DESIGN PRINCIPLES FOR INSULATED INTERNAL LOOPLESS MRI RECEIVERS

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Abstract- **A theoretical analysis of insulated internal loopless MRI receivers is presented. Insulated loopless receivers are ideal for local, high resolution imaging of the vasculature and other internal organs. However, there are currently no analysis techniques or design principles for these devices. By using a Galerkin method of moments combined with an application of the volume equivalence theorem, we solve for the intrinsic SNR distribution of insulated loopless receivers. As insulation thickness is increased, the resonant antenna length increases while the noise resistance decreases. Both of these effects, when used together, can greatly improve the SNR magnitude and distribution of loopless receivers. Design principles outlined here will allow for optimization of loopless receivers for a variety of internal, high resolution imaging applications.**

***Keywords* - MRI, loopless, internal receiver, insulation**

I. INTRODUCTION

Traditionally, MR receivers have been designed as loop-type resonators. These receivers (i.e., coils) are placed around the entire body or on the surface of a specific body part that is to be imaged. Subsequently, in an effort to increase the available SNR, coils were integrated into catheters so that they could be positioned intravascularly, closer to the target tissue [1, 2]. However, because they require both outward and return electrical leads, these loop receivers are not ideal for small, linear catheter structures. In addition, signal sensitivity for small loop receivers falls off as $1/R^2$ (where R is the distance from the coil).

As a result, loopless MR receivers – which are essentially unbalanced dipole antennas – were designed [3]. Because they require only a single electrical lead, these antennas are easily incorporated into catheters and other interventional devices. Sensitivity falls off as 1/R for loopless receivers, an improvement over small loop receivers. These antennas are being developed for applications in vascular, esophageal, and transurethral prostate imaging.

At present, the only analysis of loopless receivers is for the case of a bare wire placed in a homogenous, conductive medium [3]. However, most actual loopless receivers are surrounded by an insulating dielectric layer (Insulation is added to increase device safety and biocompatibility.). As will be shown, insulation strongly affects the behavior of these receivers and therefore cannot be neglected.

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In this work, a theoretical analysis of insulated loopless MRI receivers is presented. As the insulation thickness is increased, resonant antenna length and field of view increase while noise resistance decreases. With proper design, insulation can improve both the safety and SNR of internal loopless MRI receivers.

II. METHODOLOGY

The signal-to-noise ratio for MR receivers can be objectively compared by finding the intrinsic SNR [4]. Using the reciprocity principle, this intrinsic SNR is:

$$\Psi_I = \frac{\sqrt{2}\omega\mu M_0 H_+}{\sqrt{4k_B TR}}$$

where ω is the Larmor frequency, μ is the magnetic permeability of the sample, M_0 is the total transverse nuclear magnetic moment in a 1 ml sample, H_+ is the right-hand circularly polarized component of the magnetic field generated by the coil with unit input current, k_B is the Boltzmann constant, T is the sample temperature, and R is the input resistance seen from the input terminals of the receiver [5]. Therefore, to find the intrinsic SNR for a given receiver, we need to solve for the magnetic field it generates when driven by a unit current and its input resistance. By convolving with the magnetic field of a small current element, the magnetic field can be easily found once the current distribution on the receiver is known.

A Galerkin method of moments was used to solve for the current distribution on the loopless receiver (i.e., a dipole antenna) [6]. This method also yields the input resistance of the antenna. Piecewise sinusoids were used as the testing/basis function, as described previously [7]. To model the effect of insulation, the volume equivalence theorem was used – introducing polarization currents to account for the effect of dielectric layers [8].

The model system consisted of an infinite medium with $\varepsilon_r = 70$ and $\sigma = 0.4$ S/m. The relative permitivity of the insulating layer was 3.3. The antenna had a radius of 0.25mm and was assumed to be perfectly conductive. In all simulations, the antenna was center driven, producing a balanced dipole antenna. While actual loopless MR receivers are unbalanced, the fundamental effects of insulation will hold for both balanced and unbalanced receivers. Balanced dipole antennas were chosen to simplify the analysis. All simulations were coded and executed using MATLAB (The Mathworks, Inc., Natick, MA).

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III. RESULTS

A. Effect of insulation on resonant length and noise resistance

Figure 1 shows the effect of insulation thickness on the quarter wave resonant pole length and noise resistance for loopless receivers. As insulation thickness is increased, the resonant length increases. The bare antenna resonant length of 9.5 cm is nearly doubled to a value of 18.5 cm by 1 mm of insulation. Noise resistance decreases as insulation thickness increases. With 1 mm of insulation, noise resistance drops by ~30% from the bare antenna case.

B. Effect of insulation on SNR distribution

Figure 2 shows the intrinsic SNR distribution for three loopless receivers: one uninsulated, one with 0.1mm insulation, and one with 1mm insulation. Each receiver length is set by the quarter wave resonance, therefore the insulated antennas are longer than the uninsulated antenna (as shown in Figure 1). SNR contours are plotted parallel to the antenna axis at three radial distances. Peak SNR increases at all radii as insulation thickness increases. In addition, as insulation thickness increases, the SNR distribution becomes more uniform along the antenna axis. Therefore, the insulated receiver has a larger field of view than the uninsulated receiver.

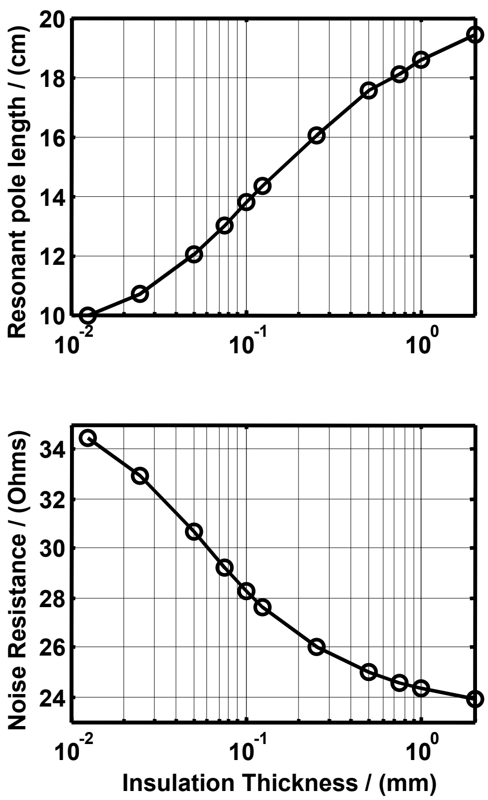

Fig. 1. Panel A: Quarter wave resonant pole length as a function of insulation thickness. With 1 mm of insulation, the resonant length is increased by nearly two times. Panel B: Noise resistance as a function of insulation thickness. 1 mm insulation decreases noise resistance by ~30%.

C. To maximize SNR, it is necessary to both add insulation and use the quarter wave resonant length

In Figure 2, both insulation thickness and antenna length were different for each receiver. Therefore, the increase in SNR could be explained as solely a length or insulation dependent effect. Figure 3 demonstrates that this is not the case. Panels A-D show the real (solid line) and imaginary (dotted line) parts of the current distribution along several antennas and Panel E shows the SNR at R=0.5 cm for all

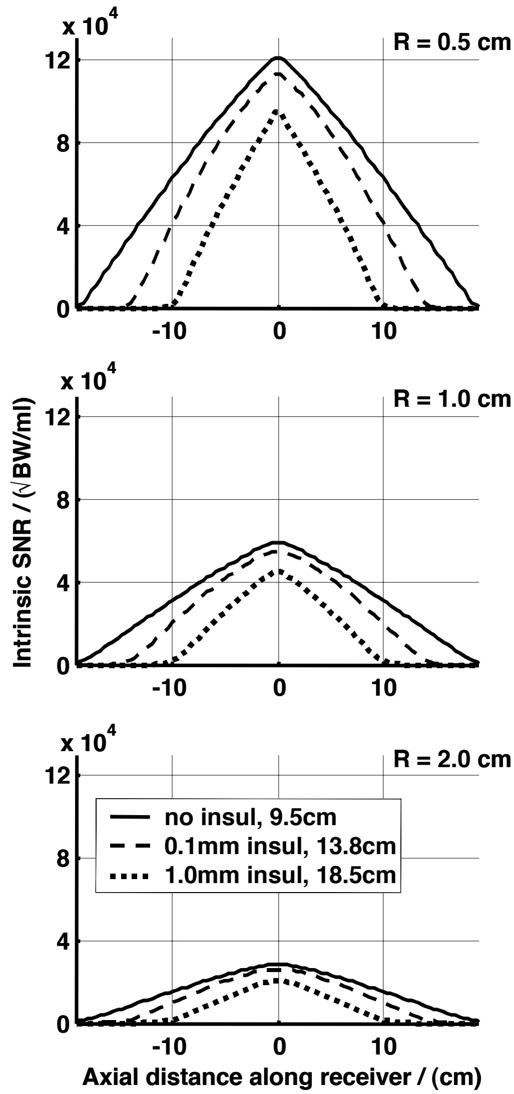

Fig. 2. Intrinsic SNR contours parallel to the antenna axis at three different radial distances (R=0.5 cm, R=1.0 cm, and R=2.0 cm). At all radii, insulation increases the SNR of the antenna. Note also that as insulation is added, the width of the SNR profile increases.

receivers. Panel A is a 9.5 cm uninsulated receiver; its SNR is shown as a solid line in Panel E. If 1.0 mm of insulation is added to a 9.5 cm antenna (Panel B), SNR increases only modestly compared to the uninsulated case (Panel E, dotted line). If the antenna length is increased to 18.5 cm but insulation is not added (Panel C), peak SNR drops slightly (Panel E, dashed line). It is only by both adding insulation and increasing length (Panel D) that a significant SNR increase is achieved (Panel E, + line).

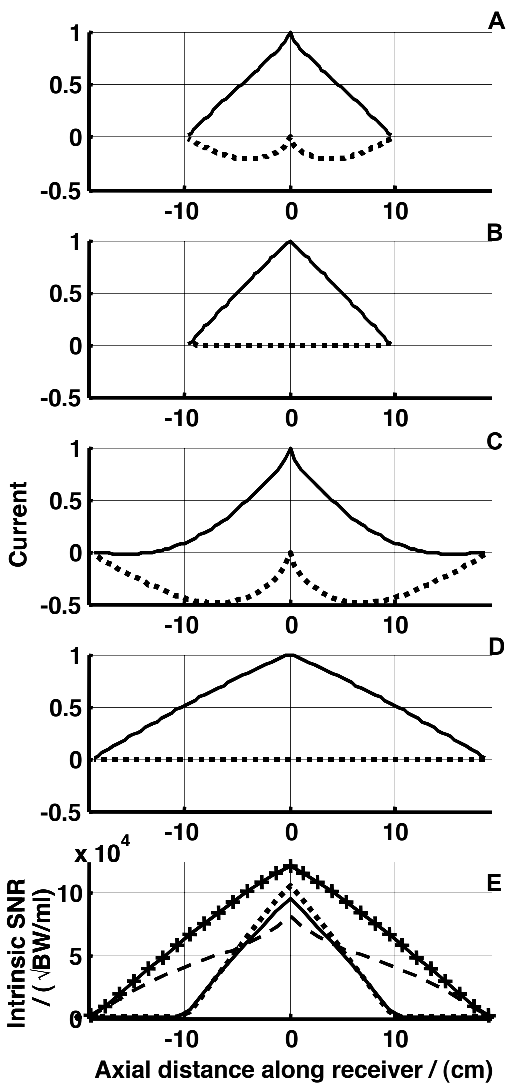

Fig. 3. Panel A-D: Real (solid lines) and imaginary (dotted lines) components of current distribution on 4 loopless antennas: 9.5 cm uninsulated (Panel A), 9.5 cm w/ 1.0 mm insulation (Panel B), 18.5 cm uninsulated (Panel C), and 18.5 cm w/ 1.0 mm insulation (Panel D). Note that the current distribution markedly broadens only when both the length is increased and insulation added (Panel D). Panel E: SNR contours at R=0.5 cm for each antenna: 9.5 cm uninsulated (solid line), 9.5 cm insulated (dotted line), 18.5 cm uninsulated (dashed line), and 18.5 cm insulated (+ line). Maximal SNR gain is achieved only when the antenna is insulated and lengthened.

IV. Discussion

A. Effect of insulation on resonant length and noise resistance

Insulation both increases the resonant length and decreases the noise resistance of loopless receivers. In the human body, the MR receiver is surrounded by a high relative permitivity ($\varepsilon_r \sim 70$). At 64 MHz, the quarter wave length in this medium is ~ 10 cm. Therefore, the quarter wave length for the uninsulated antenna is also ~ 10 cm. However, as insulation is added to the antenna, the effective permittivity that the antenna 'sees' decreases ($\varepsilon_r = 3.3$ in the insulation). and therefore, the quarter wave length increases.

The input resistance of the antenna is explained by both radiative power loss and deposition of power in tissue around the antenna. Because physiological tissue is conductive (σ~0.4 S/m), electric fields set up by the antenna will deposit power. When the antenna is insulated, electric fields are moved from conductive biological tissue into nonconductive dielectric. Therefore, local power deposition and antenna resistance are decreased.

B. Effect of insulation on SNR distribution

Adding insulation to the antenna had the effect of simultaneously increasing the receiver's SNR and field of view. Typically, increasing the field of view of an MR receiver increases noise and therefore decreases SNR. Examining the intrinsic SNR formula (Methods), H^+ should be maximized and resistance minimized to increase SNR. Adding insulation achieves both of these goals.

When the antenna is insulated, the quarter wave length resonant length increases and the current distribution on the receiver is broadened (Figure 3D). Magnetic field strength, which determines antenna sensitivity, is proportional to the local current density. Therefore, insulation leads to a broadening of the antenna's sensitive region.

Simultaneously, as previously described, insulation reduces antenna resistance. For a linear dipole antenna, the highest electric fields are concentrated in the region near the antenna. Therefore, even though adding insulation expands the axial extent of the electric field distribution, the high fields are confined to the insulation layer, where no power loss occurs. The combination of increased magnetic field extent and decreased power loss (i.e. lower R) explains the simultaneous increased SNR and field of view when the antenna is insulated.

C. To maximize SNR, it is necessary to both add insulation and use the quarter wave resonant length

Adding insulation alone does not appreciably increase the SNR of the loopless receiver. In some cases, adding insulation can even decrease SNR. Appreciable SNR gain is only realized when insulation is added and the appropriate quarter wave resonant length is used. This length simultaneously maximizes the breadth of the current distribution and minimizes noise resistance, both of which contribute to an optimal SNR profile.

V. Conclusion

Using theoretical methods, we have outlined design principles for insulated loopless MRI receivers. Insulation affects both the distribution of current on the antenna and the noise resistance. By using the proper antenna length (i.e., the effective quarter wave length), SNR for any insulated loopless receiver can be optimized. For example, an intravascular loopless antenna for aorta imaging would require a very long field of view (to cover the large extent of the aorta wall). Thicker insulation should be used to increase SNR and provide a large field of view for this receiver. On the other hand, a urethral antenna for prostate imaging may only require a fairly small field of view (a few centimeters). Thinner insulation can be used for this receiver. Subsequent experimental work to verify these results is warranted.

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