Hybrid Intravascular Imaging Coils

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Introduction

The use of MRI in minimally invasive, intravascular therapeutic procedures, has increased the need for imaging coils that provide accurate visualization of the vasculature [1-2], particularly in vessel wall imaging procedures for identification and characterization of atherosclerotic plaque components [3]. Several antenna designs including dipole antennas, single loops and opposed solenoids have been proposed and successfully used in intravascular imaging procedures [4-7]. Of these coil designs, the opposed-solenoid configuration is one that has great potential for improved intravascular imaging. The opposed-solenoid antenna is based on groups of helical loops separated by a gap region, with current driven in opposite directions on either side of the gap. Within the gap, there is a substantial radial protrusion of field lines beyond the diameter of the helical loops, which provides a homogeneous region of high sensitivity suitable for endovascular imaging [4-6]. However, one major drawback of the opposed-solenoid imaging antenna is the small area of longitudinal coverage when compared with other designs. This small longitudinal coverage reduces the device's effectiveness for survey imaging in the coronal or sagittal planes, where the objective is to quickly obtain low resolution images of the vasculature in order to identify disease or pathology before more detailed, high-resolution imaging is performed to characterize that pathology. In this project we seek to modify the opposed solenoid coil in a manner which would provide extended longitudinal coverage for survey imaging while retaining the highly homogeneous and uniform capability of the opposed-solenoid imaging coil. We will accomplish this objective through the addition of single-loop coil elements to a standard opposed-solenoid imaging coil.

Materials and Methods

Theoretical spatial sensitivity profile of an unmodified opposed-solenoid coil was first calculated to serve as a basis for comparison to improvements offered by the hybrid coils (Fig 1). By combining a standard opposed-solenoid intravascular imaging coil with single loop windings outside of the opposed-solenoid coil, a hybrid imaging coil is created (Fig 2). Opposed-solenoid imaging coil dimensions were obtained from previously optimized parameters [8]. Single loop coils were created with long axis lengths of 6.5-16.5mm, short axis lengths were the same as the diameter of the opposed solenoid coil, and separation distances of 0-6.5 mm from the opposed-solenoid coils. The winding direction of the single loop coils was either the same direction or counter-wound. Computers simulations, based on the Biot-Savart law, were used to calculate the B_1 field generated by these geometric coil configurations [4, 9]. All simulations were performed using MATLAB on a PC. The solenoid coils were approximated using 128-sided polygons and loop coils were approximated using rectangles. Calculated B_1 fields were then related to coil sensitivity by the principle of reciprocity [10]. Key assumptions that were made in these simulations include: (i) the opposed solenoid coils are placed along B_0, (ii) the coils are small in size, (iii) electrical effects from components such as capacitors and diodes and circuit resistance are not taken into consideration, and (iv) that the dielectric properties of tissues do not give rise to wavelength effects over the coil volume.

Following simulations, a hybrid imaging coil was constructed for validation of simulation results. The coil was constructed from 30 AWG copper magnet wire and mounted on a 3 mm diameter plastic tube (Fig 2 – will be redone). Variable capacitors were used to provide precise tuning and matching of the coil and micro-coaxial cable was used to connect the coil to the MR receiver. Imaging on a uniform saline phantom was performed in a Siemens Sonata 1.5T imager. Images were compared with sensitivity plots obtained from simulations.

Results

Biot-Savart simulations reveal that single loop coil windings in the same direction produce symmetrical field enhancement on opposite sides of the opposed-solenoid windings (Fig 3A) while the counter-wound windings produce an asymmetrical effect on enhancement (Fig 3B). Phantom imaging experiments using the hybrid coil showed the following results: average grayscale values of 1486±46 were observed in the enhancement region between the opposed solenoid windings (Fig 4B) and 1354±66 in the regions of the single loop windings (Fig 4A and 4C). Sensitivity was observed along the entire length of the single loop windings.

Discussion and Conclusions

The single loop/opposed-solenoid configuration was chosen because these two winding patterns are easily integrated onto a standard catheter. The single loop coil also represents one of the simplest wiring configurations available to obtain the sensitivity sufficient for survey imaging applications. Biot-Savart simulations show that the addition of a single loop winding provides added sensitivity in the regions outside of the enhancement region. Simulations also show that counter-wound single loop coils produce asymmetrical enhancement on each side of the opposed-solenoid coil. This asymmetrical enhancement is attributed to the different flux direction and their interactions with the field from the opposed-solenoid coil. Although the enhancement pattern differs on opposite sides of the single-loop coil, the enhancement offered by single loop coils wound in the same direction is preferred. Desires to increase longitudinal coverage must be tempered with several drawbacks that are present from increased device length. One such issue is that a long imaging coil traversing tortuous blood vessels may become bent and distorted, which would result in the coil being detuned. Increasing device length also increases overall circuit resistance, which has a negative impact on Q and device SNR. Finally, too large of a coil may result in a self-resonant frequency lower than the Larmor frequency. With these considerations in mind, an overall total device length of 22 mm was deemed to be a good compromise. In phantom imaging experiments, axial images acquired in the enhancement region still retained good radial homogeneity. The design provides an overall 50% improvement in longitudinal coverage and up to 45% improvement in signal amplitude in the region covered by the single coil windings when compared to a conventional opposed-solenoid imaging coil. Axial imaging shows device sensitivity in all directions, although the sensitivity profile was not radially homogeneous (Fig 5B). This is sufficient for survey imaging, but would cause distortions in grayscale intensity levels of the vasculature, making it unsuitable for detail imaging applications. In summary, we found that Biot-Savart simulations are a useful tool to examine the performance of hybrid coil designs for intravascular imaging applications. We have also found that hybrid coils are a possible alternative to other concepts proposed to extended coverage [11]. Although the sensitivity profile of the single loop coils is not radially symmetric, the combination of a single-loop with an opposed-solenoid coil provided an extended imaging range in the longitudinal direction and enables both low-resolution survey imaging to identify and isolate pathology and then high-resolution imaging for further characterization of that pathology.

References

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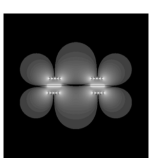

Fig 1. A plot of B_{xy} sensitivity for an opposed solenoid coil. High-resolution imaging is performed in the central region between the two counter-wound solenoid coils.

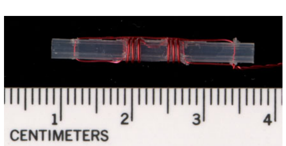

Fig 2. A picture of a hybrid imaging coil. This particular configuration consists of an opposed-solenoid coil in the middle, flanked by single loop coils. The device is mounted on a 3.0 mm plastic tube.

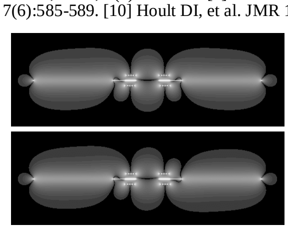

Fig 3. B_{xy} sensitivity plots for the hybrid coil design. Single loop coils are wound either in the same direction (top) and counter-wound (bottom)

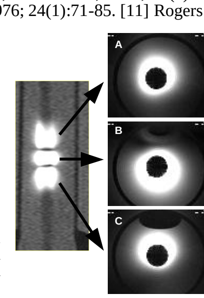

Fig 4 (left). Phantom imaging experiments with the hybrid coil. Axial images from opposed-solenoid and single-loop regions show the ability for imaging in both regions.

Fig 5 (right). Axial B_{xy} sensitivity plots for the hybrid coil design. The region between the opposed solenoid coils is homogeneous and circular (top) while the region from the single loop coil shows distortions from a circular profile (bottom)