

Design and use of a folded four-ring double-tuned birdcage coil for rat brain sodium imaging at 9.4 T

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ARTICLE INFO

Article history:

Received 8 August 2017

Revised 20 November 2017

Accepted 4 December 2017

Available online 6 December 2017

Keywords:

Dual-tuned

Birdcage

²³Na

X-nuclei

Rat brain

Coil

ABSTRACT

A folded four-ring quadrature birdcage coil was designed and constructed with a double-tune configuration of an outer high-pass coil for ¹H (400 MHz) and inner low-pass coil for ²³Na (105.72 MHz at 9.4 T). The coil was evaluated on the bench and in the scanner, comparing its performance with that of single-tuned coils and a large four-ring coil. All coils were tuned and matched and the isolation between two quadrature ports was found to be better than −13.7 dB for ¹H and −27 dB for ²³Na. Signal-to-noise ratios (SNRs) were calculated and ²³Na flip angle maps were acquired. ²³Na SNR of the folded four-ring reached ~93% of that obtained with the single-tuned coil. A set of *in vivo* ¹H and ²³Na axial images to cover the whole rat brain were obtained. The performance of the folded four-ring coil and its benefit for ²³Na imaging experiments have been demonstrated. This proposed four-ring coil could avoid length restrictions, e.g. the shoulders, by folding the outer rings vertically. This facilitates the construction of double-tuned four-ring birdcage coils just to fit the head, leading to higher filling factors and better SNR.

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1. Introduction

Studies using non-proton (X-nuclei) MRI have been of great interest over recent years due, in part, to the increasing availability of ultra-high field MRI [1,2]. The second most abundant NMR-active element in living organisms after hydrogen is ²³Na [3]. Sodium participates in the vitally important sodium-potassium exchange across cell membranes and characterises cell metabolism. Tissue sodium concentration can provide substantial information on a number of pathologies [4,5]. Due to their lower natural abundance and lower MR sensitivity compared to that of the proton, imaging ²³Na and other X-nuclei is challenging, although its shorter T₁, approximately 39 ms at 9.4 T in an *in vivo* normal rat brain [6], allows averaging multiple acquisitions. B₀ shimming with ²³Na is also problematic due to its low signal, therefore the concurrent acquisition of proton imaging is advantageous. Double-resonant RF coils are often used to cope with this requirement, but designing a well-performing, double-tuned coil is in general a very challenging task. Conventionally, a double-tuned coil can be designed in various ways, for example, modifying

a birdcage using alternate rungs, four-ring, traps or PIN-diodes [7–11] or combining geometrically isolated double-tuned surface coils [12,13].

Among them, the four-ring birdcage coil design is preferred since it does not contain additional lossy components, such as trap circuits [9] or PIN-diode switches [11], which lead to decrease of power efficiency and degradation of image quality. This four-ring approach, adding two additional end-rings on a conventional birdcage coil employs tuning at one resonance frequency using the inner end-ring structure and at the other frequency using the outer structure [8]. Several configurations of the four-ring birdcage can be used, such as low-pass for both inner and outer, or low-pass for inner and high-pass for outer [14]. The inner part tends to be set at the X-nuclei and with a low-pass configuration [15]. Thus, this four-ring coil resonates at two frequencies, and efficiency and sensitivity are maintained at both frequencies with ~5% loss at 1.5 T [8]. However, it requires an optimised inner and outer rung length ratio, which normally causes a substantial increase in overall coil length [8]. This requirement of additional length for the outer end-rings restricts the accessible space, which can be problematic, particularly for *in vivo* human and/or animal brain studies. There were several attempts to simplify the outer birdcage using different structures such as an Alderman–Grant coil [16] or a split birdcage [17].

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In this work, we designed a double-tuned four-ring birdcage coil with a modification that entailed folding the outer end-rings by 90° to remove the length restriction issue. We evaluated the performance of this design compared with single-tuned coils and a double-tuned larger four-ring birdcage coil on a phantom and in an *in vivo* healthy rat brain at 9.4 T.

2. Methods

A folded four-ring quadrature birdcage coil was designed and constructed with a double-tuned configuration as shown in Fig. 1 (a); an outer high-pass coil for ^1H (400 MHz) and an inner low-pass coil for ^{23}Na (105.72 MHz) corresponding to the respective Larmor frequencies at 9.4 T. The RF coils with inner/outer rings were tuned respectively using 47/12 pF non-magnetic fixed capacitors ($C_{\text{Na}}/C_{\text{H}}$, 100B, American Technical Ceramics, USA) and fine adjustment of their frequencies and of 50 Ω matching condition was carried out using 1–10 pF trimmers (NMAP10HVE, Voltronics, USA). In each channel, both ^1H and ^{23}Na cable traps were inserted, which were built using a capacitor (3 pF for ^1H and 50.9 pF for ^{23}Na) attached to the shield across a 5-turn inductor wound from the coaxial cable. As reference coils, geometrically identical single-tuned birdcage coils (Fig. 1b) tuned to each nucleus (^1H and ^{23}Na) and a large (allowing it to fit the shoulders) four-ring birdcage coil (Fig. 1c) were constructed for comparison. All the coils were driven in quadrature. The transmit/receive (T/R) RF chain included home-built quadrature hybrids, T/R switches and commercial low noise pre-amplifiers (WanTcom Inc., USA) for ^{23}Na frequency.

A uniform phantom (100 mm length and 28 mm diameter) containing 45 mM NaCl solution in deionised water was prepared in order to determine the coil condition and for the signal-to-noise ratio (SNR) comparison of the MR images. The response and quality factors (Q_{Un} , Q_{L} and Q_{Ratio}) of the coils was measured on the bench using a network analyser (ZNB, Rohde & Schwarz, Germany) and analysing S-parameters under loaded conditions and when connected directly to the coils.

All the MRI experiments were carried out on a home-integrated 9.4 T small animal scanner [2,18] based around a modified Siemens TRIO console (Siemens Healthineers, Erlangen, Germany). Using the ^1H configuration, the static magnetic field was shimmed and standard calibrations were performed. Anatomical and structural images were also obtained. All the imaging parameters used in this study are described in Table 1.

In order to acquire flip angle maps of the ^{23}Na coils, a double angle method [19] was used and B_1 homogeneities of all ^{23}Na coils were compared. For this purpose a 3D FLASH ^{23}Na sequence was utilised with two flip angles, 60° and 120°. Relative uniformity (RU, %) was then calculated using Eq. (1) by dividing the number of pixels within the phantom area whose relative deviation is smaller than $\pm 10\%$ of the mean B_1 field through the overall number of pixels [20,21]:

$$RU = \frac{\text{Number of pixels with } \left(\left| \frac{B_1 - \bar{B}_1}{\bar{B}_1} \right| \times 100 < 10 \right)}{\text{Total number of pixels}} \times 100 \quad (1)$$

The SNR of the proposed coil was also compared with that of the reference coils under the same conditions. Noise images with zero transmit power ($P_{\text{Tx}} = 0$ W) were additionally obtained. The SNR values were calculated using the NEMA method [22]; signal mean of the selected ROI from the magnitude image divided by noise standard deviation from the noise image of the identical ROI chosen for the magnitude image.

In vivo ^1H and ^{23}Na MR images were then obtained with the folded four-ring birdcage coil using female Wistar rats. All animal experiments were approved by the Animal Protection Committee of the local government according to the German Protection of Animals Act. The rats (~346 g) were housed under standard housing conditions in the animal facility. Rats were anaesthetised with 2–5% isoflurane in oxygen, and during the measurement breathing rate and body temperature were continuously controlled. The acquired MR data were processed and analysed using Python (Python Software Foundation) and Osirix (Pixmeo, Switzerland).

3. Results

It was found that all coils were tuned and matched well to 105.72 MHz (^{23}Na) and 400 MHz (^1H) as return losses of each channel of the coils were less than -22 dB and the isolation between two quadrature ports were better than -13.7 dB for ^1H and -27 dB for ^{23}Na .

Fig. 2 shows the ^1H scout images obtained with the test phantom and the *in vivo* rat viewed in three orthogonal (Coronal, Sagittal and Axial) planes.

Fig. 3 shows the uniform phantom ^1H (left column) and ^{23}Na (middle column) images obtained using folded four-ring (top row), single-tuned (middle row) and large four-ring (bottom

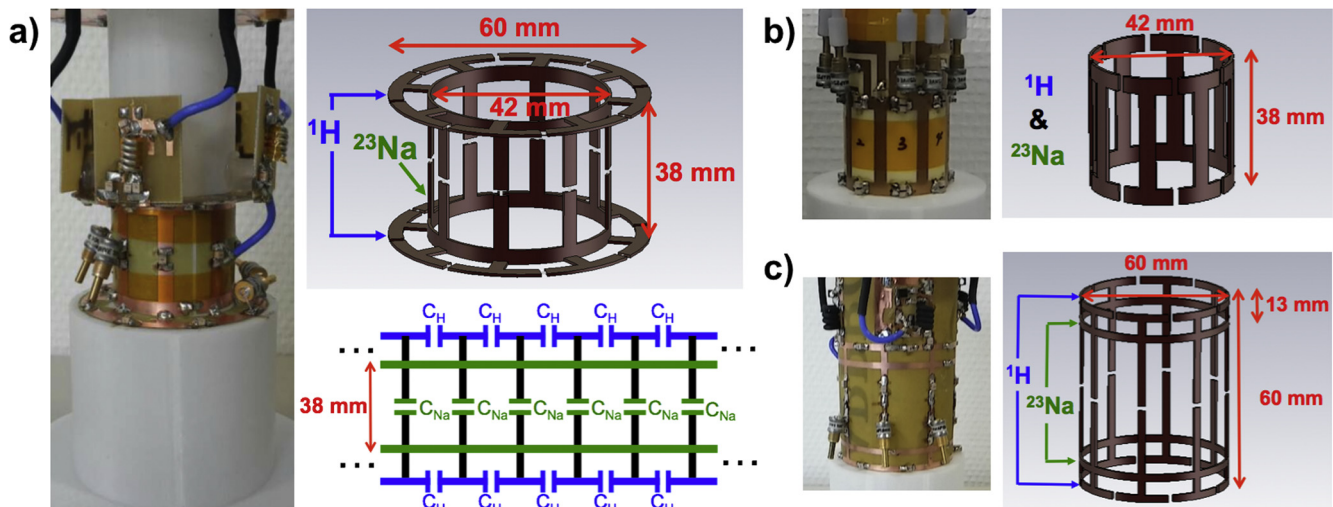


Fig. 1. Photographs, dimensions and schematic diagram of (a) the proposed 90° folded four-ring double-tuned birdcage coil, (b) the single-tuned ^1H and ^{23}Na birdcage coil, (c) the large four-ring birdcage coil.

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