Thick Film YBCO Receive Coils for Very Low Field MRI

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Abstract—Superconducting receive coils can be used to improve the signal to noise ratio of a MRI system. The greatest improvement is seen in cases where it is the coil noise dominates the noise. This is the case for low field MRI where surface coils are used. The properties of large area (100 mm square) YBCO thick film coils designed for a compact very low field MRI system are reported. The properties are compared with copper and silver mimics.

I. INTRODUCTION

Magnetic Resonance Imaging (MRI) is one of the most powerful imaging techniques available to modern medicine. Conventional MRI systems require high magnetic fields to generate a sufficient signal to noise ratio (SNR) to be able to create images in a reasonable time. High field MRI systems require superconducting magnets which lead to the systems being expensive in terms of capital cost, running costs and space requirements.

If the use of expensive high field magnets is to be avoided it is necessary to increase the available SNR at lower fields. Since the use of a lower field means a lower signal, the SNR must be recovered by having a lower noise level. It has been shown that high T_c superconductor receive coils can improve SNR [1-4] if the coil noise dominates the system. This is true in the case of surface coils used in low field systems. This paper describes results in the development of a very low field MRI system.

II. BACKGROUND

There are two main sources of noise that affect the signal, body noise which is due to losses in the patient's tissue and coil noise which is due to the resistance of the coil. The SNR can be expressed in terms of the noise resistances as [5]

$$SNR \propto \frac{1}{\sqrt{R_{coil}T_{coil} + R_{body}T_{body}}} \quad (1)$$

where R_{coil} is the coil resistance, T_{coil} , R_{body} is the effective

body resistance and T_{body} is the temperature of the body. For a N turn surface coil of radius a the body resistance is given by [6]

$$R_{body} = \frac{0.033(\mu_0 \pi N \omega_0)^2 a^3}{\rho_{body}} \quad (2)$$

where ω_0 is the Lamour frequency and ρ_{body} is the electrical resistivity of the body. The Lamour frequency is given by

$$\omega_0 = \gamma B_0 \quad (3)$$

where B_0 is the applied magnetic field and γ is the gyromagnetic ratio, which for hydrogen is $26.8 \times 10^7 \text{ T}^{-1}$.

In high field systems the noise is dominated by the body noise. At low fields and using a surface coil, i.e. a is small, the body noise is reduced. Thus the SNR is dominated by the coil noise. Since the coil noise dominates in these systems the SNR can be improved by reducing the noise due to the coil by reducing its temperature or resistance. The resistance of a superconductor is much lower than that of a metal at the frequencies used in MRI. It is not, however, zero because of a.c. loss mechanisms. The fact that superconductors require low temperatures to operate also improves the SNR. It is important to note that cooling a conventional metal coil will also improve the SNR. As a result it is important to compare the results of superconducting coils with cooled metal coils rather than just with conventional room temperature coils.

This paper discussed results that form part of a project to develop a compact, low cost MRI system that will operate at a very low field (0.01 T). These investigations are centred around proving the subsystem design in a conventional low field system before moving to lower fields. The results described here are for thick film YBCO coils operating at 77 K in a conventional 0.15 T MRI system. YBCO thick films have the advantage over thin films in that they are lower cost and they are easier to produce in the large areas that are required for the MRI coils. Large areas are required because the field of view is dependent on the size of the receive coil. Comparisons are made with copper and silver coils of the same design.

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TABLE I
Q OF COILS TUNED TO 6.1 MHz

Coil	Q at Room Temp	Q at 77 K
Copper	108	437
Silver	65	244
YBCO	NA	3338

III. COIL PROCESSING

A. YBCO Thick Films

The production of $\text{YBa}_2\text{Cu}_3\text{O}_7$ thick films is discussed in detail elsewhere [7]. In brief, a YBCO powder is made by mixing BaCO_3 , CuO and Y_2O_3 powders together, heating them to about 900°C and then grinding to form a fine powder. The powder is mixed with solvents and polymers for form a thick ink. The ink is deposited on to both sides of a 100 mm square 1 mm thick 3 mol% yttria stabilised zirconia substrate by doctor blading. The coated substrates are then sintered in oxygen at around 1050°C . After firing the thick film is masked and one side is patterned in to a 4 turn coil. The other side of the substrate, with the aid of a superconducting via through the substrate, allows the contact pads for the two ends of the coil to be in close proximity at the edge of the substrate. Silver pads are applied to the contacts by firing on a silver paste. Coils with a higher number of turns were produced but are not suitable for use at 6.1 MHz as their self resonant frequencies were below 6.1 MHz. This was due to the high self capacitance caused in part by the high dielectric constant of the substrate material.

B. Metal coils

Copper coils of the same geometry as the superconducting coil were produced by etching copper coated fibreboard. Silver coils were produced by screen printing a silver ink onto a 100 mm square 1 mm thick alumina substrate and firing at about 800°C .

IV. MEASUREMENTS

All the coils were tuned to a resonant frequency of 6.1 MHz and matched to $50\ \Omega$ using a combination of fixed ceramic chip capacitors and variable PTFE capacitors. Low

Fig. 1. Signal to noise ratio for copper, silver and superconducting coils as function of distance from the coil

temperature measurement were made in liquid nitrogen in a polystyrene vessel. The coil was close to the top of the vessel (0 to 1 cm from the lid). The lid of the vessel was 1 cm thick and provided adequate insulation for the patient.

C. Q Measurements

The Q of the coils was measured using a HP4194A Impedance/Gain-Phase Analyser in Gain-Phase mode. The coil was excited by a single turn loop and a second loop measured the coil's response. The loops were weakly coupled to the coil. The results are shown in Table II.

D. SNR Measurements

SNR measurements were carried out in a SMIS IMIG 0.15 T whole body MR imager. The coils were connected to the imager in the same manner as a commercial surface coil. SNR measurements were carried out by taking images of a cylindrical phantom of a solution of 150 mM NaCl with 1 mM CuSO_4 in water. The images were acquired using a spin echo sequence with the parameters given in Table II. The SNR results as a function distance from the coil are shown in Fig. 1.

V. WRIST IMAGES

MR images of a human wrist were taken using some of the coils with the imaging parameters given in Table II. A quick

TABLE II
IMAGING PARAMETERS

Image	Sequence	Size (pixels)	Acquisition BW (kHz)	Averages	Slice thickness (mm)	Repetition Time (ms)	Echo Time (ms)	Acquisition Time (s)
Phantom	Spin Echo	128×128	10	1	7	700	22	90
Scout Scan	Gradient Echo	256×256	20	1	10	105	12	17
Wrist	Spin Echo	256×256	20	2	4	570	22	450

Fig. 2. MRI images taken using a) a room temperature copper coil, b) a 77 K silver coil, c) a 77 K YBCO coil. D) is a scout scan using the YBCO coil at 77 K

gradient echo image was acquired, also called a scout scan, to determine the position of the wrist in the imager and thus to define the region of interest and orientation for the full wrist images. Fig. 2. shows coronal wrist images through the same slice using a) a copper coil at room temperature, b) a silver coil at 77 K and c) a YBCO coil at 77 K. Also show (Fig. 2d) is a scout scan for the YBCO coil. It is interesting to note the quality of the scout scan considering its acquisition time was only 17 s compared with 450 s for the full images. Images of this quality were not expected with the scout scan and it suggests that to optimise the system it will be necessary to choose a different imaging sequence than would be used for conventional coils. It is clear from the images in Fig. 2 that the image obtained using the superconducting coil is clearer and has less noise than the others. It also shows that the image quality is maintained over a larger area.

VI. CONCLUSION

Thick film YBCO MRI receive coils have been manufactured and tested in a 0.15 T system. The SNR and thus image quality achieved is superior that of cooled silver and copper. The SNR of the superconducting coil is about a factor of 3 greater than that of silver cooled to 77 K. The fast gradient echo scout image was of surprisingly good quality suggesting that work is required to determine the optimum image sequence for superconducting coils.

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