Approaching the Ultimate SNR in Parallel MRI with Finite Coil Arrays

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INTRODUCTION:

In recent years the radio frequency (RF) electrodynamics (ED) of parallel imaging (PI) have been the subject of several theoretical studies. By calculating the maximally achievable, so-called ultimate SNR, fundamental limitations of PI have been identified and analyzed in detail (1,2). Most importantly it was found that (I) the amount of feasible reduction in PI is inherently limited and (II) increases with the onset of wave behavior at very high B_0 and in large objects (3).

In theory, the ultimate SNR could be reached with a "complete coil array", whose coil sensitivities span the entire solution space of the Maxwell equations. Yet it is unclear as yet whether this limit can be approached with real coil arrays with a finite number of elements.

In order to investigate this question, in the present work we numerically study the SNR performance of finite RF coil configurations and compare it quantitatively with the corresponding ultimate SNR.

THEORY:

As a model setup a source-free, dielectric, spherical object was assumed, surrounded by an array of circular coils. An approximately even distribution of N such coils across the sphere's entire surface was achieved by iterative, numerical optimization. A constant coil radius was then chosen such that the closest neighboring coils just touched. The advantages of this specific arrangement are: (I) it allows expressing each coil's full-wave RF ED fields semi-analytically (4) and (II) the choice of a spherical object permits direct SNR comparisons with the ultimate SNR (SNR_U) according to Ref. (1).

Based on the RF fields of the coil array, coil sensitivity matrices (S) and the array's noise covariance (Ψ) can be calculated, which then allows investigating the SNR performance of PI (Cartesian SENSE, (1,5)):

$$SNR^{PI} \propto B_0^2 \Big/ \sqrt{R\left[(S^H \Psi^{-1} S)^{-1}\right]_{0,0}}\,. \qquad [1]$$

METHODS:

In order to approximate the situation in the human head, the diameter of the spherical object was set to 0.2 m and its dielectric properties were assumed to match average in-vivo brain conditions (6). All evaluations were performed for a central, transverse imaging plane. The circular coils were placed on a shell of 0.22 m in diameter, such that each coil's symmetry axis intersected the center of the sphere.

Equation [1] was separately analyzed in terms of (I) the SNR obtained with full Fourier encoding (R≡1, SNR^{full}) and (II) the geometry factor (g), according to (5):

$$g = SNR^{full} / \left[SNR^{PI}\sqrt{R}\right] \qquad [2]$$

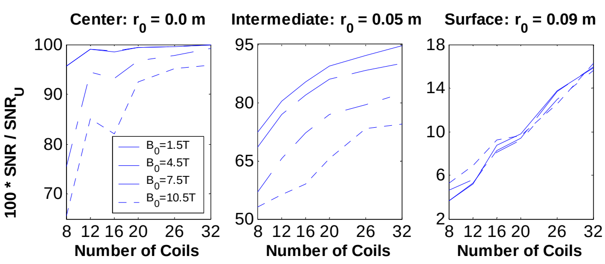

Fig. 1: SNR^{full} at three different radial positions in the sphere versus number of coils. SNR_U*=ultimate SNR.*

RESULTS & DISCUSSION:

Figure 1 shows the convergence of SNR^{full} towards its ultimate value as the number of coils increases. Four different field strengths B_0 = 1.5, 4.5, 7.5, 10.5 T and three different radial pixel positions r_0 = 0 m, 0.05 m, and 0.09 m are considered. Apparently, at low B_0 the ultimate SNR for the sphere's center can be readily approached with relatively few array elements. However, the convergence of the SNR is significantly delayed for more peripheral positions and high B_0. At the most superficial position, in particular, the SNR achieved with up to 32 coils falls far short of the ultimate value. In these situations more and smaller coils are required, either to focus sensitivity close to the surface, or to reduce destructive flux interference at high B_0.

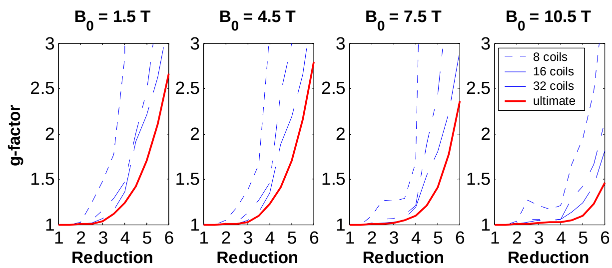

Fig. 2: g factor in the center of the sphere (r_0=0m) versus the reduction factor R for varying number of coils.

Figure 2 illustrates the convergence of g as a function of the 1D reduction factor R towards the ultimate g factor for r_0 = 0 m, again as a function of N. Several field strengths B_0 = 1.5, 4.5, 7.5 and 10.5 T and reduction factors between 1 and 6 are considered. Again, with increasing N the g factor converges towards its ultimate values. However, the convergence speed reduces with increasing R.

It is important to note that only sample noise was considered in the present study, neglecting noise from the coil conductor and electronics. These contributions can be mitigated by enhancing the coil technology, e.g. by cooling. Nevertheless, the significance of coil noise will generally increase with N, suggesting that in practice the SNR will reach a maximum and decrease beyond some critical N. This critical value will depend on the properties and size of the object, on B_0, as well as on technical RF parameters such as the specific resistance of the coil conductor and the noise figure of the preamplifier.

Note also that the density of the coil grid varies slightly with N. E.g., N = 12 permits highly efficient dodecahedral coil packing with 5 closest neighbors for each coil. Presumably this is one explanation for slight irregularities in the otherwise smooth convergence of the SNR and g in Figs. 1, 2.

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