Analysis of intravascular MR antenna designs by simulation of sensitivity profiles

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Synopsis: Intravascular MR antennas hold potential to enable tracking of guidewires and catheters through bloodvessels and to obtain high-resolution images of vessel walls. Previous research on intravascular MR antennas describes promising designs for these applications. To quantitatively compare and optimize intravascular antenna designs we developed a numerical method, based on Biot-Savart’s law. This method was validated and used to calculate sensitivity patterns of models of intravascular MR antennas, in order to select and optimize promising designs for practical development and further testing.

Introduction: Intravascular MR antennas hold potential to enable tracking of guidewires and catheters through bloodvessels and to obtain high-resolution images of vessel walls. Previous research on intravascular MR antennas describes several promising designs for these applications. To quantitatively compare and optimize these and other intravascular antenna designs, numerical simulation is very useful. It allows easy adjustments of the design variables to satisfy requirements of different applications (e.g. imaging and tracking), without the need for manufacturing and testing. In this work, a numerical method is validated and models of intravascular MR antennas of interest are used to simulate sensitivity patterns, in order to select and optimize promising designs for practical development and in vitro testing.

Methods: Investigation of literature demonstrates that the double-loop [1], triple-loop [1], dual-opposed solenoids [2], and saddle-coil [3] (Figure 1) possess good qualities for intravascular MR imaging. For tracking the double-helix [4], opposed double-helix [4], center return [2], and solenoid [5] are promising designs, with the sensitivity pattern used as the main selection criterion. For tracking, a strong localized sensitivity pattern is required, whereas an extended and homogeneous sensitivity pattern is desired for imaging. The sensitivity patterns of the antenna designs were determined by using a numerical method based on Biot-Savart’s law. This static model neglects mutual induction and frequency dependency. The correctness of this model was verified with a frequency dependent dynamic model, the Numerical Electromagnetic Code (NEC).

The suitability of the designs for tracking and imaging was examined by comparison of the strength and homogeneity of the sensitivity pattern of the different designs, as determined by both static and dynamic simulation.

Results: Comparison of the static and dynamic simulation showed distinctions in the observed sensitivity patterns, especially close to or in the antenna. At a distance of 1 mm from the antenna surface, considered as a typical vessel distance for intravascular imaging, distinctions in the sensitivity patterns of the two models were negligible. Comparison of simulated designs indicated that at distances smaller than the typical vessel distance, the triple-loop design outperformed other designs as a result of a combination of high signal strength and favorable homogeneity (Figure 2). At the typical vessel distance and beyond, the signal strength of the dual-opposed solenoids design exceeded the signal strength of the other designs, however, at the expense of an inhomogeneous sensitivity pattern (Figure 3). For all designs, a larger distance to the antenna surface resulted in a higher homogeneity of the sensitivity pattern, proving the dual-opposed solenoids design to be favorable for larger distances. Observation of the sensitivity patterns of the promising designs for tracking showed that the sensitivity pattern of the center return was very suitable for this application. This design has a very strong sensitivity pattern centered along the axis of the antenna.

Discussion: The sensitivity patterns of various intravascular MR antennas were modeled with the help of numerical methods, simplifying comparison and optimization of different designs. Validation of the static approach showed that the static modeling can be used for pre-selection of the designs, whereas the dynamic model should be used to calculate a given design more thoroughly. Results prove the triple-loop and the dual-opposed solenoids to be the most suitable designs for imaging, respectively at a maximum distance of 1 mm from the antenna surface and beyond. The center return represents a good design for tracking. The presented results are obtained with the antennas situated parallel to the main field ($B_0$). As the antennas will be used in tortuous blood vessels, these results will be verified for different orientations of the antennas with respect to the main field. The numerical methods will also be used to simulate the sensitivity pattern of new, in literature unknown antenna designs. Future in vitro investigations of optimized designs will be carried out to validate the simulation results.

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