Magnetic resonance imaging with a multi-tunable metamaterial-inspired radiofrequency coil

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Abstract. We present the initial experimental results obtained using a two-part receive/transmit (Rx/Tx) radiofrequency (RF) coil design for small animals magnetic resonance imaging at 7 T. The assembly uses a butterfly-type coil tuned to 300 MHz for scanning the \textsuperscript{1}H nuclei and a non-resonant antenna with a metamaterial-inspired resonator tunable over wide frequency range for X-nuclei. \textsuperscript{1}H, \textsuperscript{31}P, \textsuperscript{23}Na and \textsuperscript{13}C are selected as test nuclei in this work. Coil simulations show the two parts of the RF-assembly to be efficiently operating at the required frequencies. Simulations and phantom imaging show sufficiently homogeneous transverse transmit RF fields and tuning capabilities for the pilot heteronuclear experiments.

1. Introduction
Small-animal MRI is a powerful noninvasive tool for preclinical research. It provides critical information on disorders or novel substances by studying in detail the physiological changes in various organs of the animal. Such research benefits from image quality improvement and scanning methods diversity expansion, although the two often lead to one another. This, in turn, results in the preclinical small-animal imaging being predominantly performed in high and ultra-high magnetic fields.

On the other hand, the common trend of increasing the static magnetic field \cite{1} in MRI and the associated sensitivity growth has recently led to the possibility of routinely obtaining \textit{in-vivo} non-hydrogen nuclei images without isotope enrichment. Nevertheless, imaging more than one non-hydrogen nucleus, while obtaining reference \textsuperscript{1}H images requires a multi-tunable coil design \cite{2, 3, 4}. A principle of such operation using a metamaterial-inspired design has recently been demonstrated \cite{5} along with the comparison of metamaterial-based device performance to some classical radiofrequency (RF) coil solutions \cite{6}.

2. Methods
Here, a multi-tuned RF coil design previously suggested for 11.7 T imaging \cite{5} was adapted for 7 T imaging and experimentally tested. The design comprised two separate Rx/Tx elements placed on the opposite sides of the object to be imaged. The two parts corresponded to the butterfly-type RF coil for \textsuperscript{1}H imaging and a metamaterial-inspired multi-tunable coil for X-nucleus imaging (Fig. 1).

The \textsuperscript{1}H 40 \times 60 \text{mm}^2 copper butterfly coil was implemented on a PCB substrate with dimensions 65 \times 41 \times 1.5 \text{mm}^3 made from FR-4 material with \( \varepsilon = 4.3 \) and \( \tan \delta = 0.033 \) at...
Figure 1. A – $^1$H butterfly-type coil model with tuning/matching capacitors. B – X-nuclei tuneable coil model. Feeding of the X-nuclei coil is provided via inductive coupling to a small loop coil.

100 MHz (Fig. 1, A). Adaptation of the $^1$H-imaging part from the original design was performed by selecting the necessary capacitors (six SMD capacitors 8.2 and 33 pF, and two variable capacitors SGNMA3T10005 1–10 pF).

The metamaterial-inspired X-nuclei coil was assembled using 5 telescopic brass wires connected at their ends to metallized PCBs substrates made from Arlon AD1000 with $\varepsilon = 10$ and $\tan \delta = 0.002$ in the operating frequency range (70-300 MHz) with dimensions $71 \times 49 \times 0.5$ mm$^3$. The metallized part consisted of 5 patches with dimensions of $30 \times 10$ mm$^2$. The capacitive load was provided by overlapping the patches with two metalized Arlon PCB substrates with dimensions $34.5 \times 49 \times 0.5$ mm$^3$ (Fig. 1, B). This structure supported a number of different eigenmodes [7], with the lowest frequency eigenmode having been selected for X-nucleus imaging. The mode tuning was implemented similarly to the original design, i.e., by changing the length of the metal wires and the overlap of patches with small PCB boards [5]. The mode excitation was provided via a small nonresonant loop antenna.

The proposed two-coil design was simulated with the load comprising a simple homogeneous rectangular phantom ($\varepsilon = 59$, $\sigma = 0.79$ S/m) with dimensions $154 \times 44 \times 37$ mm$^3$. All electromagnetic simulations were performed in CST Studio Suite 2020 in frequency domain solver.

Next, the assembled coil S-parameters were bench-measured using vector network analyzer. For the $S_{11}$ parameter measurements the VNA was connected using single port which powered either the feeding loop coil of the metasurface-inspired part, or the butterfly coil.

In order to assess the RF-assembly imaging capabilities it was tested in a horizontal 300-mm-bore 7T scanner. The coil magnetic field distribution was measured and compared with the simulation results. Imaging was performed on a multi-nuclear phantom produced according to a 7 T muscle phantom recipe [8]. The experimental field maps were acquired after tuning the $^1$H coil part to the 300.8 MHz and the X-coil part to the 79.6 MHz for sodium imaging.

Imaging capabilities were assessed on a 3-section 3D-printed phantom with different solutions in each section for $^1$H and $^{23}$Na imaging. The solutions in 3 sections were variations of the 7T muscle phantom recipe above with NaH$_2$PO$_4$ being substituted in the 2$^{nd}$ and 3$^{rd}$ sections by 2:1 mixture of MnCl$_2$ and NaCl, and pure MnCl$_2$ respectively. $^1$H-imaging was done using a FLASH pulse sequence with $TE = 3$ ms, $TR = 150$ ms, 1 ms block excitation pulse, $100 \times 100$ mm$^2$ coronal plane FoV, a $100 \times 100$ matrix and a 2 mm-thick slice. $^{23}$Na-imaging was done using a FLASH pulse sequence with $TE = 3.28$ ms, $TR = 10.45$ ms, 0.45 ms block excitation pulse, $100 \times 100$ mm$^2$ coronal plane FoV, a $128 \times 128$ matrix, 8192 averages and a 40 mm-thick slice.

3. Results
The S-parameter spectra were obtained for the operating ranges of X-coil and H-coil in the ranges of 60-140 MHz and 250-350 MHz, respectively. The results showed the possibility of
Figure 2. S\textsubscript{11}-parameters of the coil assembly. A – \textsuperscript{1}H coil tuning (at 300.3 MHz) calculated in simulation and measured on-bench and after the coil was installed in the scanner. B – X-coil tuning, when tuned to the \textsuperscript{31}P resonant frequency (at 121.8 MHz). C - X-coil tuning, when tuned to the \textsuperscript{23}Na resonant frequency (at 79.7 MHz). D - X-coil tuning, when tuned to the \textsuperscript{13}C resonant frequency (at 75.7 MHz).

configuring a multiresonance coil for the reception and transmission on some of the the nuclei of interest frequencies (Fig. 2). For all spectra, the reflection coefficient at the work frequency was less than -10 dB. It confirms the possibility of tuning the metamaterial-inspired resonator to the Larmor frequencies of some nuclei of interest (\textsuperscript{31}P - 121.8 MHz (Fig. 2,B), \textsuperscript{23}Na - 79.7 MHz (Fig. 2,C) and \textsuperscript{13}C - 75.7 MHz (Fig. 2,D)).

Axial and coronal field profiles of the used coils (Fig. 3) demonstrated the simulated $|\mathbf{B}_1^+|_{\text{RMS}}$ and the $|\mathbf{B}_1^+|$ distribution maps measured in experiment to qualitatively match, confirming the correct practical design implementation.

The multi nuclear 3-section phantom images were successfully obtained by using \textsuperscript{1}H-coil and X-coil, tuned to the Larmor frequency of \textsuperscript{23}Na (Fig. 4).

4. Discussion
The RF-assembly assessment at 7 T has experimentally shown its possibility to be tuned to a number of frequencies corresponding to a set of biologically-relevant nuclei, including \textsuperscript{1}H, \textsuperscript{31}P, \textsuperscript{23}Na and \textsuperscript{13}C. Field mappings provide a confirmation of the ability of the coil to generate the desired imaging field of view in the coronal and axial planes.

Imaging data shows the possibility of heteronuclear imaging with the proposed coil design. Still, further protocol optimization is required for finding the optimal scanning conditions for the \textsuperscript{23}Na imaging.

5. Conclusion
The presented data confirms the possibility of heteronuclear imaging with the suggested double-coil assembly, which opens up a perspective of expanding the experimental capabilities of a small-imaging MR-scanner.
Figure 3. A-D – $^1$H-coil field maps. A – simulation, axial plane; B – measured, axial plane; C – simulation, coronal plane; D – measured, coronal plane. E-H – X-coil field maps at the $^{23}$Na resonant frequency. E – simulated, axial plane; F – measured, axial plane; G – simulated, coronal plane; H – measured, coronal plane. All fields are normalized to the same dynamic range.

Figure 4. A - $^1$H image of a 3-section phantom filled with uniformly with aqueous NaH$_2$PO$_4$ solution, B – $^{23}$Na image of a 3-section phantom. Section 1, “M” contains aqueous NaH$_2$PO$_4$, section 2, “R”, contains a solution of NaCl and MnCl$_2$. Section 3, “I”, is filled with the MnCl$_2$ solution.

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