Parallel Imaging Performance as a Function of Field Strength – An Experimental Investigation using Electrodynamic Scaling

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INTRODUCTION: With the simultaneous development of ultra-high field technology and parallel imaging (PI) methodology, it has been noted that their intrinsic benefits are complementary and the two methods tend to compensate for the drawbacks of the other: while PI offers enhanced encoding efficiency at the price of SNR, ultra-high field strength in turn provides enhanced basic SNR but is prone to B_0 inhomogeneity problems and SAR limitations. Therefore, the combination of PI and high field is expected to be particularly synergistic. Furthermore, recent theoretical studies have predicted that PI performance may improve substantially with B_0 field strength (1,2). The objective of this study was to experimentally investigate the B_0 dependence of PI performance and compare the results with theoretical predictions. Using the concept of electrodynamic scaling, field strengths in the range between 1.5T and 11.5T were mimicked using a single setup of scanner hardware, phantom geometry and coil configuration.

THEORY: For the parallel SENSE technique (3), SNR performance is quantified by the so-called geometry factor (g). The g factor is calculated from the coil array sensitivity profiles and the receiver noise correlation matrix, which closely correspond to the electromagnetic fields produced by the RF coils when operated with unit input currents. This suggests that instead of actually changing B_0, the field strength dependence of PI performance may equivalently be investigated by mimicking the effect of changes in B_0, and hence in the Larmor frequency, on the RF fields. This method, similar to concepts proposed in Ref. (4), will be referred to as *electrodynamic (ED) scaling*. The RF electromagnetic fields inside a source-free dielectric and conducting sample are governed by Maxwell's equations. Assuming homogeneous material properties, these equations can alternatively be stated in a dimensionless form as (5):

$$\left(\Delta+\kappa^2\right)\mathbf{H}\left(\mathbf{r}/L\right)=0,\quad \nabla.\mathbf{H}\left(\mathbf{r}/L\right)=0,\quad \mathbf{E}\left(\mathbf{r}/L\right)=\frac{1}{L(\sigma-i\omega_0\varepsilon)}\nabla\times\mathbf{H}\left(\mathbf{r}/L\right),\qquad \text{with: } \kappa=\sqrt{\mu\omega_0\left(\varepsilon\omega_0+i\sigma\right)}\,L \tag{1}$$

where **H** and **E** are, respectively, the RF magnetic and electric fields, **r**/L is a dimensionless spatial position vector, L is a characteristic length of the object (e.g its diameter), κ is the dimensionless wave number, ω_0 is the Larmor frequency, ε is the object's permittivity, σ its conductivity and μ its permeability. Analysis of these equations shows that a target and a model configuration, operated at different B_0, will generate the same electromagnetic fields $\mathbf{H}(\mathbf{r}/L)$ and $\mathbf{E}(\mathbf{r}/L)$, except for scaling, if both setups are geometrically similar, i.e. identical except for length scaling, and have identical dimensionless wave numbers κ.

METHODS: The concept of ED scaling was applied to investigate the field strength dependence of PI performance with an 8-element coil array and a spherical model phantom (diameter = 18 cm). The targeted object was assumed to be of the same size. The target material properties were set to those of average brain tissue. The target field strength $B_{0,T}$ was set to values between 1.5T and 11.5T, the model field strength was fixed at $B_{0,M}$=7T. In order for the dimensionless wave numbers of the model and target setups to be matched, the following requirements for the material properties ε_M and σ_M must be met:

$$\kappa_M \equiv \kappa_T \quad\Leftrightarrow\quad \varepsilon_M=\frac{B_{0,T}^2}{B_{0,M}^2}\varepsilon_T,\quad \sigma_M=\frac{B_{0,T}}{B_{0,M}}\sigma_T. \tag{2}$$

Table 1 summarizes the material properties of the target and model setups for the various target field strengths. Adjustment of the model material properties was achieved by pair-wise mixing of four liquids (decane, ethanol, purified water, N-methylformamide) and adding small amounts of sodium chloride. Measurement of ε_M and σ_M was accomplished using a dielectric probe measurement system (HP85070, HP, USA) connected to a network analyzer. All imaging experiments were performed on a 7T system (Magnex / Varian) equipped with an 8-element microstrip TEM coil array (6).

In order to proof the principal concept of ED scaling, the Maxwell equations were solved numerically for corresponding target and model setups. For these calculations, the coil was simplified to a single circular element, permitting the use of a semi-analytical procedure (7). The agreement between the computed target and model coil sensitivity profiles (S) was quantified by the relative root-mean-square (RMS) error. As shown in Tab.1, significant errors occur mainly for the smallest target field strengths. These errors are mainly due to modified boundary conditions in the model setup compared to the intended target arrangement.

RESULTS and DISCUSSION: ED scaling experiments were conducted for $B_{0,T}$ in the range between 1.5 and 11.5 T. Figure 1 shows resulting RF coil sensitivity maps obtained for $B_{0,T}$= 1.5T, 7.5T and 11.5T. These maps confirm that increasing $B_{0,T}$ gives rise to enhanced asymmetry and structure in the sensitivity profiles.

For each ED scaling experiment, geometry factors were calculated with SENSE reduction factors (R) between 1 and 5.5. Generally it was found that with increasing $B_{0,T}$ the g factors initially deteriorate slightly but improve significantly after reaching some critical $B_{0,T}$, which depends on R. Notably, the strongest improvement of the g factor occurs in the center, which is often the region in which SNR is lowest. In order to compare these experimental PI performance data with results obtained for the center of a sphere by theoretical ultimate SNR analysis (1) (Fig.2, left), geometry factors were averaged over a central, circular region with a diameter of 9 cm (Fig.2, right). Experiment and theory show excellent qualitative agreement, demonstrating that PI performance indeed improves with field strength. In the unfavorable regions of enhanced g factors, the experimental g values are significantly higher than in theory, reflecting the non-ideality of the 8-element coil.

CONCLUSIONS: The performed study gives rise to following three main conclusions: (I) The experimental results for PI field strength dependence are in agreement with theoretical ultimate PI performance predictions (1). (II) Enhanced PI performance is, therefore, expected at high field strengths. For a head-sized spherical phantom with the same material properties as brain tissue, the beneficial effect occurs above approximately 5 T. (III) The concept of ED scaling has proven a valuable tool for the investigation of RF field characteristics in a wide range of field strengths.

B_0 [T]	ε_T	σ_T [S/m]	ε_M	σ_M [S/m]	RMS [%]
1.5	82.9	0.40	3.8	0.09	11.7
3	63.1	0.46	11.6	0.20	9.6
4.5	56.6	0.50	23.4	0.32	4.1
6	56.4	0.53	39.2	0.46	1.2
7.5	51.4	0.56	59.0	0.60	0.5
9	50.0	0.59	82.7	0.75	1.9
10.5	49.1	0.61	110.4	0.91	3.0
11.5	48.5	0.62	131.0	1.02	3.7

TABLE 1:

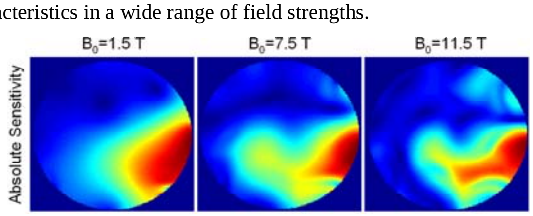

FIGURE: 1

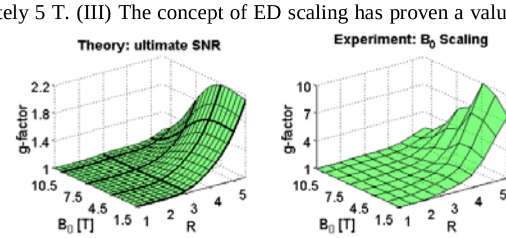

FIGURE: 2

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