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Investigating the influence of dielectric pads in 7T magnetic resonance imaging – simulated and experimental assessment

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Abstract: Dipole radiofrequency (RF) elements have been successfully used to compose multi-channel RF coils for ultra-high fields (UHF) magnetic resonance imaging (MRI). As magnetic components of RF fields ($B_1$) can be very inhomogeneous at UHF ($B_0 \geq 7$ T), dielectric pads with high dielectric constants were proposed to improve the $B_1$ efficiency and homogeneity [1]. Dielectric pads can be used as a passive $B_1$ shimming technique thanks to inducing a strong secondary magnetic field in their vicinity. The use of such dielectric pads affect not only the $B_1$ field but also the electric field. This in turn affects the specific absorption rate (SAR) and consequently the temperature distribution inside the patient’s body. To study these effects, a 29 cm-long transmission dipole RF coil element terminated by two meander was used for 7T MRI [2]. Using a cylindrical agarose-gel phantom, numerical and experimental results were analyzed with respect to homogeneity and amplitude of the magnetic and electric fields generated by the RF element in various configurations with and without dielectric pads. Calculated and measured $B_1$ results were cross-checked and found to be in good agreement. When using dielectric pads $B_1$ homogeneity and magnitude increase in regions where it was previously weak or insufficient. Calculations suggest that SAR distribution will change when using the pads.

Keywords: 7T MRI, dielectric pads, experiment, electromagnetic simulation, dipole RF coil, phantom, $B_1$, homogeneity, SAR, MRI safety.

1 Introduction

In MRI both transmission and receiving of signal are done through RF elements (RF coils). At UHF the magnetic component $B_1$ of RF fields can be very inhomogeneous inside the body, since the wavelength becomes comparable to the dimensions of the human head. For this reason, the task to create specific RF elements for the use at 7T scanner is challenging. RF coil’s design includes a rigorous assessment of the electromagnetic (EM) fields generated and evaluation of patient/object’s safety during MRI procedures [2, 3]. However, when a specific RF coil is designed, it is impossible to predict all the usages that the MRI operator can handle: when different sized and shaped objects are analyzed using this coil, there is a detuning and impedance mismatch caused by the different load in the coil, which already generates intrinsic $B_1$ inhomogeneity. This is a very common problem for patients geometry that differs from the standard human model.

One of the methods to correct the $B_1$ transmitted field is using passive RF shimming, which can be done by placing high permittivity materials, more commonly, between the patient/object and the coil. Previous studies show that using such dielectric padding also alters SAR distributions and magnitudes, presenting increase or decrease on its magnitude depending on the aim of the measurement [1].

Investigations of the influence of positioning dielectric pads are especially important for 7T MRI brain scanning, due to the comparable dimensions between the human head and the RF wavelength, which is not an issue at lower $B_0$. In this study, a transmission RF element for 7T MRI was used to analyze the incident RF magnetic field distribution and the impact on it, when using dielectric pads. SAR predictions were done to estimate energy absorption inside the object.
2 Materials and methods

2.1 Dipole coil configuration

The dipole element used in this study was described in [2], but 29cm in length, intending its use as an element in a multi-channel coil for 7T MRI [4]. The element consists of a metallic strip line of width of 15mm terminated by two meander and a metal ground plate printed on Rogers RO4003 substrates (εr=3.55; thickness ts=0.5mm; length ta=290mm; width ws=100mm), which are separated by 19mm of air and connected at each extremity by a copper strip (thickness tg=0.5mm; width we=15mm) and an end-capacitor (Cs=1pF). The meander geometry is unchanged in comparison to [3]. The matching network consists of two shunt capacitors Cs=5.6pF, a series capacitor Cs=3pF and a balun with 180° delay coaxial cable placed at metal ground plate center (Fig. 1). The simulation model of the unloaded element in air, including matching network circuit, was continuously improved, in order to obtain a homogeneous magnetic field distribution and a small input reflection coefficient (S11). The final model is very similar to the fabricated dipole coil, counting with a different matching circuit (a series resistor of 41Ω, a series capacitor of 5.36pF, no balun). It is intended to improve the numerical model in order to get as close as possible to the fabricated element, which means, that some losses from the materials, cables and others also need to be counted in the model.

Different simulation scenarios were defined including the loaded coil in conjunction with a virtual phantom and dielectric pads, both with similar characteristics to the phantom and the pads used in the experimental setup (described in 2.3).

Local SAR predictions were done by post-processing the magnitude of electric field E(r) and the local material properties (σ is specific electrical conductivity, ρ is material mass density, r is position vector and V is volume), as in:

\[
SAR = \frac{1}{V} \int_V \frac{\sigma(\vec{r})}{2\rho(\vec{r})} E^2(\vec{r})dV.
\]

At 298MHz the material parameters were assumed as: phantom (σρ=0.92S/m, εr=58.2, ρp=1000kg/m³); dielectric pad (σρ=0.08S/m, εr=110) [1, 4]. To ensure reliability in the simulated results all the calculations were performed with a very fine mesh, setting the convergence criterion for the adaptive solutions to 0.006.

2.2 Simulation setup

The design of the dipole coil was done using HFSS (high frequency structure simulator) combined with the Circuit Design tool in the commercially available ANSYS package. Such combination enables the user to perform rapid optimizations and design detailed electronic devices.

The simulation model of the unloaded element in air, including matching network circuit, was continuously improved, in order to obtain a homogeneous magnetic field distribution and a small input reflection coefficient (S11). The final model is very similar to the fabricated dipole coil, counting with a different matching circuit (a series resistor of 41Ω, a series capacitor of 5.36pF, no balun). It is intended to improve the numerical model in order to get as close as possible to the fabricated element, which means, that some losses from the materials, cables and others also need to be counted in the model.

3 Results and discussion

3.1 B1 field distribution

Simulated results. To study the interaction of the phantom with the surrounding magnetic field and to analyze the influence of positioning the dielectric pads (close to the region where the B1 field is not homogeneous), simulations for the
different configurations were performed and are presented in Fig. 2. A voltage of 77.8V was applied on the element’s port.

![Fig. 2: Simulated results for the magnetic field $B_1$ strength in a plane $xz$ along the dipole element and positioned at the half width of the element: (a) Config. 1, (b) Config. 2, and (c) Config. 3. The black box represents the phantom, and the central line inside it will be used in Fig. 3.](image)

The $B_1$ strength distribution in a line positioned in the center of the phantom along $x$ axis (Fig. 2) was compared for the three configurations (Fig. 3). It shows that using dielectric pads, higher $B_1$ values can be achieved in comparison to Config. 1, presenting similar distribution for a region $x > 30\, \text{cm}$. When compared with phantom lateral positioned (Config. 2) higher $B_1$ values are achieved in 67.7% of the line.

**Experimental results.** Magnetic field distributions inside the cylindrical phantom were also measured, as can be seen in Fig. 4. A calibration was done for each configuration to reach the best transmission voltage (Tx) necessary to apply in the dipole element, aiming to get good images. For Config. 1 the voltage 72.2V was applied, the element’s excitation for Config. 2 and 3 was 77.8V, and Config. 4 received 155.6V. The same values were used for each corresponding simulation.

It appears that when the phantom is positioned outside the homogeneous region, the magnitude of $B_1$ is smaller at one side of the phantom and is not high enough to excite equally all the spins (see Fig. 4(b) and Fig. 2(b)). Trying to improve $B_1$ homogeneity in this region, two dielectric pads were inserted and the same Tx voltage as in Config. 2 was applied, however, this setup didn’t generate good images. Due to detuning and mismatching of the dipole element when inserting dielectric pads, the peak of S11 curve has shifted to a lower frequency (as posterior confirmed in a network analyzer) and for this reason, a new calibration was performed and a higher transmission voltage was applied, allowing us to obtain a more homogeneous $B_1$ field region inside the phantom (Fig. 4(d)).

**Simulated versus measured results.** Comparisons between calculated and experimental transmitted $B_1$ fields were carried out for two lines in the central coronal plane: along $x$ and $y$ axis, having as common point the phantom’s center (Fig. 5). The comparison of the results shows that the $B_1$ distribution along $x$ and $y$, as for $z$ axis (not presented here), are similar in its extension, but differs slightly in amplitude. To achieve the best agreement, the value of end-capacitors in the model was altered to $C_e=0.3\, \text{pF}$, which could represent not explicitly modeled losses. Using this capacitor value, the simulated coefficient was $S11=-48\, \text{dB}$ while $S11=-20\, \text{dB}$ were measured.
3.2 SAR predictions

As seen in Fig. 2 and 4, dielectric pads positioned near to the phantom can improve $B_1$ homogeneity inside a region of interest. However, it is also important to analyze how the configuration with pads (Config. 3) will influence the object’s energy absorption using our hardware setup, i.e. one dipole coil, phantom and dielectric pads. Simulations in Fig. 6 show different SAR distribution inside the phantom for Config. 3 in comparison to Config. 2, especially in the region that had higher $B_1$ improvement, presenting no hot-spots and only small changes in SAR. In accordance to [1], SAR variation when using dielectric pads depends on the aim of the measurement and is sequence dependent. Since the aim of this work was to homogenize $B_1$ inside the whole phantom, an increase in SAR due to the extra loss introduced by the usage of pads was expected.

4 Conclusions

Numerical and experimental investigations show that using dielectric pads can improve the $B_1$ homogeneity distribution inside an object and can also address higher $B_1$ magnitude for regions where it was previously not high enough. Additionally, simulations inform that local SAR distribution will change when using pads. The cross-check of results indicates that simulation model and measurement agree very well. However, improvement in the validation process are intended, notably with regard to real losses of the experimental setup, detuning and impedance mismatch when using pads, and calculation of temperature, which can be validated by dedicated MRI sequences.

Author Statement

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