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 ^{23}Na 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 (^{39}K) concentration is ~15 times higher than in the extracellular compartment ^{39}K-Magnetic Resonance Imaging (^{39}K-MRI) could provide direct information about pathological changes in intracellular ion concentrations after ischaemic stroke. However, ^{39}K MRI suffers from 100 times lower signal/noise (S/N) compared to ^{23}Na-MRI which is caused by ~6 times lower gyromagnetic ratio, and the much faster T_2* decay. In a recent study by our group, a triple resonant resonator setup was used to acquire a first *in vivo* ^{39}K 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 ^{39}K surface resonator was developed and tested for the measurement of ^{39}K signal in the normal live rat brain. Similar surface coil was simulated at room- (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 ^{39}K (18.7 MHz) Radio-Frequency (RF)-surface coil of (i.d.: 20 and 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 ^{1}H birdcage resonator (Bruker BioSpin GmbH, Ettlingen, Germany), the B_1-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. ^{1}H T_2-weighted images were acquired 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 4mm. The total measurement time (TA) was 2min and 59sec. A 3D Chemical Shift Imaging (CSI) sequence was used for ^{39}K-MRI to achieve a with voxel resolutions of 2 x 2 x 2 mm^3 (after two-fold 3D zero-filling), TR = 20ms, and TA = 30min. The *in vivo* experiments were carried out under appropriate animal license and ethics approval. One adult female rat (~350g) was scanned *in vivo*. The ^{1}H edge image was superimposed onto the ^{39}K 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® Micro Wave Studio (CST AG Darmstadt, Germany) for both coils. The copper conductivity was set to σ_{RT}=4.5x10^7 S/m at room-temperature and σ_{CT}=2.4x10^8 S/m at cryogenic temperature [6]. The s_{11}-retrun loss (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 ε_r=78, σ=0.45 S/m, and 30-mm diameter – modelling the rat head. Both coils are tuned and matched to the resonance frequency of ^{39}K 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:

$$S_{RF} \approx (B_1/I)\Big/\sqrt{R_{coil}T_{coil} + R_{sample}T_{sample}} \quad (1) \qquad R_{sample} = R_{total} - R_{coil} \quad (2) \qquad \frac{SNR_{CT}}{SNR_{RT}} = \sqrt{\frac{RT.Q^{-1}_{unloaded.RT} + RT.Q^{-1}_{sample}}{CT.Q^{-1}_{unloaded.CT} + RT.Q^{-1}_{sample}}} \quad (3) \qquad Q^{-1}_{sample} = Q^{-1}_{loaded} - Q^{-1}_{unloaded} \quad (4)$$

Once the steady state of the EM-simulation at both temperatures was obtained, the coil resistance R_{coil} 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.

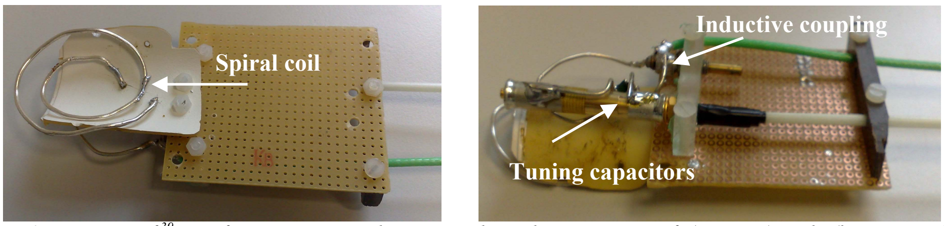
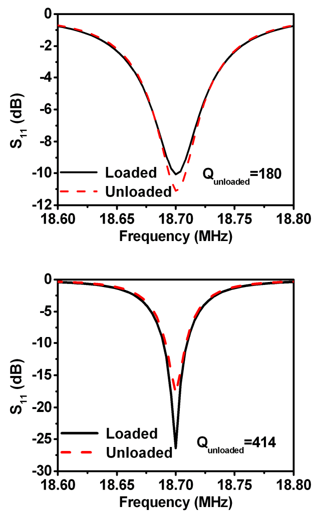


Fig. 1. Prototype of ^{39}K surface resonator with tuning and matching circuits. Left (top view), right (bottom view).



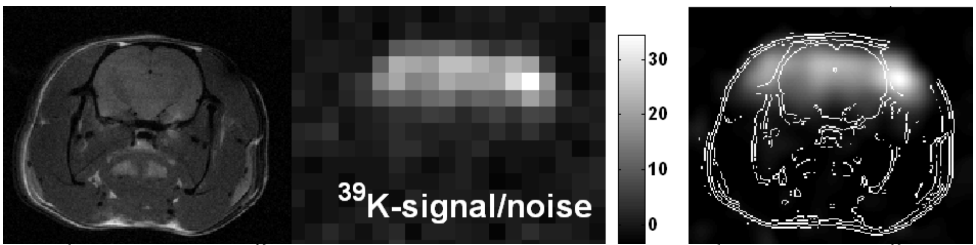


Fig. 2. ^{1}H (first column) and ^{39}K (second column) images as well as superimposed ^{1}H edge image with ^{39}K image (third column).

Fig. 3. Simulated return losses (s_{11}) for both RT- (top) and CT- (bottom) coils.

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 ^{1}H and ^{39}K images are shown in Fig. 2. The S/N achieved in the ^{39}K images was 21±5 in (4x4x4) mm³ voxel size and 24min acquisition time. Previously a SNR of 4 was achieved in similar *in vivo* experiment 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 CSI technique in conjunction with improved resonator sensitivity achieved approximately 5 times higher SNR in half the acquisition time. Furthermore excellent ^{1}H 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 414 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 ^{39}K-MR imaging studies of the rat brain at 9.4T. In conclusion, ^{39}K-MRI of the rat brain is possible at 9.4T using a CSI sequence and a single-tuned surface resonator and ^{39}K resonator sensitivity can be further improved by cryogenic cooling.

References: [1] Wetterling *et al.*, MRM 2011. [2] Tyson *et al.*, Stroke. 1996; 27, 957-964. [3] Heiler *et al.*, ISMRM 19:p.1491, Montreal (2011). [4] Augath *et al.*, JMR 200, 134-136 (2009). [5] Darrasse *et al.*, BIOCHIMIE 85, 915-937 (2003). [6] Hu *et al.*, IEEE I&M 99, 1-11 (2011).