QUADRATURE LOWPASS BIRDCAGE COIL FOR LOW FIELD OPEN MRI SCANNER

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Abstract: The main goal of this research was to demonstrate the utility of using a quadrature birdcage coil in lowpass version for magnetic resonance imaging (MRI) in open scanner at very low static field. When used in horizontal bore MRI systems, the birdcage coil is able to produce circular polarized field using quadrature excitation, thus reaching SNR improvement of $\sqrt{2}$ as maximum value. The birdcage coil in high-pass version can be employed even in a vertical bore MRI scanner, by combining the sinusoidal and the end-ring resonant modes.

In this paper we investigated the lowpass birdcage coil configuration to operate with a vertical bore MRI system, producing two B_1 fields components perpendicular to the vertical B_0 field.

Its implementation is convenient because it requires one half capacitors with respect to the high-pass design. Moreover, at low field the high near-electric field losses, that represent the main disadvantage of the low pass design, can be neglected.

Experiments performed on a quadrature birdcage coil prototype mounted on an open MRI scanner, showed that both SNR and homogeneity degree increase with respect to the linear birdcage.

Introduction

In 1985 Hayes et al. described the first application of the birdcage coils in magnetic resonance imaging (MRI) systems, evidentiating its capacity to generate wide field of view (FOV) with elevate radio frequency (RF) magnetic field homogeneity and high signal to noise ratio (SNR) [1]. Since then, birdcage coils are extensively used in transmit/receive mode in horizontal bore MRI systems (solenoidal magnets), operating in quadrature mode to produce a circularly polarized magnetic field, reaching a SNR improvement of a maximum value of $\sqrt{2}$. However, in vertical B_0 MRI systems (open magnets), the quadrature birdcage coil performance obtained with solenoidal magnets fails because one of the B_1 components is parallel to the B_0 direction. Fujita [2] demonstrated the ability of a quadrature highpass birdcage coil to generate a uniform B_1 field perpendicular to the birdcage coil axis using the sinusoidal mode and a uniform B_1 field parallel to the birdcage coil axis using the end-ring mode, i.e. Helmholtz pair. However, the transverse B_1 field homogeneity of the birdcage depends on the number of legs: more legs there are, more homogeneous the B_1 distribution will be inside the sample volume. But a high number of legs means a high number of capacitors that causes a lowering of the quality factor and a cost increase of the coil.

The lowpass version of birdcage coil has the advantage of using a number of needed capacitors that is halved, each one with smaller values of capacitances compared with the highpass design. Moreover, at low field the high near-electric field losses that represent the main disadvantage of the lowpass design can be neglected [3]. But in the lowpass configuration the end-ring mode is coincident with the zero frequency mode, that cannot be employed in MRI. In this study we will support the hypothesis that a quadrature low-pass birdcage coil can operate in a vertical MRI system, by exploiting the particular current pattern in the birdcage conductor.

In fact, we designed a quadrature birdcage coil prototype, tuned at 7.66 MHz. The prototype was mounted in a low magnetic field imaging open scanner (0.18T) to test the field homogeneity degree and the images quality factor when compared to the same birdcage coil operating in linear sinusoidal resonant mode.

Materials and Methods

Basic design characteristics of lowpass birdcage coil consist of two end rings connected by N parallel legs with capacitors inserted in the legs. These coils resonate in $N/2$ modes. The end ring resonant mode has a resonant frequency of zero, which corresponds to a direct current (DC), and the second lowest resonant frequencies of the birdcage coil (sinusoidal mode) is capable of producing a highly homogeneous magnetic field, useful for MRI applications. From birdcage theory [4], we know that the geometry of the lowpass version, for the dominant mode, provides a sine function distribution in the end-rings currents and a cosine function distribution in the legs currents. This is the basic theory we used for demonstrating the possibility of designing a quadrature birdcage coil in lowpass version. In fact, we employed the birdcage as a receiver coil in a vertical MRI system, with a rectangular pick-up coil coupled to a single mesh of the birdcage and lied in the plane parallel to the direction of the B_0 field; we developed it to detect the dominant mode. According the previous theory, we "cut" the end-rings conductors located at 90° respect to the position of the pick-up coil without perturbing the current pattern of birdcage sinusoidal mode, because in these points there are no currents in the conductors. Then, adding a capacitor on each end-ring, we created two resonant loops (hereafter referred to as "end-ring coil"), where the currents produce a B_1 field along the longitudinal axis of the coil (B_{1ER}), perpendicular to the radial one corresponding to the sinusoidal mode ($B_{1\sin}$) and perpendicular to B_0 field, providing a quadrature detection (Figure 1). In a such way, we can consider the birdcage and the end-ring coil as two perfectly isolated coils.

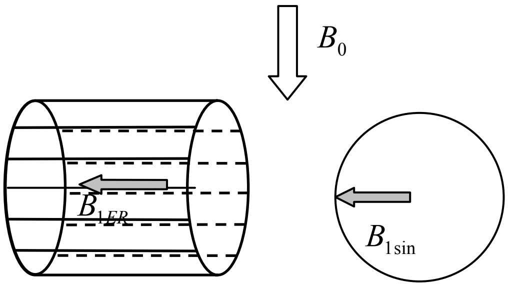

Figure 1: The spatial orientation of the magnetic fields in our birdcage coil

In general, the length and diameter of the birdcage determine its sensitive volume and have to be adapted to the sample volume to be imaged.

Choosing the diameter and the length of the birdcage in order to satisfy the Helmholtz condition (the radius of the loops equal to the distance between the two loops), the end-ring coil behaves like a Helmholtz pair. This produces a highly uniform B_1 field along the axis of the coil. However, a maximum sensitivity of the birdcage coil is achieved in the middle plane if the ratio between length and diameter is 0.7, although it brings to a field homogeneity decrease in axial direction [5]. Moreover, using a birdcage coils simulator previously developed by authors [6], we noted that the field homogeneity of the sinusoidal resonant mode in the central transverse plane of the coil increases while the coil length becomes higher. So, various dimensions choices of the quadrature lowpass birdcage permit to find a suitable compromise between the desired properties, in terms of sensitivity and optimized B_1 uniformity along the coil axes.

We emploied a previously described [7] lowpass birdcage coil of 11 cm height and 14 cm diameter, using a cylindrical rod conductor of 4.5 mm diameter and 2nF high quality capacitors (Q > 10.000 at 1 MHz), obtained with two 1nF capacitors in parallel configuration (ATC100B-American Technical Ceramics, USA). The coil resonates at 7.66 MHz that corresponds to 0.18 T static magnetic field for proton imaging.

A pick-up rectangular (w=6 cm, h=11 cm) coil was coupled to a single mesh of the birdcage coil for detecting the B_1 field produced by the sine resonant mode. According the preceding theory, we cut the end-rings conductors located at 90° respect to the position of the pick-up coil without perturbing the current pattern of the birdcage dominant mode. Then, we calculated the capacity value (1360pF) necessary to insert in each cut end-rings to tune the resonant frequency of the two mutually coupled loops at 7.66MHz.

For the experiments with MRI scanner, the coil has been used as a receive-only coil. The signals emitted by the coils have to be transferred to the preamplifiers while preserving the SNR of the NMR experiment in the coils. The pick-up coil takes the RF signal corresponding to the B_1 field produced by the sine resonant mode to an ultra low noise preamplifier (CLC5509 National Semiconductor), while for extracting the end-ring coil mode, we used a direct coupling and a differential amplifier using two ultra low noise operational amplifiers (CLC425 National Semiconductor).

Results

The birdcage has been used in quadrature mode as receiver coil in a vertical B_0 MRI system produced by Esaote Biomedica (E-Scan 0.18T, open MRI dedicated to musculoskeletal limbs studies).

The fine-tuning of the coil within the MRI system was performed by moving a concentric RF shield (copper foil tape fixed around a PVC former, diameter 20cm, length 20cm) about the longitudinal axis of the coil [8], changing the mutual inductance between the coil and the shield and providing a mechanism for adjusting the resonant frequency without the physical constraints of adjustable tuning capacitors in the coil placed in the narrow gantry of the scanner.

To measure SNR and field homogeneity, we used a homogeneous phantom of saline solution that simulates the ankle conductivity (a 7cm diameter bottle constituted of 55mM of NaCl and 5mM of $NiCl_2$).

We acquired T_1-weighted Spin-Echo imaging sequence with parameters: TE=18msec, TR=500msec, slice thickness=10mm, FOV=18x14cm, number of signal averages=1, pixel dimension=0.7 mm. The results obtained with the quadrature coil were compared with those obtained using only the sinusoidal mode of the birdcage.

The SNR was measured on both image series as follows: firstly a rectangular window was defined inside the phantom and the mean value of the relevant pixels was evaluated; then, the same window was positioned on the image background and the relevant pixels standard deviation was evaluated. Finally, the ratio between the mean value and the standard deviation was calculated to obtain the SNR. The SNR was measured in the central transverse planes perpendicular to the coil axis and in the longitudinal planes parallel to the coil axis. RF field homogeneity was measured along the three principal axes of the coil.

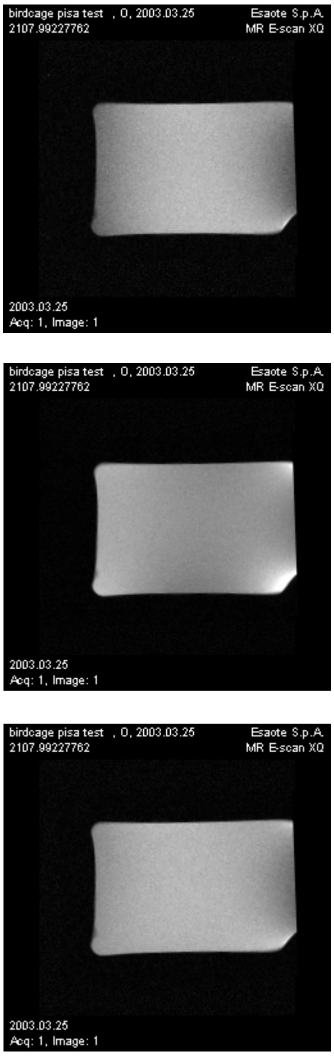

Figure 2: Homogeneous knee phantom images in the longitudinal plane of the sinusoidal, end-ring and quadrature mode, top to bottom

We found that field homogeneity in the central trasverse plane for the linear and quadrature coils is almost the same.

The image homogeneity along the z profile was defined evaluating the length of the region where the root mean square deviation respect to the intensity value in the profile centre is less than 10 %. Figure 2 shows the homogeneous knee phantom images in the longitudinal plane of the coil.

Table 1 shows the values of SNR and homogeneity degree for the coil. As may be seen from this table, it may be concluded that the images obtained by using the quadrature coil are more uniform and with higher SNR respect to the linear coil.

Coil type	SNR transverse plane	SNR longitudinal plane	z axis homogeneity (cm)
sinusoidal mode	45	44	7.4
end-ring mode	45	45	5.2
quadrature mode	53	54	10.0

Table 1 : Test results for the values of SNR and homogeneity degree for the coil

Conclusions

We have demonstrated the possibility to use successfully a lowpass birdcage coil in quadrature mode for a vertical Bo MRI system, exploiting the current pattern in the coil conductors. This quadrature coil was compared with the same birdcage coil in linear mode, using only the sinusoidal one, in a MRI open scanner. The results showed that quadrature coil provides better field homogeneity along longitudinal plane, with an increase of 35% respect to the linear coil, and a higher SNR, with a 18% and 23% increases for transverse and longitudinal planes respect to the same linear coil.

The results seem to be very promising and further steps of this work will have to concern coil dimensions choice to find a suitable compromise between the desired properties of the coil, in terms of sensitivity and optimized B_1 uniformity along the coil axis.

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