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Design and implementation of a $^{1}H/^{31}P$ dual-tuned head coil at 7T

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Synopsis

Keywords: Hybrid & Novel Systems Technology, New Devices, dual-tuned, RF coil, high-field

Motivation: To develop an advanced RF coil that enables both ^{1}H structural and ^{31}P metabolic imaging at 7T, overcoming current limitations of separate coil systems.

Goal(s): Develop a novel $^{1}H/^{31}P$ dual-tuned RF coil to achieve homogeneous, extended coverage for ^{1}H imaging and high SNR for ^{31}P imaging at 7T.

Approach: Integrated a Tic-Tac-Toe RF coil design for ^{1}H transmission and a quadrature birdcage design for ^{31}P.

Results: The simulated results showed high B_1^+ uniformity and coverage and the implemented $^{1}H/^{31}P$ coil prototype enabled both ^{1}H and ^{31}P imaging, providing a feasible solution for structural and metabolic imaging within a single MRI session.

Impact: The dual-tuned RF coil enables advanced neuroimaging at 7T, providing detailed structural and metabolic imaging within a single session. By eliminating the need for repositioning or coil switching, this design enables more efficient imaging workflows and precise anatomical-metabolic alignment.

Introduction

With advancements in 7T MRI, there is a growing need for RF coils that support both proton (^{1}H) imaging and phosphorus (^{31}P) spectroscopy, enabling structural and metabolic studies of the human brain. However, existing $^{1}H/^{31}P$ coils often lack the ^{1}H signal-to-noise ratio (SNR) and homogeneity needed for reliable whole-brain imaging and necessitate coil switching, leading to multiple imaging sessions, longer scan times, and participant discomfort. To address these limitations, this study develops a dual-tuned $^{1}H/^{31}P$ RF coil for 7T, integrating two well-established designs: the Tic-Tac-Toe (TTT)[1-3] coil for ^{1}H imaging and the birdcage coil[4] for ^{31}P spectroscopy.

Methods

The $^{1}H/^{31}P$ dual-tuned coil combined a 60-channel ^{1}H Tic-Tac-Toe (TTT) transmit design and a 2-channel quadrature birdcage coil (Figure 1a-b). The birdcage coil, with an optimized octagonal shape, is fitted within the TTT structure, aligning its center with the human brain when positioned. The TTT shield extended straight from the octagonal structure, allowing the birdcage coil to be inserted within it. Additionally, a cut in the shield positioned in the top of the coil (Figure 1a) helped the birdcage generate a homogeneous ^{31}P B_1^+ field. We used our in-house Finite-Difference Time-Domain (FDTD) algorithm to simulate the electromagnetic behavior of the TTT coil at 297.2MHz and the birdcage coil at 120.3MHz (Figure 2), using detailed anatomical models from the Virtual Family[5] (Duke, 34-year-old male, and Ella, 26-year-old female). An in-house developed RF shimming tool[1,2,6] optimized the amplitudes and phases to improve B_1^+ field and SAR.

The coil frame was 3D printed using PEKK polymer, and TTT panels were printed with PAEK and shielded with a 17.5μm copper layer. The TTT panels were tuned to 297.2MHz and matched to 50Ω by inserting copper rods and fixed capacitors. The high-pass birdcage coil's end rings, made from 5mm wide and 0.13mm thick copper, included capacitors at their centers to tune the coil to 120.3MHz and match to 50Ω. Tuning was performed inside the copper shield to account for any changes in capacitor values that may occur during partial assembly. Additionally, a 9.56nH inductor and a 30pF capacitor were added at the end of the birdcage leg to decouple from the ^{1}H signal at 297.2MHz.

For initial testing, we implemented 30 channels of the TTT coil with circularly polarized excitation for

Figures

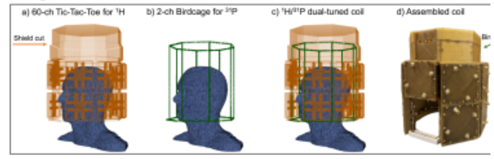

Fig 1. $^{1}H/^{31}P$ dual-tuned RF coil design. a) 60-channel Tic-Tac-Toe coil for ^{1}H; b) 2-channel quadrature birdcage coil for ^{31}P; c) $^{1}H/^{31}P$ dual-tuned coil integrating components (a) and (b); d) assembled $^{1}H/^{31}P$ RF coil.

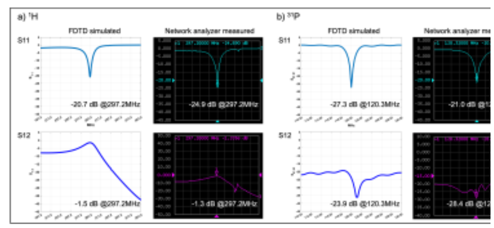

Fig 2. Simulated and measured S11 and S12 of the $^{1}H/^{31}P$ dual-tuned RF coil. FDTD simulated and network analyzer measured results at a) the ^{1}H resonant frequency at 7T (297.2MHz); b) the ^{31}P resonant frequency at 7T (120.3MHz).

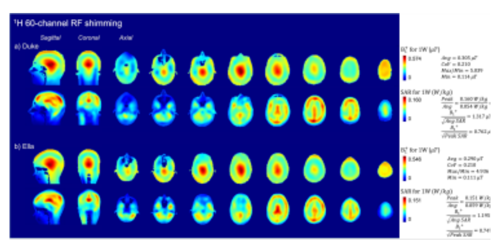

Fig 3. Simulated B_1^+ field and SAR for the 60-channel RF shimming of the $^{1}H/^{31}P$ dual-tuned coil

^{1}H transmission, along with the 2-channel quadrature excitation for the birdcage for ^{31}P, as a prototype. *In vivo* data were acquired using the following sequences: MPRAGE (TR/TE/TI=3000ms/1.8ms/1200ms, TA=3min, voxel size=1.25mm x 1.25mm x 1.25mm), and ^{31}P CSI FID (TR/TE=540ms/0.29ms, FA=90°, NA=1, TA=1min, FoV=340mm x 340mm x 340mm, matrix size=16 x 16 x 16).

Results

As shown in Figure 2, the FDTD simulated, and network analyzer measured s-parameters matched consistently at both the ^{1}H and ^{31}P resonant frequencies. Figure 3 shows the optimized B_1^+ field and SAR for the 60-channel ^{1}H transmit configuration at 297.2MHz using the Duke and Ella models, demonstrating satisfactory B_1^+ coverage extending to the cerebellum, with SAR levels within established limits. Figure 4 presents the B_1^+ field and SAR for the ^{31}P component at 120.3MHz, where achieving homogeneous B_1^+ coverage is less challenging due to the larger wavelength relative to the head size.

Figure 5 shows the experimental *in vivo* data acquired with ^{1}H 30-channel circularly polarized and ^{31}P 2-channel quadrature excitation coil prototype. It demonstrated the coil's capability for ^{1}H structural imaging and ^{31}P MRS.

Discussion and Conclusion

Simulation results showed satisfactory B_1^+ coverage for both ^{1}H and ^{31}P components, confirming the coil's capability for structural and metabolic imaging. Experimental data obtained from the dual-tuned prototype coil confirmed performance for both nuclei. While the current prototype implemented circularly polarized 30-channel transmit channels for ^{1}H, future work will focus on implementing optimized 60-channel RF shimming case and a 31-channel receive insert to improve SNR at ^{1}H.

Acknowledgements

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at the ^{1}H resonant frequency of 7T (297.2MHz):

a) Duke model (34-year-old male, 155 lbs); b) Ella model (26-year-old female, 126 lbs).

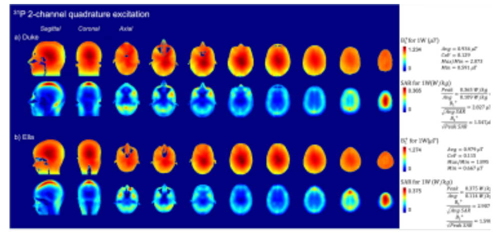

Fig 4. Simulated B_1^+ field and SAR for the 2-channel quadrature excitation of the $^{1}H/^{31}P$ dual-tuned RF coil at the ^{31}P resonant frequency of 7T (120.3MHz):

a) Duke model (34-year-old male, 155 lbs); b) Ella model (26-year-old female, 126 lbs).

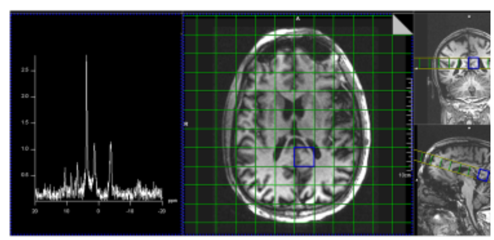

Fig 5. Experimental *in vivo* data acquired using the ^{1}H 30-channel circularly polarized and ^{31}P 2-channel quadrature excitation dual-tuned RF coil prototype. The ^{31}P spectrum, obtained from CSI FID (TR/TE=540ms/0.29ms,

FA=90°, NA=1, TA=1min, FoV=340mm x 340mm x 340mm, matrix size=16x16x16), is overlaid on MPRAGE (TR/TE/TI=3000ms/1.8ms/1200ms, TA=3min, voxel size=1.25mm x 1.25mm x 1.25mm).

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