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 head1–3, abdominal4, and extremity imaging5 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, $\epsilon_r = 50$, $\sigma_r = 0.5$ 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 had a radius $r_{HPM}$, 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 $\epsilon_r$ (HPM) and conductivity $\sigma_r$ (HPM) = 0.001 S/m. The coil efficiency, $Eff_{coil}$, was evaluated at locations $L_{opt}$ along the y-axis using the field solutions obtained from difference-time-domain (FDTD) simulations, where $B_i, i = B_t, B_r, B_z$ is the magnitude of the circularly polarized component of magnetic flux density, $P_{dis} = \sum \sigma_r E_r E_t$, $\delta_{coil}$ is the analytically-determined power dissipated in the coil as heat, and $P_{coil} = (1A)^2(\sigma_r r_{coil})/2r_{coil/2}$ is the power dissipated in the sphere and the HPM, and $\delta_{coil} = 5.85 \times 10^{-6}$ m. 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% 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 designs are shown in Table 2.

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 HPMs, 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.