Dedicated two-channel phased array receiver coils for HR-MRI of the rat knee cartilages at 7T

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Introduction

MRI is an excellent tool for examining the state of the articular cartilage and more generally, the tissues constituting the whole knee joint. Numerous studies previously described the assessment of small animal knee cartilage thickness and volume [1-3]. Many of these studies have limited spatial resolution and involve long scanning time due to the relatively low sensitivity of non-dedicated commercially available RF coils. Although phased array technology is now standard on clinical systems, high field experimental systems with multiple receiver channels capabilities only became available few years ago. Due to the large range of magnetic field strength and magnet bore diameters, very few array coils are available on the market (most of them dedicated to rat or mice brain). Therefore, the goal of this work was to design and built a dedicated two-channel phased array coil operating at 300 MHz (7T) based on a shared inductor decoupling method for high-resolution imaging of the rat knee joint for cartilage thickness and volume assessment. Additionally, the designed coil was duplicated and the two phased array coils were used simultaneously to image both knee joints of the same animal.

Material and Methods

Simulations of the phased array coil were made using Maxwell 2D/3D software (Ansoft Corp., Pittsburgh, USA) based on the finite element method. The simulations were performed using a sinusoidal excitation at 300 MHz to calculate the B_1 field, the inductance L, the resistance R of each element of the array coil and the mutual coupling M between the two elements. The two-channel array coil was built on a plastic cylinder with a 21 mm outer diameter. Each element consists in a rectangular loop (12 x 12.5 mm^2 internal and 18 x 20 mm^2 external dimensions). One conductor of this loop is common for the two elements. The S-parameters and the quality factor were measured with an ENA300 network analyzer (Agilent Technologies Inc., Santa Clara, CA, USA). The decoupling between the two channels was achieved using a fixed capacitor inserted in the common conductor. The value determined by simulation was experimentally adjusted to minimize the S_{21} transfer parameter between the two channels. Both channels were tuned at 300.3 MHz corresponding to the proton's resonance frequency at 7 T and matched to 50 Ω impedance line using non-magnetic case A series 100 and 710 ATC capacitors (American Technical Ceramics, New York, USA). The tuning/matching and active decoupling circuit was designed to be interfaced with the system decoupling box. The MRI experiments were performed on a 7T Biospec (Bruker, Ettlingen, Germany) equipped with 4-proton receiver channels. The designed phased array coil was compared to a Bruker 15 mm diameter surface coil. Experimental characterization (signal uniformity and SNR) was performed on cylindrical phantoms filled with salty water (NaCl 0.45%) mimicking load conditions. For *in vivo* experiments, the ethical guidelines for experimental investigations with animals were followed, and the experimental protocol was approved by the Animal Ethics Committee of our institution. Gaseous anesthesia was performed on adult rats placed in supine position. The 15 mm diameter surface coil was placed in contact with the medial side of knee joint and the designed array coil was placed on top of patella to encompass the whole knee joint. The HR-MRI of the rat knee joint was performed using a 3D Gradient-Echo Fast Imaging (GEFI) sequence with the following parameters: 25° flip angle, 50 ms TR, 3.4 ms TE, 42 kHz rbw. A total of 64 partitions (312 µm thick) were acquired with a FOV of 30 x 30 mm^2 and an acquisition matrix size of 512 x 384. Acquisition volume was reconstructed to a 512 x 512 x 128 matrix leading to a 156 µm partition thickness and an in-plane pixel of 59 x 59 μm^2. The scan time for the GEFI sequence was 45 min. The femoral and tibial plateaus (medial and lateral) articular cartilage volumes were extracted using an interactive touch-sensitive screen with a 1280 × 1024 pixel matrix. The user segmented the knee cartilage compartments directly on this screen using the supplied pen. The articular cartilage was segmented on each MRI slice. Each segmented area was then assigned to its corresponding cartilage compartment using gray-scale code labels leading to the three articular cartilage volumes. Additionally, a proof of concept was performed using two independent phased array coils (one for each knee joint). The phased array coils were decoupled using a 20 x 25 mm^2 copper sheet, placed at equal distance between the two array coils. Additional supply voltage sources were used for tuning and matching of the second array coil. Both legs were acquired within the same scan using a similar acquisition as for a single knee joint with the same pixel size but with a larger FOV in a coronal plane.

Results

The measured quality factor of the unloaded coil was about 130 for every single channel. The quality factor of the loaded coil decreased to 110. The decoupling capacitor value mounted on the circuit was about 56 pF corresponding to a simulated mutual inductance of 9.4 nH. The isolation between the two channels was 27 dB. The decoupling between the two array coils separated by a thin copper layer for multiple knee imaging was 28 dB. The SNR gain in the ROI for the two-channel array coil was up to 2.2 compared to the SNR obtained with the 15 mm diameter surface coil. The signal intensity was more uniform with a SNR standard deviation of 5 compared to 27 measured on images acquired with the surface coil. The 2.2 gain in SNR was used *in vivo* to decrease the voxel size from 59 x 59 x 156 μm^3 to 51 x 51 x 94 μm^3. Such acquisition was suitable to define the cartilage borders on each MRI slice leading to the three pre-defined articular cartilage volumes (Fig. 1). The images of both knees acquired simultaneous with the two array coils within the same scan time and with the same voxel size depicted good image quality with no significant SNR degradation, compared to the single phased array coil (Fig. 2). Using simultaneously a set of two array coils, the both rat knee joints were scanned without SNR degradation compared to single knee acquisition. Since the total scan time was kept constant, this results in a gain in SNR per knee joint of $2^{1/2}$.

Conclusion

The developed two-channel phased array coil improved the SNR as well as the signal uniformity within the knee joint compared to the commercial reference surface coil. Both parameters are mandatory to perform the segmentation process and to quantify cartilage morphology (thickness, volume). Due to limited size of small animal joints, cartilage assessment is very challenging but HR-MRI associated to phased array coils could be the non-invasive method to monitor disease progression and treatment response. HR-MRI of both joints performed simultaneously dramatically increase throughput. It would be extremely valuable when diseased or treated knees have to be compared to normal counterparts in the contra lateral joint.

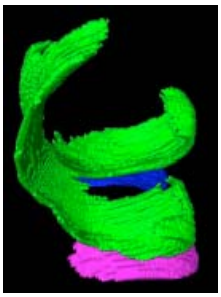

Fig. 1: A volume rendering of the femoro-tibial rat cartilages (green: femoral; pink: lateral tibial; blue: medial tibial) performed after the segmentation procedure. The volumes for the femoral, lateral tibial and medial tibial cartilages were respectively 8.5, 2.6 and 2.1 mm^3.

Fig. 2: Image acquired simultaneously using two similar two-channel array coils positioned on the right and left rat knees.

References

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