Magnetic Resonance Imaging at 7 Tesla with Dedicated Radiofrequency Coils
Application to Cervical Cord and Knee

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Abstract: Magnetic Resonance (MR) Imaging is a valuable tool in the diagnosis and monitoring of various musculoskeletal pathologies. New Ultra-High Field (UHF) 7 T MRI systems, with their enhanced Signal-to-Noise Ratio, may offer increased image quality in terms of spatial resolution and/or shorter scanning time compared to lower field systems. However, these benefits can be difficult to obtain because of increased radio-frequency (RF) inhomogeneity, increased Specific Absorption Rate (SAR) and the relative lack of specialized and commercially available RF coils compared to lower field systems. This study reports the feasibility of imaging in bones and cartilages at UHF with a 7 T MR scanner available at the IMAGO7 Foundation (Pisa, Italy). Dedicated radio-frequency coils for proton imaging have been designed, developed, optimized for different anatomical regions and validated *in vivo*, and are now ready for clinical research studies. The performance of the RF coil prototypes in targeting different anatomical regions are also demonstrated, obtaining images of the neck (the cervical cord) and of the knee (trabecular bone and cartilages).

1 INTRODUCTION

The current research in the field of Magnetic Resonance (MR) biomedical imaging (MRI) is moving towards increasingly higher static magnetic field strengths. Whereas 3 Tesla scanners are becoming widespread in clinical applications, scanners working at higher static magnetic fields are currently available only at a limited number of laboratories in the world, and only for research purposes.

There are about 60 MR systems for human studies operating at 7 Tesla or above worldwide, and they have already demonstrated the great capability and potential of Ultra-High Field (UHF) MR, and many technical challenges remain (Ugurbil, 2003; Kraff, 2015).

The IMAGO7 Foundation in Pisa (Italy) owns and manages the first and only 7 Tesla whole-body MR scanner (950-MR scanner, GE Medical Systems, Milwaukee, WI) in Italy. In this framework, a research collaboration between the IMAGO7 Foundation and the Italian National Institute for Nuclear Physics (INFN) aims to develop important hardware components, such as RF coils for specific MR applications, and to exploit the UHF

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potential in several research areas, including MSK imaging.

Among the clinical applications that will benefit from the improved resolution and signal-to-noise ratio (SNR) obtainable at high magnetic field is the muscoloskeletal (MSK) system. UHF MR imaging of the MSK system, including small joints, offers important potential advantages over lower field systems in increased sensitivity and enhanced contrast. However, these benefits can be difficult to obtain because of increased radio-frequency (RF) inhomogeneity, increased Specific Absorption Rate (SAR) and the relative lack of specialized and commercially available RF coils compared to lower field systems.

A number of *in-vivo* studies of the musculoskeletal (MSK) system at high field strengths have already been carried out (Majundar, 2008; Farooki, 2002; Gambarota, 2007; Regatte, 2007; Krug, 2009), including the investigation of the possibility to perform sequential studies during the clinical and instrumental follow up of neuromuscular disorders (Retico, 2015). The latter can be useful for a variety of applications: a) to allow an earlier diagnosis also in asymptomatic patients; b) to improve the monitoring of the progression of muscle involvement; c) to provide valuable information on the efficacy of ongoing therapeutic studies (drugs, gene or stem cell therapy), representing a possible alternative to serial muscle biopsies. Moreover, at UHF, for this application fat suppression should be used to reduce the chemical shift artifacts between fat and water frequencies.

This paper presents two RF coil prototypes suitable for 7T MSK applications targeting the geometry of different anatomical regions (neck and knee) based on quadrature Tx/Rx surface RF coil suitable for the detection of the proton signal and the first images acquired *in vivo* by means of these dedicated RF coil prototypes. In fact, dedicated neck coils are fundamental for studying the spinal cord in several pathologies of the central nervous system such as multiple sclerosis, or myelopathies of different origin. In particular the high resolution and SNR of the UHF can be exploited to investigate the gray matter and the fiber bundles within the spinal cord of patients with amyotrophic lateral sclerosis. Moreover, UHF MRI of the knee (Krug, 2009) can allow an accurate characterization of morphology and biochemical quality of the cartilages for clinical assessment of early pathological conditions of cartilage in osteoarthritis, and can allow the quantification of trabecular bone architecture useful for clinical assessment of osteoporosis.

This paper is organized as follows: first, the choice of the coil design is motivated according to the available MR system and the anatomical region under investigation; then, the choice of the hardware components and the coil construction details are provided; finally the results, consisting of the first *in vivo* images acquired on human subjects, are presented.

2 MATERIALS AND METHODS

2.1 Quadrature Tx/Rx Surface RF ^{1}H Coils for 7 T MRI

The availability of commercial RF coils for UHF MR systems is still limited. Therefore, UHF research sites often set up RF laboratories to develop suitable coils for specific applications.

The choice of the RF coil design depends on the target anatomy, on the desired MR acquisition modality (e.g. MRI, MR spectroscopy (MRS), multinuclear MRS, …) and it is constrained by the available MR system equipment.

This study focuses on the adult human neck (for the cervical cord applications) and knee (for trabecular bone and cartilage applications). Two coils have been designed, with geometrical optimization for accommodating an adult human neck and an adult human knee, respectively.

The MR system available at the IMAGO7 Foundation is a 7 T scanner currently equipped with two channels for transmission, which can be either both for proton (i.e. ^{1}H, I and Q channels) or one for proton and one for another nucleus (i.e. ^{1}H and MNS channel).

As a linearly polarized surface coil for proton MRI is expected to suffer transmit field inhomogeneity problems typical at UHF, in an attempt to obtain more informative structural images a specific coil design has been used. It consists of a quadrature surface coil, where the two channels are both used for proton.

For both the prototypes the coil housing is designed using the AutoCAD CAD package; the supports have to be designed according to the target anatomy, and has to be comfortable, easy to use and safe. To this purpose we left 10 mm between the inner surface (where the coil circuits will lie) and the outer layer (where the neck or the knee will be positioned). Concerning the choice of the materials, we used for the mechanical support a polycarbonate structure obtained by 3D printing.

The coil circuits consist of a printed circuit board (PCB) in FR4, board thickness 200 micron, copper thickness 35 micron. The circuits are covered by a protective paint to avoid oxidation.

The coils presented here are constituted of two partially overlapped loops driven in quadrature. The shape of the mechanical frame of the RF coil is a semi-cylindrical saddle of inner radius 70 mm and outer radius 85 mm.

The support of the neck coil presents a flat portion to best accommodate the neck lying on the coil in the supine position while the support of the knee coil presents a hemi-cylindrical geometry (Figure 1).

The RF circuit consists of two loops with dimensions 170 mm along the horizontal axis, 60 mm and 130 mm along the vertical axial for the central and peripheral part, respectively. The two loops are geometrically decoupled by a partial overlap of 18 mm (adjustable). Referring to Figure 2, the list of components used for assembling the coil is given in Table 1.

Figure 1: The quadrature Tx/Rx surface RF coil suitable for the detection of proton signal in the neck (left) and in the knee (right).

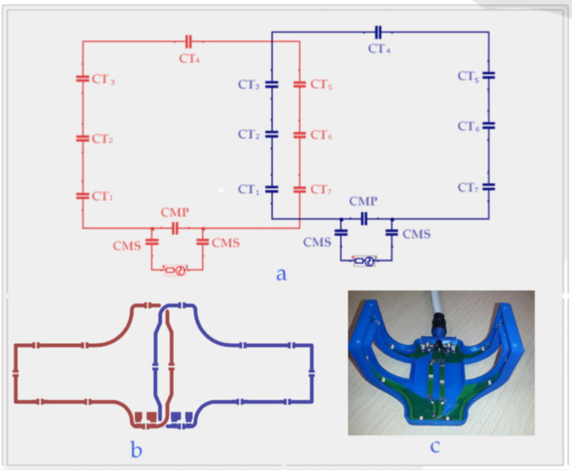

Figure 2: Circuit of the quadrature ¹H RF surface coil made by two square loops with partial overlapping.

Table 1: RF components of the single-tuned quadrature ¹H RF coil.

CT_1	6.8 pF
$CT_{2,5}$	5.1 pF
$CT_{3,4,6,7}$	4.2 pF
CMS	22 pF
CMP	1.0 pF

The tuning procedure of the ¹H loop is performed after measuring the inductance, which implies the following operation: 1) a known capacitor has been added to the loop; 2) the correspondent resonance frequency has been measured through a Vector Network Analyzer (VNA, E5071C, Agilent Technologies); the inductance is determined by analytical calculation. Next, the loop has been tuned to 298.03 MHz, i.e. the Larmor frequency of the ¹H at 7 T. Next, the coil has to be matched: matching can be achieved either with or without a load, i.e. in the unloaded/loaded condition. A capacitive matching with load is performed; the Q factor is calculated through appropriate VNA measurements, and the corresponding resistance is derived (Mispelter, 2006). The matching capacitor was determined by using a Smith Chart procedure (Smith, 1995). The workbench measurements provided the following values: matching < -17 dB on both channels, coupling < -15 dB. The Q factors are 120 and 20 for both channels, in loaded and unloaded conditions, respectively. The simulated B_1^+ and E maps obtained for unitary input power of 1 kW are shown in Figure 3, which demonstrates that quadrature operation of the 7 T surface coil improves B_1^+ field homogeneity with respect to a linearly polarized surface coil.

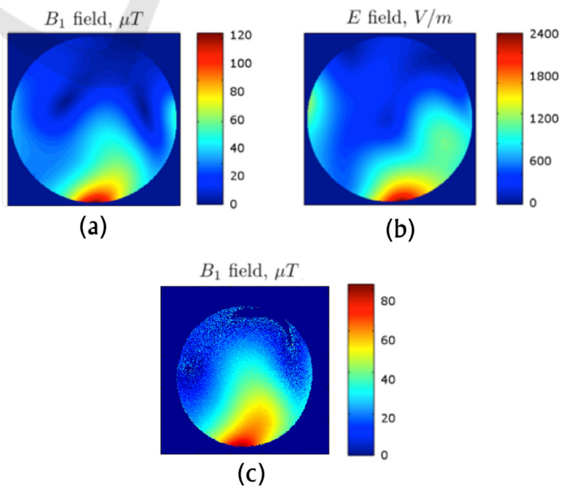

Figure 3: Simulated B_1^+ (a) and E (b) field maps of the quadrature ¹H RF surface coil for unitary input power of 1kW. Measured B_1^+ (c) for the same input power.

2.2 Human Image Acquisitions

Six healthy and one pathological (alteration of the patellar cartilage) volunteers were considered for the preliminary acquisitions reported here. Healthy volunteer age ranged between 24 to 61 years, the pathological volunteer was 62 years old. In our Institute clinical studies follow the ethical guidelines of our local ethics committee. Informed written parental consent was obtained before enrollment in the study. As expected, any side effect from muscle MRI examination has not observed.

Morphological images have been acquired by means of 3D MERGE and 3D FIESTA sequences, optimized taking into account the relaxation times of the tissues of interest at 7 Tesla. In order to evaluate also the biochemical behaviour of the cartilage in the pathological subject, T2 and T2* maps (Krug, 2009) have been also computed.

3 RESULTS

The neck RF coil was used to obtain images of the neck and the cervical cord in healthy subjects (Figure 4).

The sequence used to obtain the image reported in Fig. 4 was a 3D MERGE with 0.5 mm in-plane resolution, TR = 30 ms, TE = 17.5 ms, thickness = 2.2 mm.

The image obtained demonstrates that this coil provides excellent anatomical images of the cervical spine, where spinal gray matter and white matter can be clearly depicted.

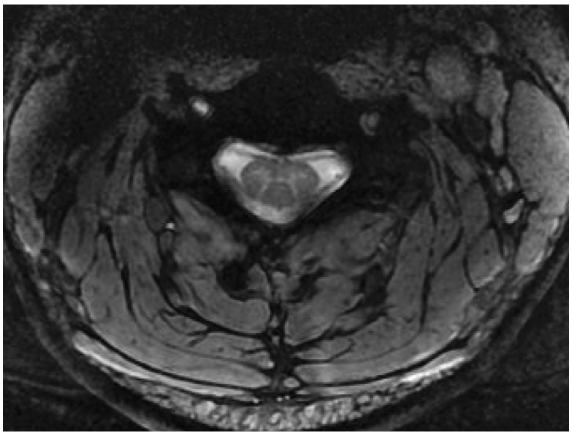

Figure 4: Cervical cord of a healthy volunteer acquired at 7 T with the quadrature ^{1}H surface RF coil and a 3D MERGE sequence. Note the high quality of the image with a clear depiction of the H shape of the spinal grey matter.

The knee RF coil was used to obtain images of the knee in healthy volunteers, in order to assess both the architecture of the trabecular bone and the morphology of the cartilage (Figure 5). The sequence used to obtain the image reported in Fig. 5 was a 3D FIESTA with 0.156 mm in-plane resolution, FA = 20, TR = 6.3 ms, TE = 2.5 ms, thickness = 0.8 mm.

The patellar cartilage was then segmented by means of the ITK-SNAP (Yushkevich, 2006) software tool, obtaining the results reported in Figure 6 (in the three axial planes and in the 3D volume rendering). Then the volume of the segmented cartilage has been quantified, obtaining the result of 1779 mm^3.

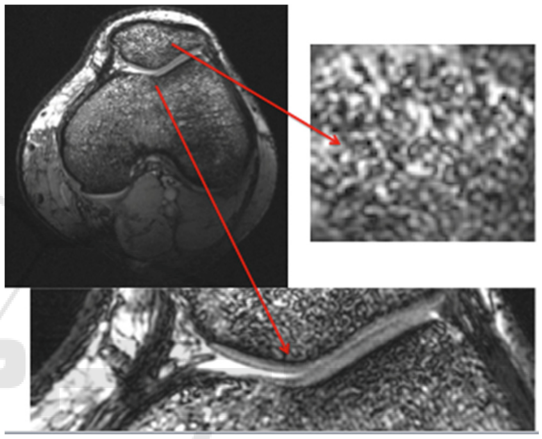

Figure 5: Knee of a healthy volunteer in which clearly depicts the trabecular architecture of the bone and the cartilages.

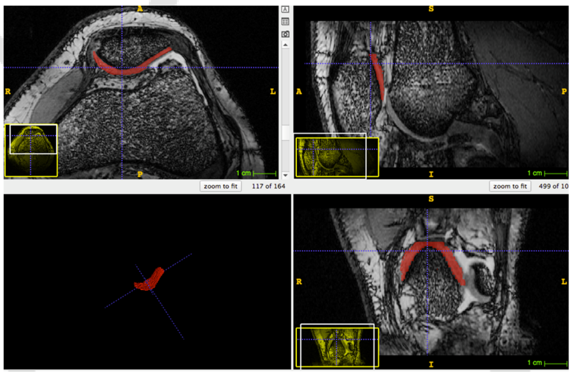

Figure 6: Segmentation and 3D rendering of the patellar cartilage of a healthy volunteer.

The knee RF coil was also used to obtain images of the knee in the pathological volunteer, in which the pathological change is clearly evident.

The sequence used to obtain the image reported in Figure 7 (left knee) was a 3D FIESTA with 0.156

mm in-plane resolution, FA = 20, TR = 6.3 ms, TE = 2.4 ms, thickness = 0.8 mm.

The sequence used to obtain the image reported in Figure 8 (right knee) was a 3D FIESTA with 0.156 mm in-plane resolution, FA = 20, TR = 9.0 ms, TE = 3.4 ms, thickness = 0.8 mm. In Figure 9 is reported an example of T2* map calculation of the same slice of Figure 8, realized by means of a 3D MERGE sequence with 6 echo times. In these images, of the right knee, the lack of cartilage in the medial facet of the patella and other alterations of the cartilage are clearly highlighted.

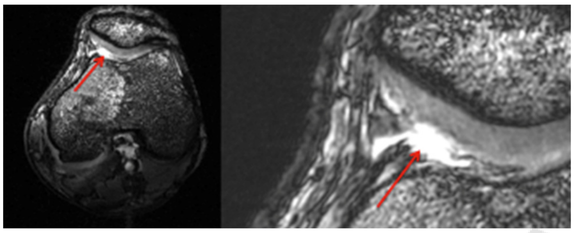

Figure 7: Left knee of the pathological volunteer.

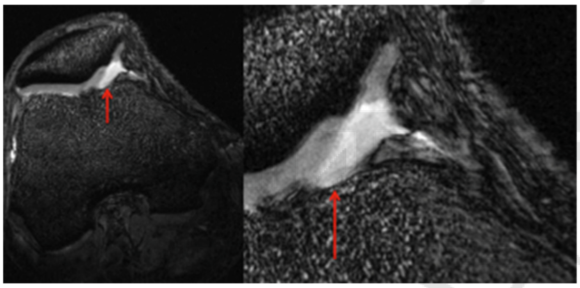

Figure 8: Right knee of the pathological volunteer.

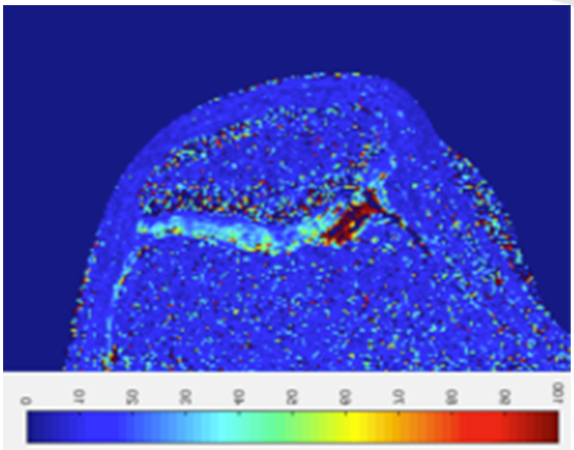

Figure 9: T2* map of the right knee of the pathological volunteer.

4 CONCLUSIONS

We presented the recent achievements in human MRI with a 7 T MR whole-body scanner. We designed and developed dedicated RF surface coils for ^{1}H imaging. The RF coil prototype for neck has been validated *in vivo* on healthy volunteers. The obtained results in the cervical spinal cord demonstrate a high image quality and if confirmed in a larger sample of patients might constitute a promising tool in exploring a complex anatomical region that is prone to susceptibility artifact at UHF. The RF coil prototype for knee has been validated *in vivo* on healthy and pathological volunteers. Due to the low amount of water in the bone and the small size of the cartilage, this district is well suitable for a study using UHF. With this technology it was possible to carry out a thorough assessment both morphological and functional. The obtained results demonstrate that the research in trabecular bone and cartilages characterization, comprising quantitative assessment of cartilage volume and evaluation of biochemical behaviour, can take advantage from UHF MR with dedicated coils.

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