DESIGN AND SIMULATION OF A QUAD-LOOP PROBE FOR INTRAVASCULAR MRI AT 1.5 TESLA

M. Mohammadzadeh[1,3], M. Shahabadi[2], S. A. Ghasempour Shirazi[3] and H. Soltanianzadeh[4]

[1]Department of Physics, Amir Kabir University of Technology, Tehran, Iran
[2]Department of Electrical and Computer Engineering, University of Tehran, Tehran, Iran
[3]Information and Communications Technology Faculty, Tehran, Iran
[4]Radiology Department, Henry Ford Health System, Detroit, Michigan, USA

m7612942@aut.ac.ir

Abstract: Magnetic Resonance Imaging (MRI) is one of diagnostic methods which can produce images with high resolution from internal vessel walls and plaque structures. Recently, surface and volume coils have been used to improve MR signal acquisitions when image resolution is limited. Many researchers have investigated design and implementation of intravascular probes with high signal-to-noise ratio (SNR). There are three important parameters in intravascular probe design, which are SNR magnitude, SNR slope and probe flexibility. By compromising these parameters, we have proposed a new flexible and optimized SNR specification.

In this study SNR distribution and input impedance of the new probe were evaluated and compared with a conventional loop and transmission line probe. The introduced probe features high SNR, small size, flexibility, and ease of connection to the coaxial cable. The probe can be used in conjunction with an angioplasty balloon to improve intravascular surgery precision.

Introduction

MRI has the ability to characterize plaque layers and blood arteries wall [1,2]. Nowadays, images of arteries and the plaques are taken by surface coils. The main disadvantage of these coils is low SNR and consequently low resolution in the images of the internal vessel such as coronary arteries [3,4]. To increase the SNR and noise reduction of MR images, researchers designed and developed different types of the intravascular probes [5-7].

Two types of intravascular probes are loop and transmission line which each of them has adventages and limitations. Loop probe shows high SNR at a radial distance of 1.5cm, but the real part of its impedance is low compared to the noise resistance of the connecting coaxial cable. Consequently, in order to maximize signal transfer to the coaxial cable, matching and tuning circuits have to be placed close to the probe, inside the vessel. This increases the probe rigidity and thus the probability of vessel wall rapture**.** So, its SNR slope is rapid and propertional to $1/r^2$ [8]. So, transmission line probe has adventages such as low SNR slope and its matching circuit could be placed out of the vessel but its SNR magnitude is low [9-11].

The first loop probe was made by Kantor in 1983 [12] and it was high rigid. To decrease the rigidity and to increase longtudinal field of view (FOV) of probe, Atalar designed a flexible loop probe by shorthening the two ends of the transmission line wires [8]. In another effort for increasing SNR and the flexibility of loop probe, Harald et al presented two separate designs [13]. So, he peresented the quadrature loop design for the endourthral imaging [14].

To alleviate the limitations of the loop and transmission line probes, we designed a new probe with high real impedance and small size, so that we can place the matching circuit far from the probe outside the vessel. We show the proposed probe has a high SNR in comparison to the tranmission line probe and low SNR slope than loop probe.

Theory

Intrinsic SNR is a good parameter to compare and evaluate the performance of intravascular probes in MRI. This parameter is independent of the imaging parameters and pulse sequence protocols and can solely be defined by probe's parameters and moment of spins as [15]:

$$\mathrm{SNR} = \frac{V_S}{V_N} = \frac{\omega\mu H_+ M_0}{\sqrt{4K_B T R \Delta f}}, \quad (1)$$

where ω is the Larmor frequency of spins, μ is the magnetic permeability of the sample, H_+ is the magnitude of the right-hand circularly polarized component of the magnetic field generated by the probe with unit input current, M_0 is the total transverse nuclear magnetic moment in a 1ml sample, V_N is the root-mean-square of the thermal noise voltage, K_B is the Boltzmann constant, T is the sample temperature, Δf is effective bandwidth of the preamplifier matching circuit of the MRI system and probe bandwidth, and R is the real part of the probe's input impedance.

In equation (1), R and H_+ are the only effective parameters of the probe that can be manipulated to improve and increase SNR. The parameters optimum values can be obtained by choosing proper geometry and material for probe components.

Methods

Probe design

Figure 1 shows the introduced probe and two conventional loop and transmission line probes.The proposed probe consists of two perpendicular loops that are connected to each other in the supply point (point A at Figure 1). Each loop consists of double turns of coated copper (with ε_r 3.3) wires with a small gap, so that the loops impedaces are equal magnitude and phase difference of 90°. The thickness and size of the loops are given in Table 1.

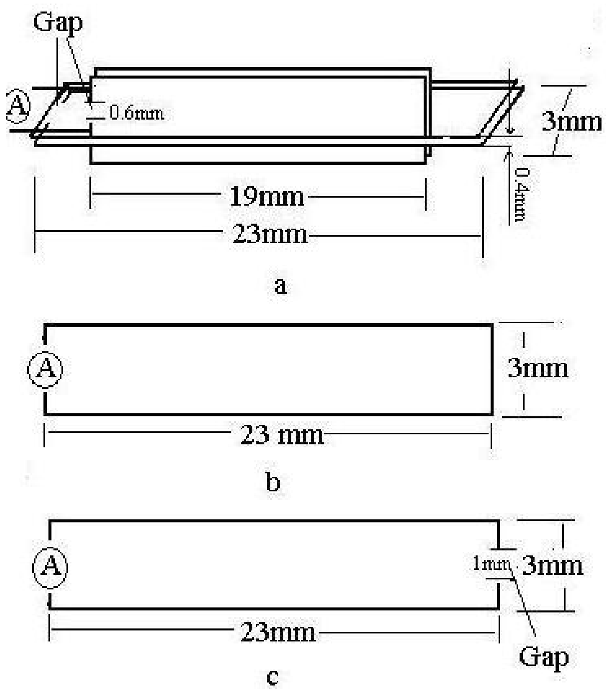

Figure 1: The proposed probe (a), Loop probe (b), and Transmission line probe (c). Points A are the place of power supply connection. Three probes are the same size.

Table 1: The physical and electrical properties of the introduced probe.

Loop number	Wire Diameter (mm)	Insulator Thickness (μm)	Loop length (mm)	Loop width (mm)
1st loop	0.25	5	23	3
2nd loop	0.24	10	19	3

The Loop characteristics are chosen so that they have equal impedance and phase difference of +45°, -45°. The circular polarized region and total Probe lengths are 1.9cm and 2.3cm which is approximately suitable to angioplasty balloon sizes, so that, it provides tissue imaging with therapy operations simultaniously. Also, this probe has characteristics such as real and large impedance (relative to coaxial cables) and circular polarization. Due to the probe's real and large impedance, the matching circuit can be placed outside the vessel and then probe's rigidity will be reduced.

Simulation

Simulation of probe SNR distribution in longitudinal and radial directions has been done in accrodance to formula 1. At first, the source current 1 A are connected to points A in Figure 1 and H magnitude around the probes has been computed. Then a 50 Ω coaxial cable with 9cm length are connected to the probes and by defining the end side of the cable as an incident port the S parameters and probes impedances were acquired.

The SNR computation was crarried out by division of H maginitude to Real paprt of impedance. Computing SNR distribution is done by High Frequency Structures Simulation (HFSS) and MATLAB in Saline phantom. Saline has electromagnetic characteristics of $\mu_r=1$, $\varepsilon_r=80$, $\sigma=0.8$ S/m (Figure 2a).

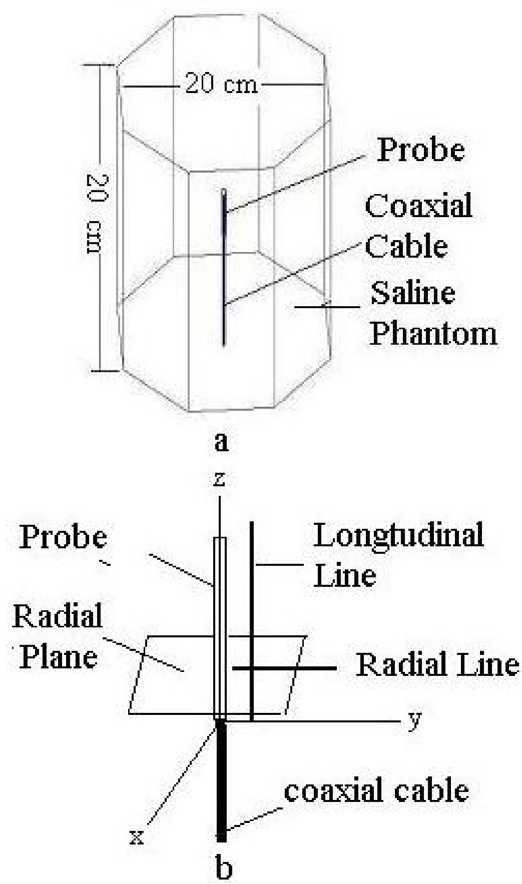

Figure 2: The saline phantom (a), The simulation plane and lines (b). The radial plane are extended in x,y=-20 to 20 mm at z=5 mm. Radial line is placed at z=5, x=0 and y=2 to 5 mm.

Results

Three indexes for the SNR distribution curves are: the area of 5% level region in radial direction, the maximum value, and radial and longitudinal slopes. Curve level 5% indicates FOV in radial (which most of the plaque and vascular wall structure is analyzed in this direction) and longitudinal directions. Decrease of SNR variation is also a criterion of ghost artifact reduction in invivo imaging. A good parameter to evaluation of SNR variation is the ratio of standard deviation to mean value of dataset, computation.

$$Slope_{SNR} = \frac{S_{SNR}}{M_{SNR}}, \qquad (2)$$

where S_{SNR} *is* standard deviation *and* M_{SNR} is mean value of SNR dataset.

Figure 3 shows SNR distribution for the proposed, loop and transmission line probes in radial direction in plane z=5mm (Figure 2b). Circular symmetry is shown in this figure. Area of the 5% SNR Curve distribution for the probes is shown in Table 2.

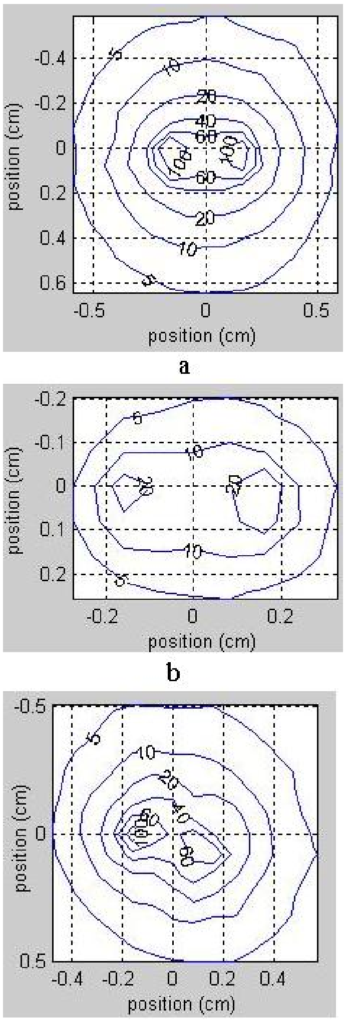

Figure 3: SNR distribution in Radial plane (Fig 2.b) for the (a) Loop (b) Transmission line (c) Proposed probes.

Table 2: FOV areas for the proposed, loop, and transmission line probes

Probe Type	FOV (cm^2)
Loop	0.78
Transmission Line	0.16
proposed	0.63

Figure 4 Shows SNR changes in radial and longtudinal directions for the loop, transmission, and introduced probes (Simulation lines are shown in figure 2b). The maximum value of SNR and its slope for the probes has been extracted from SNR curves and illustrated in Table 3.

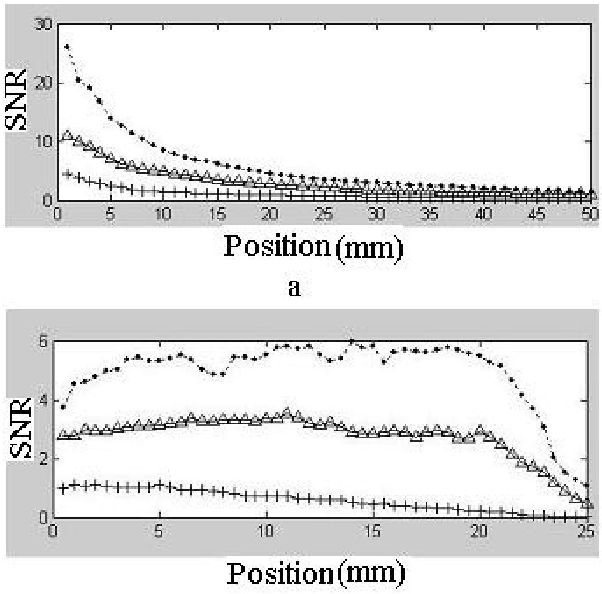

Figure 4: SNR curves in radial (a) and longitudinal (b) directions for the loop (•), transmission line (+) and proposed (Δ) probes in accordance to simulation lines are shown in figure 2b.

Table 3: The SNR maximum and slope of probes in Radial and longitudinal directions

Probe Type	Maximum Magnitude of SNR	Slope of SNR at radial direction	Slope of SNR at longitudinal direction
loop	25.89	0.96	0.24
Transmission Line	4.45	0.88	0.62
Proposed	10.95	0.78	0.26

Discussion

Results show the new probe has compromised SNR distribution indexes which causes it will have good image resolution in intravascular imaging.

Table 2 illustrates the new probe FOV is extended three times than transmission line and decreased 20% relations to loop probe ones. So, because of circular symmetry in SNR curves, the 0.63 cm^2 FOV area is enough for the arterial imaging and this degradation is not important.

Table 3 shows the SNR maximum magnitude for the new probe has been increased 2.4 times than transmission line probe and decreased to 0.5 relations to loop probe.

The other important occurrence in SNR distribution is radial slope decreasing for the introduced probe than other probes. So, the deduction of new probe SNR slope are 23% and 12% relation to loop and transmission line probes respectively. The SNR slope decreasing is important in ghost noise reduction from arterial in vivio images.

The slope of SNR in longitudinal direction is a criterion of SNR homogeneity and probe FOV. Figure 4b shows that the SNR curve is flat for the new and loop probes but decreases linearly for the transmission line probe. So that the ratio of SNR slopes of new probe to transmission line probe is 2.4.

Conclusion

We described a new quadrate loop probe and simulate the SNR distribution of probe in radial and longitudinal directions. We have shown the SNR distribution indexes for the new probe are compromised in optimum values.

We believe that this probe has optimal parameters and by using it in intravascular imaging, the images contrast will be increased and then the vessel wall and plaque structures analysis will be carried out preciously.

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