A Novel Intravascular MRI Coil with optimized Sensitivity

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Objective: In the past, various configurations have been proposed for intravascular imaging coils. Single loop coils [1] are simple to construct, but suffer from a very inhomogeneous spatial sensitivity. Opposed solenoid coils [2] and meander coils [3] solve this problem at the cost of a quick drop-off of the sensitivity in radial direction. A variant of Helmholtz coils (Fig.1) has been proposed and optimized for active tracking of catheters [4]. Based on the Helmholtz design, a novel miniaturized coil has been developed for intravascular imaging and tracking. The main objective of this work is to optimize the spatial sensitivity of the coil for intravascular imaging.

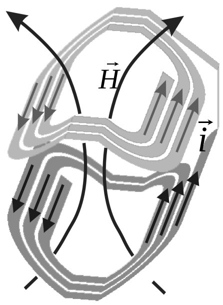

Figure 1: 3D schematic of Helmholtz-coil with three windings

Simulation Methods: It was the objective of the simulations to obtain a coil geometry that provides a radially symmetric spatial sensitivity in the central plane of the coil. Under the assumption that the coil length is sufficiently large compared with the thickness of the imaging slice at the central plane, the Biot-Savart-field of the coil in that plane was calculated analytically in 2D using MATLAB. Infinitesimal small current elements on the surface of a cylinder (∅1.67 mm, 5 F) were used to represent the coil windings. This 2D simulation approach was chosen to keep the simulation effort manageable. The number of the windings and their azimuthal position was varied. The azimuthal variation of the coil sensitivity was minimized at a radial distance of 0.25 mm from the catheter surface. The field distribution becomes more homogeneous at larger distances. Finally, an FEM simulation (COMSOL) was used to verify the field calculations in MATLAB and to evaluate the effect of the finite size of the windings (150 x 50 µm^2) for the optimum geometry found in MATLAB.

Materials and Methods: The optimum coil geometry found in the simulations was realized using micro systems technology which allows batch processing with high reproducibility. Because this technology is based on planar substrates, the coils were fabricated on a planar flexible 25 µm thick polyimide foil with a copper laminate of 18 µm on each side. The planar structure was designed such that the 3D coil structure could be obtained by wrapping the foil around the base catheter. The actual windings were shaped similar to race tracks with an overall length of 3mm using the optimum azimutal positions from the simulation (Fig. 2b). The coil structures were etched into the copper layer. Subsequently, the coil structures were thickened to 50µm by electroplating using an advanced thick resist lithography process [5] in order to achieve a high Q-factor. In the last process step, the copper interconnects were etched on the backside of the foil, and the foil-based coils were mounted on a 5 French catheter tube.

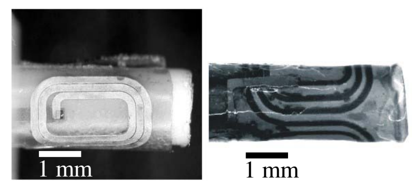

Figure 2: Foil-based micro Helmholtz coil a) former b) novel design

The coil was matched to 50Ω and connected via a coaxial cable to the scanner. The novel coil design was examined in high resolution MR phantom experiments (3D FFE, FOV 16mm, resolution 63µm x 63µm, 1mm slice) and compared with the former micro coil used for tracking.

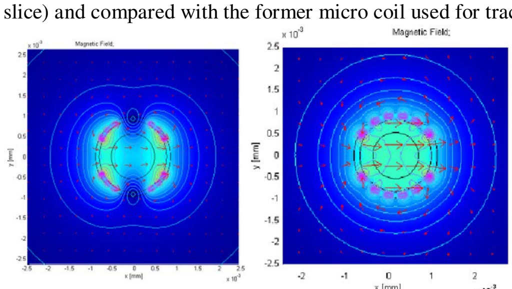

Figure 3: FEM simulation: magnetic sensitivity distribution of a) original and b) optimized design

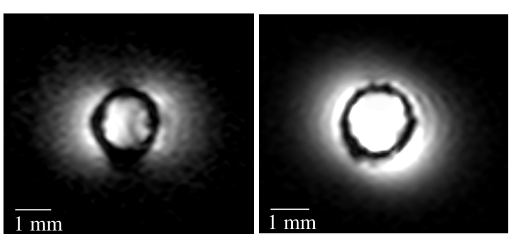

Figure 4: Microscopic MR images acquired with a) original coil b) optimized coil

Results and Discussion: The MATLAB calculations with three windings resulted in a residual field fluctuation of 5.9%. Simulations with four windings showed a further improvement of 0.54 % in field homogeneity. However, four windings also caused a 15% decrease of the Q-factor due to the required longer and narrower coil lead. Therefore, the solution with three windings was transferred to the FEM simulation in COMSOL, where a field fluctuation of 6.8 % was simulated. The result shows that the infinite current element approximation affects the simulation precision only marginally and was justified to speed up the optimization process. The best solution found was a non uniform distribution, where the outer windings are closer to each other than the inner windings. The magnetic field of the Helmholtz coil configuration decreases with $1/r^2$ in the simulation, which results in a higher penetration depth into the surrounding medium than the opposed solenoid or meander approaches which have a $1/r^3$ characteristic. The maximum of the sensitivity is still located in the center of the coil, which allows unambiguous tracking of the coil with fast and robust projection measurements.

Both, the original and the novel coil designs showed Q-factors of about 16 in air and 15 in phantom liquid, when connected and matched to the 50Ω transmission line. The novel coil provided sufficient signal for projection-based tracking. Fig. 4 shows high resolution images of the original and the optimized design. The azimuthal homogeneity of the sensitivity of the novel coil is vastly improved. Remaining fluctuations are most probably caused by an imperfect realization of the simulated winding geometry. Note, that the image intensity in Fig. 4 is also weighted with a flip angle amplification, because passive decoupling was not effective due to the small size of the coil.

Conclusion: The novel coil design has the advantage of an improved homogeneity of the spatial sensitivity in azimuthal direction. The Helmholtz-based design is superior to other coil designs due to its slower radial decay of the sensitivity. Both features were demonstrated in simulation and experiment. Further work is required to optimize the realization of the coil and to apply it to intravascular imaging.

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