Enhancing the Detector Sensitivity of a Radio-Frequency Surface Resonator for Potassium-39 MRI at 18.7 MHz: Probing Different Geometries at Various Temperatures

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***Abstract*—Potassium-39 (^{39}K) Magnetic Resonance Imaging (MRI) is a non-invasive technique which could potentially allow for detecting intracellular physiological variations in common human pathologies such as stroke and cancer. However, the low signal-to-noise ratio (SNR) achieved in ^{39}K-MR images hampered data acquisition with sufficiently-high spatial and temporal resolution in animal models so far. In order to maximize the detector sensitivity, its optimal size, geometry, and temperature was determined via Electro-Magnetic (EM) simulations and bench-top measurements. A two-turn, circular, room-temperature surface resonator was then developed and tested for the measurement of ^{39}K-MRI of a healthy live rat brain. Compared with the current-state-of-the-art as reported in the literature, the improved resonator sensitivity resulted in approximately five times higher SNR within half the acquisition time. As of the EM-simulations cryogenic-cooling could further improve the surface resonator's sensitivity four-fold at 77 K (liquid nitrogen) and six-fold at 20 K (liquid helium).**

Keywords-Cryogenic cooling, radio frequency resonator, potassium-39, ^{39}K, magnetic resonance imaging, electro-magnetic-simulations, liquid nitrogen, liquid helium.

I. 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 of the intracellular ^{23}Na concentration via Multiple Quantum Coherence 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-to-noise ratio (SNR) 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, a triple resonant coil setup was used to acquire a first *in vivo* ^{39}K image of the rat head at 9.4 T [4]. Yet, the SNR can be significantly improved 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 [5]. The thermal noise voltages received from the sample can be reduced using small surface resonators (< 40 mm) diameter. Additionally, the resistive loss can be decreased by cooling the copper resonator to cryogenic temperature (CT), leading to subsequently higher detected SNR. As a result, the unloaded *Q*-factor of the copper resonator increases by 2-3 times through cryogenic cooling at liquid nitrogen temperature (77 K) [6]. In a previous study, a conventional copper coil was cooled down by liquid helium to 30 K and 2-fold SNR improvement was achieved for hydrogen-1 (^{1}H) mouse brain imaging at 200 MHz [7].

In previous studies [5]-[9], simple analytical equations were used to estimate the SNR improvement for cryogenically-cooled coils. However, these analytical approaches were not exact enough to determine the optimal coil diameter, optimal coil geometry, and the sensitivity improvement. Recently, a simulation study and *in vivo* measurements with a cryogenically-cooled Radio-Frequency (RF)-coil for high resolution imaging at 3-Tesla were reported elsewhere [10]. Yet, the effect of the sample parameters such as sample-conductivity, -size, -geometry, and coil to sample distance were neglected in any of these studies [5]-[9]. Furthermore, when determining the receive sensitivity via the principle of reciprocity the B_1-field must be calculated accurately taking into account the effect of both coil and sample resistances. So that, 3-D full wave EM-simulations are suggested when an RF-resonator with maximum receive sensitivity across a certain volume-of-interest is required.

In this study, a single-tuned ^{39}K surface resonator was developed and tested for the measurement of ^{39}K signal in a healthy live rat brain at room temperature (RT). In order to estimate the benefits of liquid nitrogen and helium cooling, the optimal coil diameter, optimal coil geometry, and temperature was determined in order to maximize the receiver sensitivity for ^{39}K-MRI at 9.4 T. The simulations were performed using EM-simulations at RT (293 K), liquid nitrogen (77 K), and liquid helium (20 K) temperatures, respectively. The simulations were partially validated at RT through bench level and MRI measurements.

II. MATERIALS AND METHODS

A. Full-Wave EM-Simulations

Full-wave EM simulations were carried out with CST® Micro-Wave-Studio (CST AG Darmstadt, Germany). Due to the small resonator dimensions in terms of the wavelength at 18.7 MHz and due to the high *Q*-factors, the frequency domain solver (FDS) was found to be the best approach for simulating RF-resonators for various temperatures ranging from 20 K to 293 K. The EM-simulations were computed for two-coil geometries (single-loop and two-turn spiral resonators). For all cases, 1.5 mm copper wire thickness was selected. In this study, the copper conductivity was set to σ_{RT}=4.5x10^7 S/m at RT (293 K), σ_{CT}=4.65x10^8 S/m at (77 K), and σ_{CT}=357x10^8 S/m at (20 K), respectively. The S_{11}-retrun loss (i.e., the reflection coefficient measured on a network analyzer) was simulated for both coils in loaded and unloaded conditions. The sample load was modeled by a spherical phantom with ε_r=78, σ=0.45 S/m, and 30 mm diameter – mimicking the rat head in dimension and conductivity. All resonators were tuned and matched to the resonance frequency of ^{39}K at 9.4 T (18.7 MHz). The selected input power was 1W for all cases. The RF-sensitivity factor (S_{RF}) that contributes to the SNR of an image as described elsewhere [5], [10] can be computed as follows:

$$S_{RF} \approx \left(B_1/I\right) \Big/ \sqrt{R_{coil}T_{coil} + R_{sample}T_{sample}} \tag{1}$$

$$R_{sample} = R_{total} - R_{coil} \tag{2}$$

Where, B_1/I is the magnetic flux density in the receiving coil induced by a unit current, R_{coil} is coil resistance, R_{sample} is the sample resistance, T_{coil} is the coil temperature, and T_{sample} is the sample temperature. Once the steady state of the EM-simulation was obtained at each temperature, R_{coil} and R_{total} were evaluated from the real part of the input impedances for unloaded and loaded conditions, respectively. The sample resistance R_{sample} can be evaluated from (2). The transverse component of the B_1-field was evaluated at 18.7 MHz. In this study, T_{sample} was assumed to be 305 K [10].

B. In Vivo ^{39}K-MRI at 9.4 T

A two-winding double-tuned ^{39}K (18.7 MHz) RF-surface coil of 20 mm I. D and 35 mm O. D 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 T2-weighted images were acquired using a multi slice multi echo sequence with TR = 700 ms, TE = 11 ms, (0.2 x 0.2) mm^2 in-plane resolution with 3 axial slices of 2 mm thickness and an inter-slice distance of 4 mm. The total measurement time (TA) was 2 min and 59 sec. A 3D Chemical Shift Imaging (CSI) sequence was used for ^{39}K-MRI to achieve a voxel resolutions of 2 x 2 x 2 mm³ (after two-fold 3D zero-filling), TR = 20 ms, and TA = 30 min. 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®.

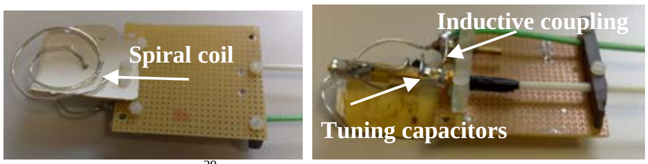

Fig. 1. Prototype of ^{39}K surface resonator with tuning and matching circuits. Left (top view), right (bottom view).

C. Validation of the EM-simulations at RT Via Bench Level Measurements

To validate the accuracy of the EM-simulations at RT, 10 single-loop surface resonators were built in house and compared via bench level measurement methods. The measured *Q*-factors are listed in Table I. Fig. 2 shows, the measured relative sensitivity profiles against the vertical (x-axis) perpendicular to the coil surface at RT. In order to compare both simulated and measured curves, the sensitivity profiles were normalized to the maximum value achieved by the smallest coil size (i.e., 14 mm) diameter.

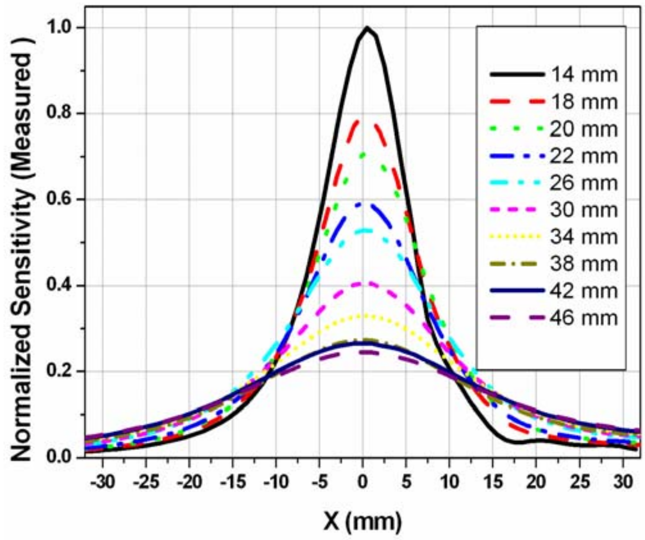

Fig. 2. Measured relative sensitivity profiles for 10-single-loop resonators at RT (293 K).

Fig. 2 shows that the smaller resonators ranging from (14-22 mm) are more sensitive at depths of 0-10 mm from the coil centre. However, the larger resonators ranging from (26-46 mm) are more sensitive at depths of 10-20 mm. To ensure a fair comparison, the mean and standard deviation (STD) values of the relative sensitivity were computed from 7-17 mm depth from the coil centre in x-axis as shown in Fig. 3. The simulated and measured normalized sensitivity distributions were relatively matched. However, the measured relative sensitivity is higher than the simulated one by 2-6 % because in the measurement, non-magnetic high *Q*-factor capacitors were used. As result, the *Q*-factor for the whole resonator circuit was increased compared with simulation and consequently the measured sensitivity was increased. In the CST simulations, variations on the tuning capacitor's *Q*-factor were neglected.

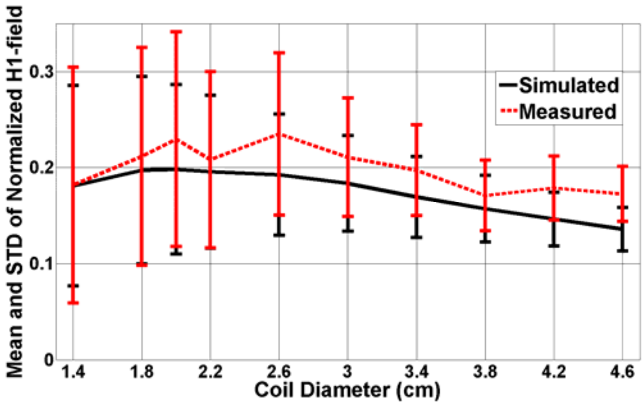

Fig. 3. Simulated and measured mean and STD values of normalized relative sensitivity for 10-single-loop resonators at RT (293 K).

Fig. 4 (a) shows, the mean and STD values of the H_1-field for a series of single-loop resonators in loaded conditions. To ensure a fair comparison, the mean and STD values of the H_1-field were computed from 7-17 mm depth from the coil centre in x-axis. The optimal coil diameter approximately is 20 mm at 77 K and 15 mm at 20 K. Additionally, the S_{RF} that contributes to the SNR can be estimated from (1). Fig. 4 (b) shows, the normalized S_{RF} distributions at 293 K, 77 K and 20 K, respectively against the coil diameter. The S_{RF} values at cryogenic temperatures (77 K and 20 K) were normalized to the maximum value achieved by the RT-coil. The predicted sensitivity gain is 3-fold at 77 K and 5-fold at 20 K. To measure the *Q*-factors at RT, all resonators were inductively matched and tuned at 18.7 MHz and measured from the S_{11}-retrun loss. The results of simulated and measured *Q*-factors for single-loop resonators are listed in Table I. The nearly similar loaded/unloaded *Q*-factor of the developed surface resonators demonstrates low sample losses at this low frequency. The bandwidth of the CT-coil was much narrower, which resulted in a higher measured *Q*-factor and hence more sensitive resonators.

Fig. 5 shows, the normalized S_{RF} distributions of two-turn spiral loop resonators at 293 K, 77 K and 20 K, respectively against the effective coil diameter (d_{eff}). In this paper, d_{eff} was defined by $2*(r_i + r_o)$, where r_i is the inner coil diameter; r_o is the outer coil diameter, and 5 mm inter-winding spacing. The S_{RF} values at 77 K and 20 K were normalized to the same reference maximum value achieved by the single-loop coil of 20 mm at RT. With d_{eff} of 20 mm (the optimal coil diameter), the two-turn spiral coil has a higher sensitivity than a single-loop coil and the predicted sensitivity gain is 2.6-fold improvement at RT. However, at CT, the predicted sensitivity gain is 7.88-fold at 77 K and 19.77-fold at 20 K. The graph proves that, relatively large cryogenic RF-surface resonators (> 25 mm) can be used for ^{39}K-MRI at 18.7 MHz without a big drop in sensitivity gain. For example, with d_{eff} of 30 mm, the predicted sensitivity gain is 4-fold at 77 K and 6.2-fold at 20 K.

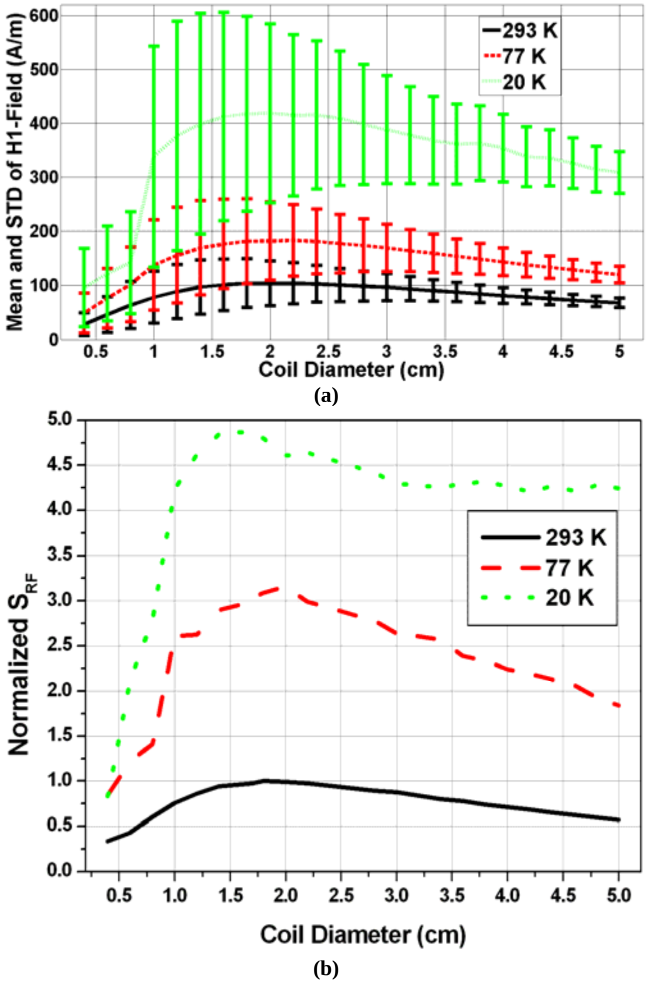

Fig. 4. (a) Simulated mean and STD values of H_1-field (loaded) for a series of single-loop resonators. (b) Normalized S_{RF} distributions for a series of single-loop resonators against the coil size.

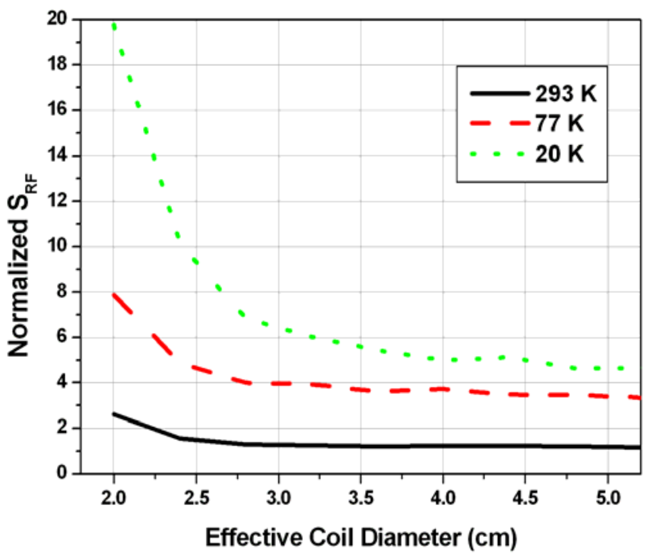

Fig. 5. Normalized S_{RF} distributions for a series of two-turn spiral coils against the coil size.

TABLE I.

Coil Dia. (mm)	Simulated *Q*-Factors					Measu-red *Q*-Factors
	293 K	77 K		20 K		293 K
	Q_U/Q_L	Q_U/Q_L	Ratio	Q_U/Q_L	Ratio	Q_U/Q_L
14	**114/110**	**360/332**	**1.0843**	**3099/2308**	**1.343**	**122/110**
18	**124/120**	**374/358**	**1.0447**	**3108/2475**	**1.256**	**132/120**
20	**126/122**	**391/372**	**1.0511**	**3116/2477**	**1.258**	**139/130**
22	**129/126**	**389/390**	**0.9974**	**3118/2474**	**1.260**	**134/131**
26	**135/131**	**426/409**	**1.0416**	**3735/2652**	**1.408**	**159/147**
30	**139/135**	**427/425**	**1.0047**	**3733/2856**	**1.307**	**161/149**
34	**146/143**	**424/422**	**1.0047**	**3723/2862**	**1.301**	**167/154**
38	**150/146**	**467/423**	**1.1040**	**3730/3110**	**1.199**	**173/161**
42	**154/150**	**468/445**	**1.0517**	**3719/3100**	**1.199**	**182/173**
46	**156/152**	**467/464**	**1.0065**	**3730/3390**	**1.100**	**189/175**

III. Discussion

For the optimal two-turn spiral coil with d_{eff} of 20 mm, the predicted sensitivity gain is 7.88-fold gain at 77 K and 19.77-fold gain at 20 K. However, the sensitivity at 77 K and 20 K decreased rapidly with increasing the coil size. The significant reduction in sensitivity due to the higher losses associated in both sample and coil compared with a single-loop resonator. This can be explained due to the two major loss mechanisms. At this small detector size and low frequency, sample loss is dominated by coil losses. At RT this disbalance can be somewhat exploited through extending the detector inductance via multi winding, increasing the effect of sample losses again. Cryogenic cooling is most effective for small coil inductances while resistive losses dominate the overall resonator losses. Hence, the two-turn spiral coil achieves the overall highest possible sensitivity in the range of 10±7 mm sample depth. The dominance of the resistive losses over dielectric sample losses was still observable in practice for developed two-turn RT coil. By comparing Fig. 5 with Fig. 4 (b), we can conclude that, the two-turn spiral coil could achieve a higher sensitivity gain with large RF-surface resonators at 77 K and 20 K.

To confirm the excellent signal sensitivity achieved with a two-turn RT coil, MRI images were acquired for such set-up. The ^{1}H and ^{39}K images are shown Fig. 6. Yet, the SNR achieved in the ^{39}K images was 21±5 in (4x4x4) mm³ voxel size and 24 min acquisition time.

Previously a SNR of 4 was achieved in similar *in vivo* experiment of a live rat head using a 3D fast low angle shot (FLASH) sequence, (3x3x6) mm³ voxel size and 54 min 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. For a relatively large two-turn spiral coil (> 25 mm), four-fold SNR improvement is expected when the coil is cooled down to 77 K and six-fold at 20 K. These significant results could further improve the available signal in future ^{39}K-MR imaging studies of the rat brain at 9.4 T. These results indicate that, cryogenically cooled surface resonator with two loops, but smaller diameter of < 20 mm can further improve the available signal in future ^{39}K-MR imaging studies of the rat brain at 9.4 T.

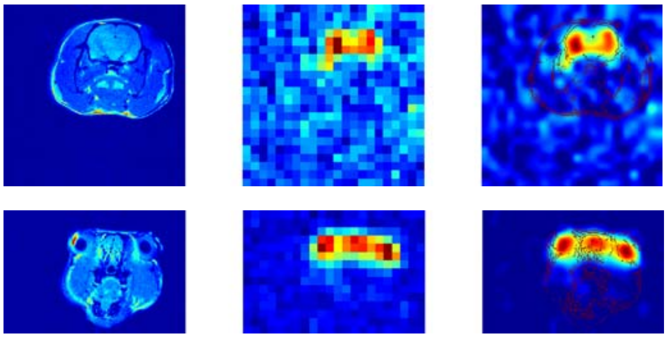

Fig. 6. ^{1}H (first column) and ^{39}K (second column) images as well as superimposed ^{1}H edge image with ^{39}K image (third column).

IV. Conclusions

Cryogenic-cooling of the surface resonator leads to a four-fold sensitivity improvement at 77 K and a six-fold sensitivity improvement is expected at 20 K. These results indicate that non-invasive rat brain tissue monitoring via ^{39}K-MRI at 9.4 T is possible with an acquisition time of 10 min and (2x2x2) mm³ voxel size.

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