coupling effect in transmit SENSE by introducing the mutual coupling coefficient matrix into the RF pulses design procedure of the transmit SENSE. Studies show that by using this precompensation technique, the mutual coupling effect on the excitation pattern can be compensated by using the corrected RF pulses as long as the mutual coupling between array elements is not high enough to cause a clear split of the element resonance peak, or in a weakly coupling case. This precompensation technique provides a valuable approach to performance optimization of transmit SENSE or parallel excitation using multichannel RF transmit arrays with non-negligible mutual coupling between array elements.

Theory and methods

The transmit SENSE uses coil array to excite the spins to achieve the desired profile. For an R-element array, the desired excitation pattern can be described by the superposition of all the individual pulse profiles weighted by the corresponding sensitivity profiles, which is described as below:

$$P_{des}(\mathbf{x}) = \sum_{n=1}^{R} S_n(\mathbf{x}) P_n(\mathbf{x}) \qquad [1]$$

where P_{des}(x) is the desired pattern, $S_n(\mathbf{x})$ and $P_n(\mathbf{x})$ are the complex sensitivity profile and the pulse profile of the nth coil, respectively. The profile $P_n(\mathbf{x})$ of each coil can be expressed as:

$$P_n(\mathbf{x}) = i\gamma M_0 \int_0^T \frac{B_{1,n}(t)}{\gamma |G(t)|} S(\mathbf{k}(t)) e^{i\mathbf{x}\cdot\mathbf{k}(t)} dt \qquad [2]$$

where M_0 is the initial magnetization, $B_{1,n}(t)$ denotes the RF pulse of the nth element of the array. $G(t)$ and $S(\boldsymbol{k}(t))$ are the accompanying gradient and the spatial frequency sampling function respectively. $\boldsymbol{k}(t)$ is the *k*-space trajectory defined by the gradient function $G(t)$. By defining

$$A(t) = \frac{S(\mathbf{k}(t))}{\gamma |G(t)|} \qquad [3]$$

the Eq.[2] can be rewritten as

$$P_n(\mathbf{x}) = i\gamma M_0 \int_0^T B_{1,n}(t) A(t) e^{i\mathbf{x}\cdot\mathbf{k}(t)} dt \qquad [4]$$

Then, the mutual coupling between the array elements is introduced into the calculating procedure. Assuming the mutual coupling coefficient between the *m*th coil and the *n*th coil is $c_{m,n}$, the excitation pattern of the mth coil becomes:

$$P_m^*(\mathbf{x}) = i\gamma M_0 \int_0^T \sum_{n=1}^{R} c_{m,n} B_{1,n}(t) A(t) e^{i\mathbf{x}\cdot\mathbf{k}(t)} dt \qquad [5]$$

Thus, the desired excitation pattern $P_{des}(\mathbf{x})$ can be expressed as the superposition of all the individual patterns weighted by the sensitivity patterns:

$$P_{des}(\mathbf{x}) = i\gamma M_0 \sum_{m=1}^{R} S_m(\mathbf{x}) \int_0^T \sum_{n=1}^{R} c_{m,n} B_{1,n}(t) e^{i\mathbf{x}\cdot\mathbf{k}(t)} dt \qquad [6]$$

where S_m(x) is the sensitivity of the mth coil. Thus, from Eq.[4] and (6) the Eq.[1] can be rewritten as:

$$P_{des}(\mathbf{x}) = \sum_{n=1}^{R} P_n(\mathbf{x}) \sum_{m=1}^{R} c_{m,n} S_m(\mathbf{x}) \qquad [7]$$

or

$$P_{des}(\mathbf{x}) = \sum_{n=1}^{R} S_n^*(\mathbf{x}) P_n(\mathbf{x}) \qquad [8]$$

where S^*_n (x) is defined as

$$S_n^*(\mathbf{x}) = \sum_{m=1}^{R} c_{m,n} S_m(\mathbf{x}) \qquad [9]$$

Eq.[8] is similar to the central equation of transmit SENSE. The difference is the sensitivity pattern S^*_n(x) equals the sum of all the individual sensitivity patterns multiplied by the corresponding mutual coupling coefficient. This corresponds to the compensation for the mutual coupling effect in the excitation procedure. The following steps for designing the pulses are the same as that in transmit SENSE: the spatial coordinate x can be discretized to vectors first, and the $P_{des}(\mathbf{x})$, $P_n(\mathbf{x})$ and S^*_n(x) can be rewritten as vectors; then these three vectors can be transformed to *k*-space style by convolution and by choosing proper k-space trajectory and the full size variable $P_{full}(\mathbf{x})$ and S^*_{full}(x) can be obtained; finally, the individual excitation pattern $P_n(\mathbf{x})$ under the effect of mutual coupling can be calculated by solving the inverse problem and each individual RF pulse can be obtained by the *k*-space analysis method. The flowchart of the improved transmit SENSE with precompensation method is shown in *Figure 1*.

To investigate the feasibility and the effectiveness of the proposed method, a simple example of transmit SENSE is simulated by solving the Bloch equation. Excitation pulses were designed using transmit SENSE and the

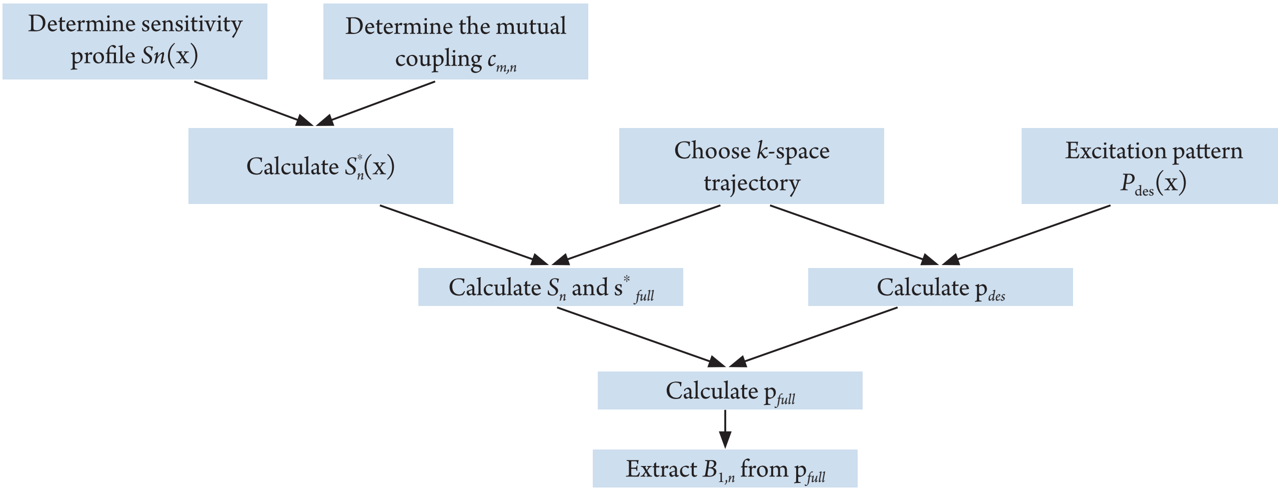

Figure 1 Flowchart of the RF pulse design procedure using the precompensation method in parallel excitation with multichannel transmit array

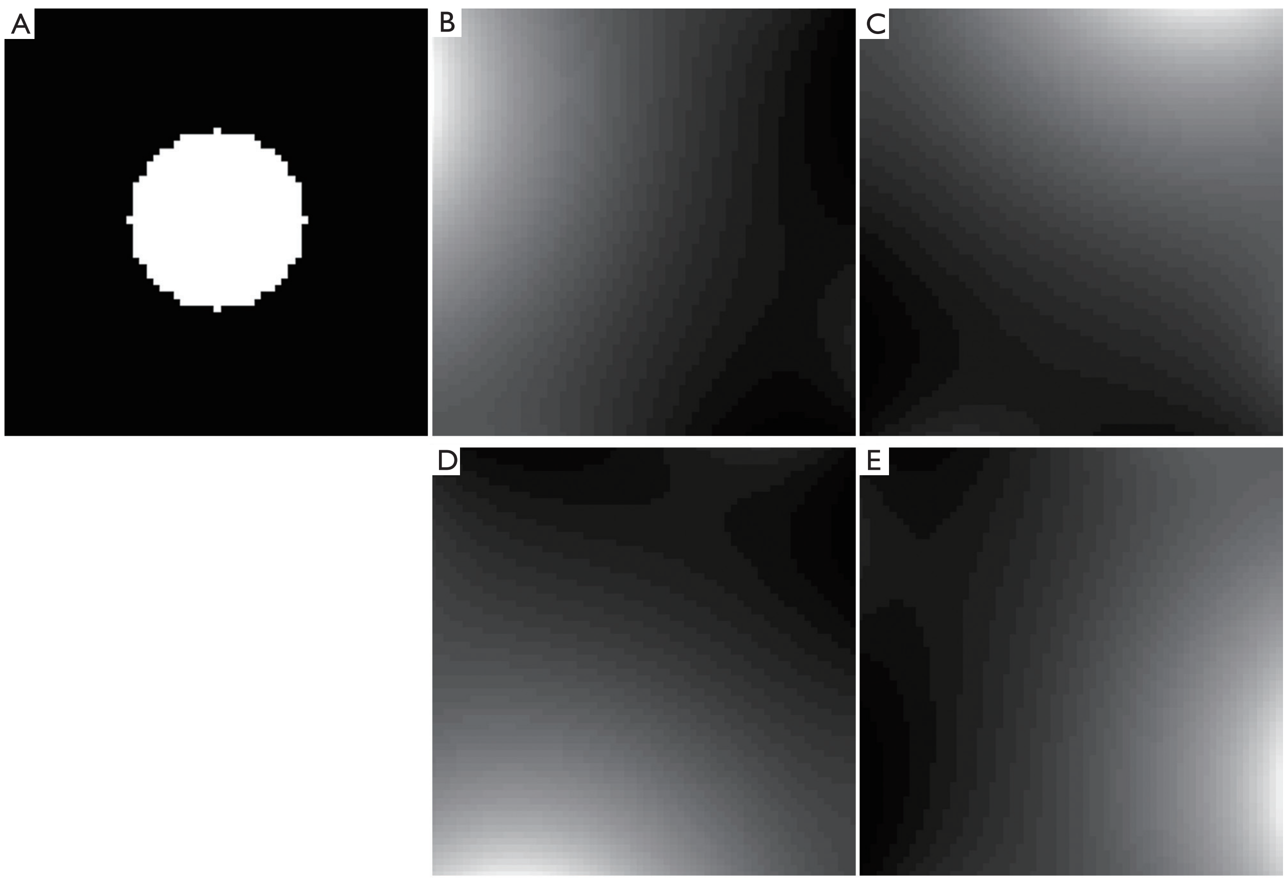

Figure 2 A. Desired excitation profile; B-E. intrinsic sensitivity pattern of each array element

precompensation method respectively for comparison. In both methods, the same spiral trajectory with 12 turns was used. The max value of k-space extension was 0.5 cycle/cm. The desired excitation pattern was a cylinder with 10 cm diameter, whose 2D profile is shown in *Figure 2A*. The desired pattern was excited using a 4-element array with

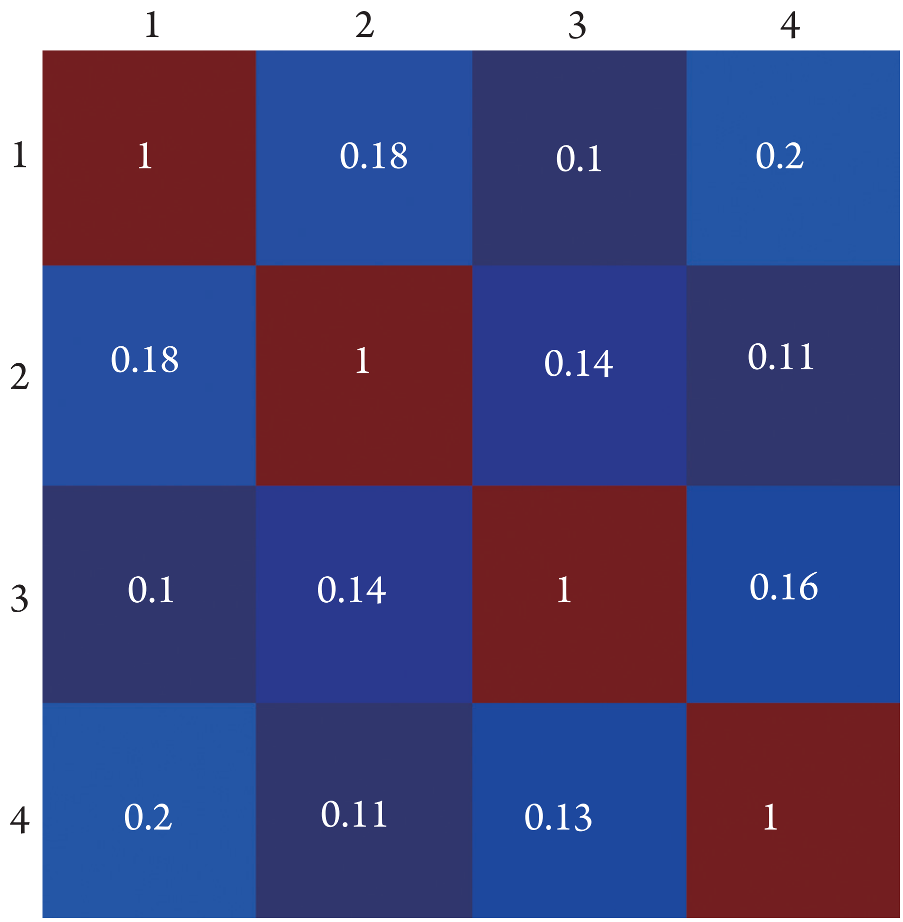

Figure 3 Mutual coupling coefficients between array elements

the reduction factor of 2. The sensitivity patterns of each element are shown in *Figure 2B-E*. The mutual coupling coefficient matrix between the elements is shown in *Figure 3*. The proposed precompensation method was applied to design the excitation pulses for implementing the transmit SENSE using the RF arrays with non-negligible mutual coupling between elements.

Results

The conventional transmit SENSE method was applied to design the excitation pulses for parallel excitation with the 4-element transmit array in which non-negligible mutual coupling between array elements exists. Based on these pulses, the excitation pattern of each array element was generated and plotted, as illustrated in *Figure 4A-D*. The resulting excitation patterns were also calculated. When the pulses were designed based on conventional transmit SENSE, the artifacts in the resulting excitation pattern is unable to be cancelled by each other. This leads to the deteriorated excitation pattern with the residual aliasing artifacts, as shown in *Figure 4E*. It is expected that the distortion of excitation pattern will become worse when the electromagnetic coupling between array elements increases.

With the use of the proposed precompensation method, the specific RF pulses were designed by taking the mutual coupling coefficients into calculation for each array element. By using these RF pulses, the mutual coupling between the elements can be compensated. The artifacts in the excitation pattern of each element (*Figure 4F-I*) can be potentially cancelled by each other through superposition, resulting in reduced artifacts in the resulting excitation pattern, as shown

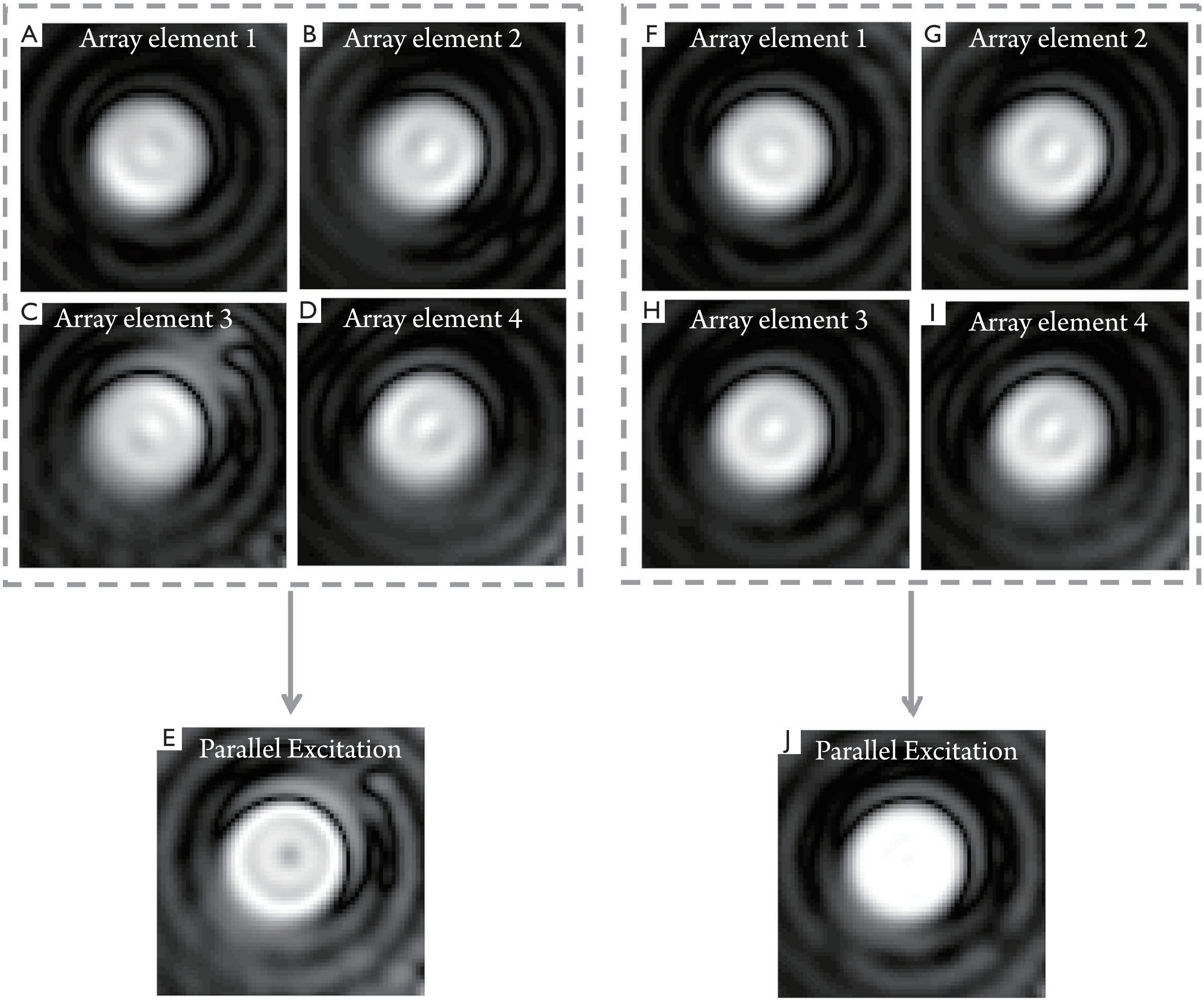

Figure 4 The excitation profiles of a 4-element coil array with non-negligible mutual coupling between array elements. A-D. individual excitation pattern of each element using conventional transmit SENSE; E. the resulting excitation pattern from 4 elements, showing that the aliasing in excitation profile of each element is unable to be cancelled, leading to considerable artifacts; F-I. individual excitation pattern of each element using the proposed precompensation method; J. the resulting excitation pattern, showing that the artifacts caused by the mutual coupling of array elements are significantly reduced due to the artifact cancellation of each element profile, yielding an improved excitation profile

in *Figure 4J*. The improved parallel excitation performance using the proposed method over the conventional transmit SENSE indicates that the mutual coupling effect of the imperfectly designed transmit array can be efficiently corrected by the precompensation technique.

Discussion

In this work, the mutual coupling coefficients between array elements have been taken into the pulses design procedure of transmit SENSE. The sensitivity patterns of all the elements are multiplied by the corresponding mutual coupling coefficient and then added together to form new sensitivity patterns. The central equation of the superposition of all the individual patterns multiplied by the sensitivity pattern is modified although the pulse design procedure is the same as that in the conventional transmit SENSE. Thus, each individual pattern can be obtained by solving the same inverse problem in transmit SENSE, and each individual RF pulse can be calculated according to the k-space analysis method.

The results of the transmit SENSE studies with a 4-element coil array by simulating the Bloch equation have demonstrated the proposed precompensation method is feasible to diminish the artifacts caused by the mutual coupling between the elements, making the parallel excitation method more tolerant to mutual coupling in RF transmit arrays, ultimately improving the quality of excitation. This is very helpful for parallel excitation because current decouple methods are unable to thoroughly eliminate the mutual coupling in RF transmit arrays. Combining this precompensation method and conventional decouple schemes together for multi-channel excitation has potential to decrease excitation artifacts and improve the excitation profile accuracy. Although this method is validated by using transmit SENSE in this work, it can also be applied to other parallel excitation methods such as the spatial domain method.

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