Transmit Array Design

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RF transmit coils for use in MRI have traditionally been designed to maximize B1 uniformity and (if doubling as receive coils) signal-to-noise ratio (SNR), while minimizing RF power [1,2]. Recently, a new class of RF transmit pulses has been created based on parallel excitation across multiple coil elements, as first suggested independently by Zhu [3,4] and Katscher [5,6]. These provide the potential to increase imaging speed by improving the practicality of inner-volume imaging, and perhaps more importantly, to ameliorate problems most acutely felt at high fields, including high RF power and B1 nonuniformity [4,7]. These applications are, for the most part, based on the use of multi-dimensional selective excitation pulses [8-13], which have been used for inner-volume imaging [13], spectroscopic localization [14], imaging of motion and blood flow [15], and bent-slice imaging [16,17], among other applications. The use of multiple independent transmit channels enables the creation of 2D and 3D excitation pulses of much shorter duration than would otherwise be possible.

An important aspect of parallel transmit methods is the development of transmit arrays that optimize the implementation of parallel excitation. There are a number of design considerations that come into play in the development of parallel transmit coils, including limiting coupling among various coil elements, maintaining a reasonable dynamic range in B1 intensity over the volume of interest, and creating coil geometries that aid RF pulse performance:

Coil Coupling

Limiting the coupling among the various transmit coils is important for maintaining the integrity of the transmit field from each coil. Parallel receive coils are usually decoupled by the use of low-input-impedance preamplifiers, which limit the currents flowing in each coil and thus reduce coupling. There is no analog to this method in parallel transmit, because the nature of RF transmission demands sufficient currents to create B1 transmit fields that tip the spins by the desired amount. Thus, other methods are required, including some already in use for parallel receive.

One method involves overlapping nearest neighbor transmit coils by an amount that zeroes their mutual inductance. An example of a head array that uses this technique is shown in Fig. 1. If a design with underlapped elements is called for, then a transformer can be inserted in series in each of the neighboring elements, where the transformer coils are wound in a direction that causes the linked flux to cancel that linked between the RF transmitter coils. An example of such an arrangement is shown in Fig. 2. This scheme can also be used to eliminate coupling between next-nearest neighbors, when nearest neighbors are optimally overlapped. Alternatively, capacitive decoupling networks can be placed between nearest-neighbor coils within the array [18,19].

An alternative to overlapping coils is to tilt them at such an angle that the net flux between nearest neighbors is zero [20]. An example of such a “Venetian-blind” array is shown in Fig. 3, where coils have been tilted in the left/right direction and overlapped in the superior/inferior direction. Figure 4 compares coupling curves as a function of coil spacing for flat and tilted arrays. The tilted arrays show reduced coupling over a much broader range of spacing, meaning that the entire array is effectively decoupled, not just nearest neighbors. This allows one to construct the array in modules, without the need for retuning when the modules are brought together.

Figure 1. Head RF transmit array with overlapped coil elements.

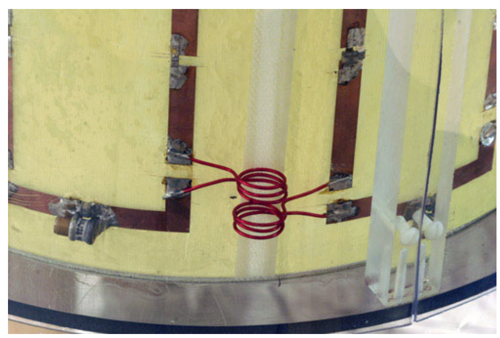

Figure 2. Transformer decoupling of RF transmit arrays

One can also reduce coupling in parallel transmit arrays through the use of microstrip arrays, which enjoy inherently low coupling between neighboring strips [21-24]. These are especially useful at high field strengths, where wavelengths become comparable to the coil dimensions. Here radiation losses grow to be significant, and strong sample/coil coupling mediates interactions among different coil elements. Microstrips address these issues by incorporating a ground plane into the resonant structure [23]. A related class of arrays uses a current-sheet antenna design to produce uniform B1 fields at high frequencies, while minimizing inter-coil coupling [25,26].

Finally, current-source RF amplifiers can be used to minimize inter-coil coupling in multi-element transmit arrays. These amplifiers produce a well-defined current in each coil element, even in the presence of coupled elements, by suppressing any induced currents in the element [27-29]. Experiments on an 8-element head coil driven by current-source amplifiers have demonstrated a suppression of induced currents by 15.5 dB relative to a comparable TEM element [28]. This method also reduces the effect of sample loading on coil tuning [29].

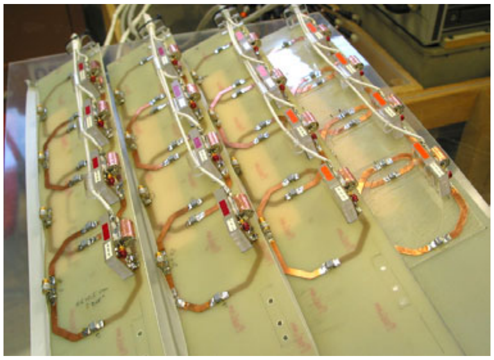

Figure 3. Venetian blind array exhibits low inter-element coupling.

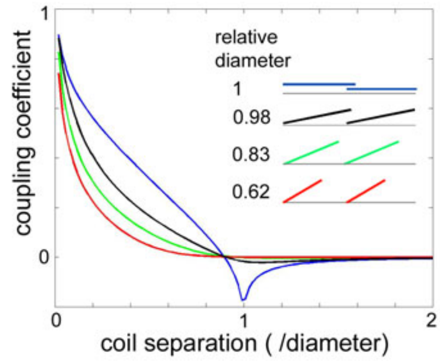

Figure 4. Coupling curves for flat (blue) and tilted arrays.

Dynamic Range

Another consideration in the design of parallel transmit arrays is the dynamic range of the B1 transmit field over the volume of interest. For arrays with relatively large dynamic range, calibration scans become more complicated and prolonged, especially when a reference acquisition using a coil with uniform B1 is not available. This is because the B1 mapping procedure must be stepped through a greater number of power levels to cover the whole dynamic range of the array [30].

Geometry Considerations

A final important design parameter for RF parallel transmit arrays is the influence of array geometry on SNR, quality of the selective excitation profile, and RF power deposition. In parallel transmit, there is no equivalent geometry-dependent noise-amplification factor [31], and thus the sensitivity of RF pulse performance to array geometry is reduced. This difference with conventional SENSE is due to the fact that the inverted sensitivity matrix is multiplied with a desired excitation pattern, which is noise free, whereas in the receive case, the inverted matrix is multiplied by acquired data containing noise.

This does not mean, however, that coil geometry is unimportant. In fact, there exists for the parallel transmit case an analog to the *g*-factor in SENSE imaging. Whereas the *g*-factor is a measure of noise amplification in

Figure 5. 8-element transmit head array, with underlapped elements.

the receive case, for transmit-SENSE it can be thought of as a metric for RF energy dissipation in the subject [32]. A study comparing RF power deposition in similar overlapped (Fig. 1) and underlapped (Fig. 5) parallel transmit head arrays shows that, in creating a uniform excitation profile, the power deposition is lower for the underlapped array [32], somewhat analogously to noise amplification in the receive case. For both arrays, however, the power deposition for accelerated (R=4) transmit was lower than for nonaccelerated transmit, a case highlighting the excitation profile-dependent aspect of parallel transmit.

In another study a simulation was performed in which a two-element transmit array (with the two coils 180° apart) was rotated relative to the excitation *k*-space trajectory, for Cartesian and spiral trajectories [33], and RF power was calculated. The power was found to be almost twice as high when the coils were aligned in the frequency direction as when they were along the phase-encode direction, for the Cartesian case, with a more modest sinusoidal variation in the spiral case. When one coil was left in place and the other coil rotated to 90°, the power increased by roughly a factor of 2 for both spiral and Cartesian trajectories. Here coil geometry had a strong influence on RF power.

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