RF-resonator for clinical MR imaging in urology and andrology

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Abstract. New diagnostic visualisation and quantification methods of nerve tracks are needed in andrology and urology applications. In order for magnetic resonance imaging (MRI) to properly image the nerves of interest a dramatic signal-to-noise ratio (SNR) increase is required. For this purpose, radiofrequency (RF) resonator based on the birdcage operating principles has been designed, fabricated, measured and compared to simulation model obtained by time domain method in CST microwave studio. The resonator concentrate RF magnetic field in the centre of the resonator, while electric field remains on the edge thus preventing tissue heating. Design and parameters of resonator was optimised for human MRI on 1.5T scanners. Using the resonator allowed to improve RF-safety for 2 times, transmit efficiency for 10 times and SNR for 14 times compared to body coil only system. Measured and computed resonance frequencies and transmit efficiency are in good agreement.

1. Introduction
Non-invasive diagnostic of the male reproductive system pathologies, such as urethral carcinoma, genitourethral sarcoma, periurethral abscesses, Peyronie disease and fractures of the penis, is commonly carried out by ultrasonography [1] (US) and computer tomography [2] (CT). However, these imaging modalities have certain limitations: US investigations often provides only a qualitative assessment and their results and depends heavily on the operator skills; CT techniques does not provide sufficient contrast in soft tissues. Magnetic resonance (MR) imaging allows getting high-resolution images with different contrast, providing a convenient modality for detecting a wide range of pathologies. One of the big problems of the genito-urethral MRI is the weak fit of the standard MR-coils to imaging of the penis. The letter results in low signal-to-noise ratio (SNR) in the images, low resolution or long scanning times, which in conjunction with small spatial dimensions of the pathologies to be imaged makes current penile MRI highly impractical.
In order to overcome this problem a new RF resonator was developed for MR signal reception and RF pulse transmission. The efficiency of such a resonator for improving the imaging procedure can be assessed based on the following parameters: transmit efficiency \(\frac{B_1^+}{\sqrt{P_{in}}}\) characterizes the generated transmission magnetic field \(B_1^+\) when the reference power is fed to the coil input, RF-safety \(\frac{B_1^+}{\sqrt{SAR}}\) is a relation between transmission magnetic field \(B_1^+\) and SAR (a measure of the rate at which energy is absorbed by the human body when exposed to a RF electromagnetic field), SNR \(\frac{-B_1^-}{\sqrt{4kTfR_{in}}}\) is a ratio of the reception field \(B_1^-\) in the RoI and the noise power spectral density.
2. Methods

2.1. Coil design

An RF resonator (Figure 1) was developed for 1.5T MR-scanners. In order to obtain high RF magnetic field homogeneity the resonator was designed similarly to the low-pass birdcage coil [3]. The phase shift between the coil legs required for the birdcage coil functioning is created by the combination of capacitors (located on top of the resonator) and distributed inductances (proportional to resonator legs length). An additional metal screen separates the patient’s body and resonator thereby improving the coil resonance characteristics. The resonator itself comprises eight telescopic brass tubes (legs) connected in parallel through the capacitor on PCB Rogers RO4003 and metal screen. The excitation of its first eigenmode provides, as in the case of birdcage coil, homogeneous magnetic field distribution [4,5].

2.2. Electromagnetic simulation

Electromagnetic simulations of the coil were performed in CST Microwave Studio 2017. Initially, simulations included the resonator, the an unmatched small loop coil and the phantom imitating the penis (i.e., a 20 mm wide cylinder with permittivity of 68.6 and conductivity of 0.45 S/m [6]). Frequency domain solver was used to calculate $S_{11}$ in the range 60–85 MHz and determine the optimal value of capacity for tuning the system to the 1.5T MR-scanner working frequency (63.85 MHz). In the further simulations transient solver was used to calculate transmit field $B_1^+$ and electric field $E$. The model included the resonator under study, the 1.5T MR-scanner body coil to provide excitation (modelled as 16-leg quadrature birdcage) and the human voxel model Laura (ITIS Foundation, Switzerland), complemented by a penis model.

2.3. Coil characterization

After the simulations showed feasibility of the coil operation, a coil prototype was manufactured according to the simulated model. Prior to the measurements the first mode was adjusted to be excited at the operating frequency of 1.5T MR-scanners. The prototype resonant frequency was confirmed by measuring the scattering parameter ($S_{11}$) with an unmatched loop probe connected to the vector network analyzer (VNA) Obzor TR1300/1. The lowest frequency minimum of the measured $S_{11}$ corresponded to the first resonator eigenmode (Figure 2).

2.4. MRI experiment

MR-scans were performed in the clinical MR-scanner (1.5T Magnetom Espree, Siemens GmbH, Erlangen, Germany). The resonator was located in a magnet isocenter with wires perpendicular to the main magnetic field $B_0$. The resonator load was emulated with a glass vial with a 20 mm radius filled with homogenous liquid imitating the penile tissues (NaCl and sucrose were dissolved in water; CuSO$_4$ was added in order to reduce spin-lattice relaxation time $T_1$). MR imaging was performed with gradient echo (FLASH) pulse sequence. Different series of images with resonator were obtained using different reference voltages applied to the feeding body coil ranging from 13V to 30V, 90° pulse corresponded to the maximum value of the signal in the center of the phantom. For SNR measurements (Table 3) a 2D spin echo (SE) pulse sequence with 90° excitation was used to acquire images of the phantom with commercial surface coil as receiver, with body coil only and body coil supplemented by the resonator. Additionally, the same 2D SE pulse sequence was applied with 0° excitation pulse to assess system noise.

3. Results

First modes measurements of the fabricated resonator showed good convergence with numerical simulation (Figure 2). Loading the resonator with either phantom or human body shifted first mode frequency of the resonator by 0.1%-0.3%. This effect is easily compensated by changing the wires length.
Figure 1. Radiofrequency resonator for 1.5T MR-scanners simulation model, model parameters: length between wires $L = 33\text{mm}$, wire length $H = 120\text{mm}$, square of each capacitor $S = 380\text{mm}^2$.

Figure 2. $S_{11}$ parameter of the resonator and simulated magnetic field distributions for the first two eigenmodes. The resonance position shows the tuning of the resonator to the MR-scanner working frequency. The resonance depth is primarily determined by the position of the unmatched loop probe.

3.1. Transmit efficiency

In hard pulse approximation the $B_1^+$ field needed to provide $90^\circ$ flip angle is $5.87\text{μT}$ during 1 ms [7]. For a body coil simulation $178\text{W}$ accepted power was needed to generate the desired field value, while with the resonator present the power was reduced to $1.5\text{W}$. Thus the resonator helps to increase the local transmit efficiency by $10.9$ times (Table 1). This is confirmed by experimental data: the use of the resonator reduced the reference voltage needed to provide $90^\circ$ pulse from $220\text{V}$ with the body coil only to $19\text{V}$, which is equivalent to an increase in transmission efficiency by $11.6$ times.

| Table 1. Comparison of transmission efficiency for a case with and without a resonator |
|-----------------------------------------|--------------------------------------------|------------------|------------------|
| Transmit efficiency                     |                                           | Body Coil + resonator | Ratio |
| $B_1^+\sqrt{P_{\text{in}}} (\text{μT}\cdot\text{W}^{-0.5})$ | Body Coil | | 0.44 | 4.8 | 10.9 |
|                                        | Simulation | | 0.17 | 1.97 | 11.6 |

3.2. RF-safety

MR-imaging with resonator also increases the RF-safety. The base RF absorption mechanism at 1.5 T is the current generation in the conductive sample by the alternating electric field of the coil. Thus decreasing the average value of the electric field in whole body leads to reduced SAR.

$$SAR = |E^2| \cdot \sigma / \rho$$
The simulation results (Table 2) show SAR reduction by 4 times for a system with a resonator. This is equivalent to 4 times less heating of tissues at the same transmit field $B_1^+$. 

### Table 2. Comparison of RF-safety for a case with and without a resonator based on simulation

| System                      | RF-safety $B_1^+/\sqrt{\text{SAR}}$ ($\mu T \cdot kg^{-0.5} \cdot W^{-0.5}$) |
|-----------------------------|--------------------------------------------------------------------------------|
| Body Coil + resonator       | 7.61                                                                 |
| Body Coil                  | 3.79                                                                 |

#### 3.3. Signal-to-noise ratio

Comparisons of the SNR (Table 3) show a 14 times gain for the resonator compared with body coil, and increase of about 2 times for the resonator compared with surface 4-element coil. SNR was calculated by the following equation:

$$SNR = \frac{\text{Mean}_{\text{in phantom}} \cdot SD^{-1}_{\text{in free space}}}{\text{in phantom}}$$

### Table 3. Summary of signal-to-noise ratio (SNR) measurements for phantom imaging

| System                           | SNR |
|----------------------------------|-----|
| Resonator + body coil            | 274 |
| Body oil only                    | 19.4|
| Surface flexible 4-element coil  | 136 |

#### 4. Conclusion

This work has shown that using the proposed RF resonator design in urology and andrology applications can improve SNR when compared to body coil only and surface coil indicating that better resolution of MR imaging can be achieved. At the same time SAR reduction shows that the diagnostics procedure becomes safer. The development of new MRI coil is aimed to allow quantitatively and qualitatively assessing previously unavailable small structures (e.g., nerves and terminal vessels) of the male reproductive system.

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