Physical insights from ideal current patterns resulting in ultimate intrinsic SNR: efficacy of traditional coil designs at low field strength and the need for new designs at high field

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Introduction

A formalism to calculate ultimate intrinsic SNR (UISNR) in a dielectric cylinder [1], based on a mode expansion with dyadic Green's functions (DGF) [2], has seen increasing use in the past few years [3,4], and a similar formulation for dielectric spheres was introduced at a recent conference [5]. Ideal current patterns [3,5] resulting in UISNR can be calculated using the same theoretical framework. In this work we show that ideal current patterns provide useful physical insights regarding the optimal design of radiofrequency (RF) detector coils. We identify familiar coil designs within optimal current patterns at low to moderate field strength, and document the emergence of less familiar patterns, e.g. involving substantial electric as well as magnetic dipole contributions, at high field strength.

Theory and Methods

UISNR in a uniform sphere or cylinder can be calculated by employing the DGF theory [2] and a complete set of current modes to define a current distribution at some distance from the object [1,3,5]. Ideal current patterns [3,5] resulting in UISNR are derived by performing a weighted sum of the individual current modes using optimal image reconstruction weights. Current patterns of any actual coil can be simulated with the same formalism by applying appropriate weighting functions to the general current distribution [3,5]. Current pattern and SNR calculations were performed for a 10 cm radius sphere and a 20 cm radius cylinder with uniform electrical properties approximating average values in the human head [6] and in dog skeletal muscle [1], respectively. The current distribution was defined at a distance of 5 mm from the surface of the objects.

Results and Discussion

Fig. 1 shows ideal current patterns as a function of time, in the case of a target voxel at the center of a sphere at 1.5 T. Ideal currents form two large distributed loops (illustrated schematically at left), centered on the x-y plane (φ = 90°) and separated by 180 degrees in the azymuthal direction, which rotate in the same sense about an axis that precesses around the direction of the main magnetic field (z). In other words, in order to maximize SNR, the receive coil should track as closely as possible the precession of the spins in the center of the object. One way of achieving this sort of field pattern is to receive with a quadrature birdcage coil [7]. Indeed, in a cylinder, the optimal pattern at low field (a snapshot is shown at the left in Fig. 2) directly resembles a sinusoidal birdcage mode rotating at the Larmor frequency (i.e. driven in quadrature). The middle row of Fig. 1 shows ideal current patterns at 1.5 T for a voxel at an intermediate position between the center and the surface of the sphere. In this case, current flows only in the proximity of the voxel of interest, alternating between distributed single-loop and distributed figure-eight or butterfly configurations every quarter of a cycle, and inverting direction every half cycle. The bottom row of Fig. 1 shows that combining three identical discrete coils (R = 35.7 mm) to form a typical loop-butterfly surface quadrature array matching the general dimensions of the ideal current patterns at 1.5 T indeed yields 94% of the optimal performance. Fig. 2, on the other hand, which separates ideal current patterns around a cylinder into divergence-free and curl-free components, documents a departure from such familiar quadrature coil behavior as field strength increases. At 0.2 T (left half of Fig. 2), the dominant contribution is from the closed-loop (divergence-free) current component resembling a quadrature birdcage mode, whereas at 7 T (right half of Fig. 2) the shape of the ideal current pattern deviates significantly towards the electric-dipole (curl-free) component. This example illustrates how unshielded electric dipole components, which are required to describe a fully-general surface current pattern [1] but which have often been dismissed as inefficient for MR based on low-field experience, can become important contributors to SNR at high field strengths.

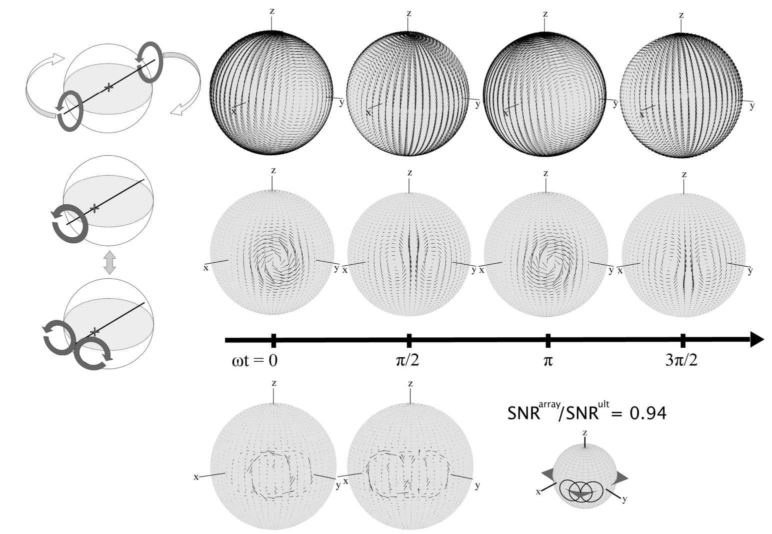

Fig. 1. Ideal surface current patterns associated with the best possible SNR in a sphere at 1.5 T. A schematic representation that shows how the current patterns evolve in time is plotted next to three-dimensional representations for four time points. Top row: for a region in the center of sphere, ideal current patterns form a distributed loop pair that precesses around the z-axis at the Larmor frequency. (In a cylinder, the corresponding pattern resembles a distributed quadrature birdcage mode.) Middle row: for a region intermediate between the center and the surface, ideal current patterns alternate between single loop and figure-eight configurations, with a phase shift of 90°. Bottom row: A suitable discretized 3-loop design driven alternately as loop and figure eight can achieve 94% of the optimum.

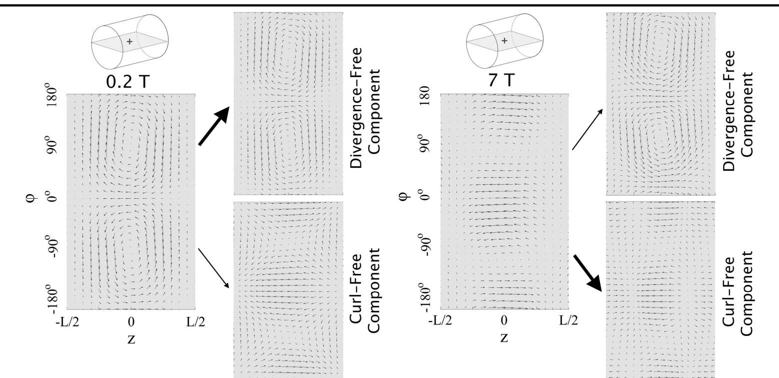

Fig. 2. Ideal surface current patterns associated with the best possible SNR at a voxel on the axis of a cylinder are compared at 0.2 T and 7 T for an arbitrary time point. The plots represent 2D "unwrapped" views of the cylindrical surface. The axial and azimuthal coordinates are on the horizontal and vertical axis, respectively. Divergence-free and curl-free contributions to the ideal current patterns are plotted separately to show the larger effect of the electric dipole component at high field.

Conclusions

The DGF formalism provides useful physical insights for the design of RF coils. Our results, for the first time, confirm and explain graphically the near-optimality of common volume and surface quadrature coil designs at low to moderate field strength: for example, for target regions near the center of the imaged object, distributed birdcage-like optimal current patterns emerge, whereas distributed loop–butterfly patterns emerge for locations closer to the surface. The complexity and variability of ideal current patterns at higher frequencies suggests that innovative coil designs, which might confound our low-field instincts, may be needed in order to approach the optimal performance at ultra-high field.

References

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