Improved surface coil performance at any depth in a lossy sphere with a dielectric disc

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Introduction: High-permittivity Material (HPM) has been used in MRI to improve radio-frequency (RF) field homogeneity and/or signal-to-noise ratio (SNR) in head[1-4], abdominal[5], and extremity imaging[6] at different field strengths. These studies on HPM indicate a promising future for further development of HPM in MRI. Meanwhile, many studies also suggest that better imaging performance will be obtained by optimizing the location, geometry, material properties of HPM for specific MRI hardware. But due to the limitation of hardware devices, the availability of the HPM on site, and the availability of the simulation software and computer hardware, an optimal configuration including the considerations of HPM and coil configurations combined has not been investigated. Also, from a coil design perspective, it is important to know whether an optimal coil design incorporating HPM would outperform an optimal coil design without HPM in imaging and whether the amount of improvement in imaging performance is high enough to encourage us to keep pursuing such hybrid coil-HPM designs.

In this study, we attempted to find an optimal hybrid coil-HPM design using a simple loop coil and a dielectric disc at 3T, including the considerations on HPM location, geometry, material properties, MRI coil location, and coil geometry. The performance of this optimal hybrid design was numerically evaluated by comparing it to the optimal single-coil design without any HPM (coil-only design).

Method: The coil efficiency of this hybrid coil-HPM design consisting of a single loop coil and a dielectric disc (shown in Figure 1) was numerically optimized by particle swarm optimization (PSO) for a location of interest L_{opt} at different depths in a lossy sphere at 3T. The lossy sphere (r_{sphere}=10 cm, $\varepsilon_r = 50$, σ= 0.5 S/m, approximating the average brain values at 3T) was centered at the origin of the coordinate system. The simple loop coil had an inner radius, r_{coil}, and a fixed strip width $w = 4$ mm. The coil axis was aligned with the y-axis. The distance between the coil center and the origin was h_{coil}. The HPM disc with a radius r_{HPM} had a fixed thickness of 1 cm and it was positioned the same fashion as the loop coil. The distance between HPM center and the origin was h_{HPM}. The HPM disc had a permittivity ε_r(HPM) and conductivity σ(HPM) = 0.001 S/m. The coil efficiency, $Eff_{\text{coil}} = |\mathbf{B}_1^+|/(P_{\text{diss}} + P_{\text{coil}})^{½}$, was evaluated at locations L_{opt} along the y-axis using the field solutions obtained from finite-difference time-domain (FDTD) simulations, where $|\mathbf{B}_1^+| = |\mathbf{B}_x + i\,\mathbf{B}_y|/2$ is the magnitude of the circularly polarized component of magnetic flux density, $P_{\text{diss}} = \sum \sigma(\mathbf{E}_x^2+\mathbf{E}_y^2+\mathbf{E}_z^2)dv$ is the power dissipated in the sphere and the HPM, and $P_{\text{coil}} = (1\text{A})^2(\pi\ r_{\text{coil}})/(\sigma_{\text{cu}}\ \delta_{\text{cu}}\ w)$ is the analytically-determined power dissipated in the coil as heat, using $\sigma_{\text{cu}} = 5.8\times10^7$ S/m and $\delta_{\text{cu}} = 5.85\times10^{-6}$ m. In the PSO, the ε_r(HPM), h_{HPM}, r_{HPM}, r_{coil}, and h_{coil} were the parameters and the parameter space was shown in Table 1. Each optimization at one location L_{opt} used 15 agents and 200 generations. The convergence condition was met for all optimizations by generation 200. The optimal coil-only configurations at the same L_{opt} were also obtained by this PSO/FDTD method to evaluate the performance of the hybrid coil-HPM design. In the coil-only optimizations, the minimum permissible h_{coil} was 0 cm. All numerical simulations were performed with commercially available software (XF7; Remcom, Inc., State College, PA); postprocessing of the EM fields was performed using Matlab (The Mathworks, Natick, MA); the PSO was programmed in XF7 environment.

Results: The optimized Eff_{coil} of the hybrid design and the coil-only configuration were normalized to the optimal Eff_{coil}(coil-only) at L_{opt} = 8.5 cm and plotted in Figure 2. The Eff_{coil}(hybrid) was better than the Eff_{coil}(coil-only) along the y-axis in the lossy sphere. The Eff_{coil}(hybrid) was improved by the least 17.5% at L_{opt} = 5.5 cm and the most 104.8% at L_{opt} = 2.5 cm. The average improvement of Eff_{coil} for L_{opt} > 5 cm was 22.6% and for L_{opt} < 5 cm was 86.8%. The configurations of the optimal hybrid design are shown in Table 2.

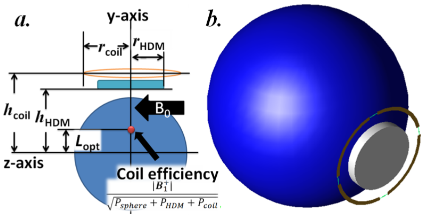

Figure 1: *a*) The geometric parameters used to find the optimal Eff_{coil} at a location L_{opt}. *b*) The configuration of the hybrid coil-HPM design used in this study. r_{sphere}=10cm

Parameter name	Min value	Max value	Increment
h_{coil}	0 or 10 cm	16 cm	0.5 cm
r_{coil}	1 cm	11 cm	0.5 cm
h_{HPM}	10 cm	16 cm	0.5 cm
r_{HPM}	1 cm	16 cm	0.5 cm
ε_r(HPM)	1	2500	50

Table 1: Parameter space used in PSO.

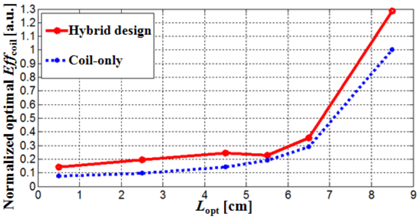

Figure 2: Normalized optimal Eff_{coil} of the hybrid design (in red) and coil-only configuration (in blue) along the y-axis at different L_{opt}.

L_{opt} [cm]	HPM configuration			Coil configuration	
	r_{HPM} [cm]	h_{HPM} [cm]	ε_r(HPM)	r_{coil} [cm]	h_{coil} [cm]
0.5	14.5	15.5	751	1.5	14.5
2.5	14.5	15.5	851	2.5	14.5
4.5	14.5	14	751	2.5	13
5.5	13	10.5	1201	6	12.5
6.5	10.5	10.5	1301	8	12.5
8.5	13.5	12	1601	1	11

Table 2: Optimal configuration of the hybrid coil-HPM design for different L_{opt}.

Discussion: An HPM disc can improve the Eff_{coil} at the center region of the sphere by 73-104%. As the location of interest moves toward the sphere surface, the improvement is reduced to approximately 20%. This suggests that a surface coil built for an ROI located deep in the object, such as the brain or the heart, could incorporate HPM to significantly improve Eff_{coil} compared to the optimal design made only of conductors. The HPM can also give coil designers more degrees of freedom in their designs. In designing a coil to image near the sample surface, using HPMs can help, but the improvement in Eff_{coil} would be much less.

The optimal hybrid designs for L_{opt} < 5 cm tended to have a small coil, a large HPM disc, and a gap between HPM disc and the sphere. This is counter-intuitive to the current general configuration of using HPM[1-6], where the HPM is typically smaller than the coil, as is the case for the optimized hybrid designs for 5 cm < L_{opt} < 7 cm.

In this study, the hybrid configuration is very simple. But, even with this simple setup, the Eff_{coil} is able to be improved by at least 73% at the center region and 18% in the superficial area. We would expect more improvement when a more sophisticated hybrid design is used.

References: [1] Yang *et al.*, JMRI 2006; 24:197–202. [2] Yang *et al.*, MRM 2011; 65:358–362. [3] Haines *et al.*, JMRI 2010;203:323–327. [4] Teeuwisse *et al.*, MRM 2012;67:912–918. [5] Heer *et al.*, MRM 2012; 68:1317-1324. [6] Sebastian *et al.*, MRM 2012;68:1325-1331.