In vivo Potassium-39 MRI at 9.4 Tesla using a room-temperature surface resonator: does cryogenic cooling help?

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Introduction: Recent MRI studies of the Tissue Sodium-23 Concentration (TSC) revealed that an irreversible increase in local TSC occurs in permanently-damaged stroke tissue [1]. Nevertheless, monitoring the intracellular 23Na concentration via Multiple Quantum Coherence (MQC) filters [2] or chemical shift reagents [3] proved difficult up-to-date. On the other hand, since intracellular Potassium (39K) concentration is ~15 times higher than in the extracellular compartment, 39K-Magnetic Resonance Imaging (39K-MRI) could provide direct information about pathological changes in intracellular ion concentrations after ischemic stroke. However, 39K MRI suffers from 100 times lower signal/noise (S/N) compared to 23Na-MRI which is achieved by ~6 times lower gyromagnetic ratio, and the much faster T1* decay. In a recent study by our group, a triple resonator setup was used to acquire a first in vivo 39K MRI image of the rat head at 9.4T [4]. Yet, the S/N can be significantly increased by using a single-tuned surface resonator. Furthermore cryogenic cooling may be advantageous at this low resonance frequency (18.7 MHz) and small resonator dimensions (<40mm diameter) [5]. In this study, a single-tuned 39K surface resonator was developed and tested for the measurement of 39K signal in the normal live rat brain. Similar surface coil was simulated at room-temperature (293 K) and cryogenic temperatures (90 K) in order to estimate the benefits of liquid nitrogen cooling.

Materials and Methods: A two-winding double-tuned 39K (18.7 MHz) Radio-Frequency (RF)-surface coil (i.d.: 20 mm, o.d.: 35 mm) was developed as shown in Fig. 1. A variable capacitor of 1-150 pF and two fixed capacitors of (200 pF and 160 pF) were connected in parallel to tune the coil at the resonance frequency of 18.7 MHz. The RF-coil was matched by inductive coupling to the 50 Ω signal line. The loaded/unloaded Q-factor ratio was measured to be 222/249. In order to geometrically decouple the developed surface coil from the 1H birdcage resonator (Bruker BioSpin GmbH, Ettlingen, Germany), the B1-field vector of the birdcage was orthogonally arranged to the surface coil’s normal vector. No change in Q-factor was observed when both resonance structures were combined to form the double-resonant coil system. 39T1-weighted images were achieved using a multi slice multi echo (MSME) sequence with TR = 700ms, TE = 11ms (0.2 x 0.2 mm)2 in-plane resolution with 3 axial slices of 2mm thickness and an inter-slice distance of 4 mm. The total measurement time (TA) was 2min and 59sec. A 3D Chemical Shift Imaging (CSI) sequence was used for 39K-MRI to achieve a voxel resolution of 2 x 2 x 2 mm3 (after two-fold 3D zero-filling), TR = 20ms, and TA = 30min. The in vivo experiments were carried out under appropriate animal license and ethical approval. One adult female rat (~350g) was scanned in vivo. The 39H edge image was superimposed onto the 39K image using a routine written in MATLAB. The S/N improvement by cryogenic cooling the resonator was estimated from simulated copper RF-coil at room-temperature (RT) of 293 K and cryogenic temperature (CT) of 90 K. Full-wave Electro-Magnetic (EM) simulations were computed for a single loop resonator with 35-mm diameter and 1.5-mm wire thickness using CST® Microwave Studio (CST AG Darmstadt, Germany) for both coils. The copper conductivity was set to σCu=5.8 x 107 S/m at room-temperature and σCu=2.4x108 S/m at cryogenic temperature [6]. The s11-reflection measurement on a network analyzer was simulated for both coils and both loaded and unloaded conditions. The sample load was modelled by a spherical phantom with εs=78, σs=0.45 S/m, and 30-mm diameter – modelling the rat head. Both coils are tuned and matched to the resonance frequency of 39K at 9.4 T (18.7 MHz). The selected input power was 1W. The S/N improvement was estimated by the loaded/unloaded Q-factor ratio for the RT and CT resonators as described elsewhere [6] using the following equations:

\[ S_{RT} = \frac{B_i}{\sqrt{r_{RT}T_{RT} + r_{unloaded}T_{unloaded}}} \]  
\[ S_{CT} = \frac{RT_{loaded}Q_{RT}^{-1} + RT_{unloaded}Q_{RT}^{-1}}{CT_{loaded}Q_{CT}^{-1} + CT_{unloaded}Q_{CT}^{-1}} \]  
\[ Q_{loaded} = Q_{loaded} - Q_{unloaded} \]

Once the steady state of the EM-simulation at both temperatures was obtained, the coil resistance \( R_{loaded} \) and the sample resistance \( R_{sample} \) were evaluated from the real part of the input impedance for unloaded and loaded conditions, respectively. \( T_{sample} \) was assumed to be 305 K.

Results and Discussion: The nearly similar loaded and unloaded Q-factors of the developed surface resonator demonstrate minor sample losses at this low frequency. The 39H and 39K images are shown in Fig. 2. The S/N achieved in the 39K images was 21±5 in (4x4x4 mm)3 voxel size and 24min acquisition time. Previously a SNR of 4 was achieved in similar in vivo experiments of a live rat head using a 3D FLASH sequence, (3x3x6 mm)3 voxel size and 54 minutes acquisition time [4]. Hence, the herein used CSE technique in conjunction with improved resonator sensitivity achieved approximately 5 times higher SNR in half the acquisition time. Furthermore excellent 39H image quality was achieved without having to exchange resonators in between scans. The simulated return losses for both the RF-coil at RT and CT in loaded and unloaded conditions are plotted in Fig. 3. The bandwidth of the CT-coil was much narrower, which resulted in a higher measured Q-factor. The unloaded Q-factor was 4更换 for the unloaded CT coil and 180 for the unloaded RT coil. The unloaded to loaded Q-factor ratios were 1.2 for the CT coil and 1.07 for the RT-Copper coil. Hence a 2.3-fold sensitivity improvement is expected when the coil is cooled down to 90 K, which could further improve the available signal in future 39K-MR imaging studies of the rat brain at 9.4T. In conclusion, 39K-MRI of the rat brain is possible at 9.4T using a CSI sequence and a single-tuned surface resonator and 39K resonator sensitivity can be further improved by cryogenic cooling.

References:  