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► To cite this version:

Marine A.C. Moussu, Luisa Ciobanu, Elodie Georget, Julia Krug, Stanislav B. Glybovski, et al.. High-Permittivity Dielectric Probes for MRM at UHF: Theoretical Model and Experimental Validation. Minnesota Workshop on High and Ultra-high Field Imaging and training courses, Nov 2019, Minneapolis, United States. hal-03164394

HAL Id: hal-03164394

<https://hal.science/hal-03164394>

Submitted on 9 Mar 2021

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High-Permittivity Dielectric Probes for MRM at UHF: Theoretical Model and Experimental Validation

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Purpose - In Magnetic Resonance Microscopy (MRM), the principle of Magnetic Resonance Imaging (MRI) is used to make images of tiny samples, with a resolution at least as good as 100 microns [1]. The reference volume probe at ultra-high field is the solenoid coil. Its achievable Signal-to-Noise Ratio (SNR) is limited by the conservative electric field induced in the biological sample that is conductive [2]. An alternative type of probes, exploiting the behavior of high permittivity dielectric resonators [3], has been proposed to overcome this limitation. The first transverse electric (TE) mode of such cylindrical structure develops a maximum of magnetic field together with a minimum of electric field near the symmetry axis [4]. The concept has first been experimentally tested and validated in MRM with prototypes built in ceramic materials [5,6]. More recently, we developed a theoretical model for MRM dielectric probes at 17 T (Larmor frequency 730 MHz), using the TE mode properties [7], in order to quantify the achievable SNR enhancement compared to the optimal solenoid coil. This model was used to predict the SNR enhancement of a prototype built with high-permittivity and low-losses ferroelectric material [8]. The ceramic electromagnetic properties were carefully chosen according to the guidelines provided by the model [9]. Our goal is to provide an easily implementable semi-analytical method to extract these properties for any B_0 field strength and any sample.

Methods - *SNR estimation*: The SNR is estimated by an intermediary quantity named SNR factor, equal to the ratio of the magnetic field induced in the sample (in the centre, at position "0") divided by the square root of dielectric power losses (Eq. 1).

$$(Eq. 1) u_{SNR} = H_{samp}(0)/\sqrt{P_{loss}}$$

Semi-analytical method (SAM): The dielectric probe is modelled by a ring, described by its inner radius r_h , outer radius r_a , height L , relative permittivity ϵ_r and loss tangent $\tan \delta$, and a sample, of same height, outer radius r_h , relative permittivity $\epsilon_{r,samp}$ and electrical conductivity σ_{samp} , both surrounded by air. The electromagnetic (EM) field distribution of the first TE mode, that has no angular variation, is derived from Maxwell's equations in cylindrical coordinates (ρ, θ, y) and using the method of Borgnis' potentials [10]. It is expressed with Bessel or Hankel functions for the radial variations, and by sinusoidal or hyperbolic sinusoidal functions for the axial variations, depending on the considered region of space, as described in [11]. Eqs. 2 and 3 express the axial H-field component within the sample and the dielectric ring, respectively. The continuity of the tangential fields at the boundaries between the regions and the separation equations of the wavenumbers ($k_i^2 = \alpha_i^2 + \beta_i^2$ in region i) give a system of equations that is numerically solved.

$$(Eq. 2) H_{samp}(\rho, y) \propto J_0(\alpha_{samp}\rho) \cos(\beta_{samp}y)$$

$$(Eq. 3) H_{ring}(\rho, y) \propto [H_0^{(1)}(\alpha_{ring}\rho) + \xi H_0^{(2)}(\alpha_{ring}\rho)] \cos(\beta_{ring}y)$$

For the SNR factor computation, the EM-field is supposed to be that of the corresponding disk resonator (as if the sample was made of the ring material). A penalty factor τ is applied to the field magnitude in the sample to account for the field decrease due to permittivity contrast between the sample and the ceramic: $H_{samp}(0) = \tau H_{disk}(0)$. This hypothesis allows to derive an analytical expression for the dielectric losses, with the E-field described by a single Bessel function (Eq. 4). The SNR factor of a dielectric resonator (DR) is finally expressed by Eq. 5 where $P_{loss, norm}^i = P_{loss}^i / H_{disk}^2(0)$.

$$(Eq. 4) P_{loss} = \frac{1}{2} \int_{V_{ring} \cup V_{sample}} \sigma(\vec{r}) |\vec{E}(\vec{r})|^2 dv \text{ with } \vec{E}(\vec{r})|_{ring} = \vec{E}(\vec{r})|_{disk}, \vec{E}(\vec{r})|_{sample} = \tau \vec{E}(\vec{r})|_{disk} \text{ and } \vec{E}(\vec{r})|_{disk} \propto J_1(\alpha_{disk}\rho) \vec{e}_\theta.$$

$$(Eq. 5) u_{SNR}^{DR} = \tau / \sqrt{P_{loss, norm}^{ring} + \tau^2 P_{loss, norm}^{sample}}$$

Reference probe: At 17 T, for a sample of diameter 4.5 mm and length 12 mm, the optimal solenoid has 4 turns, 7 mm diameter, 12 mm length and it is made with copper wire of diameter 1.5 mm [12]. The expression of the SNR factor u_{SNR}^{sol} is found in [12].

Numerical simulations were performed with CST Microwave Studio, using the Frequency Domain Solver. The dielectric resonator was excited by a non-resonant loop of diameter 1 cm.

MRI experiments: MRI data were acquired on a preclinical device at 17.2 T (Bruker BioSpin, Ettlingen, Germany) with a triaxial gradient system of maximum strength 1 T/m. The sequence parameters are given in [9]. The test sample was a commercial solution with $\epsilon_{r, test} = 50$ and $\sigma_{test} = 1 S/m$. The biological sample was a chemically fixed rat spinal cord.

Results - The resonator SNR factor computed using the semi-analytical method was compared with numerical simulations (see ref.[9]) for sample permittivities varying from 50 to 80 and conductivity from 0 to 2.5 S/m. For these conditions the relative error never exceeded 8%. Fig. 1 represents the SNR gain $u_{SNR}^{DR} / u_{SNR}^{sol}$ as a function of the ceramic properties as those used for the MRI experiments. The theoretical value of the SNR gain for the considered prototype is 2.5. In experiments performed on the test solution, the SNR gain is 2.2 as obtained with numerical simulations. Fig. 2 demonstrates that the ceramic probe performs better than the optimal solenoid when imaging the biological sample.

Discussion - The SAM estimation of the SNR factor was validated with an error inferior to 8%. The SNR gain estimation, that considers the inaccuracy of both models for the DR and the solenoid, was validated in one case. The SAM gives a correct but overestimated value of the real SNR gain.

Conclusion - In this work we addressed the possibility to model and predict the performance of a dielectric probe for MRM based on the resonator first TE mode. The developed model has been confronted to numerical simulations and experiments and validated. Future works include the extension of this model to clinical dimensions and frequencies, and the development of a similar model for the first HEM mode (higher resonant mode) of the same type of resonator, with potential for clinical imaging [13]. In this context, preliminary experiments have been performed at 22.3 T (950 MHz NMR spectrometer Bruker Avance III HD). Early results show similar sensitivities of the HEM mode of the ceramic probe and the reference birdcage coil.

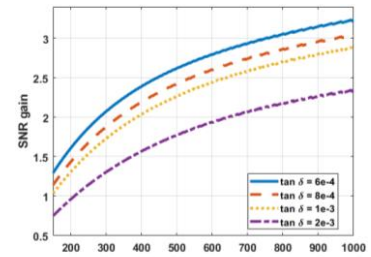


Fig. 1 SNR gain for the test sample as a function of the ceramic permittivity and for several loss tangent values.

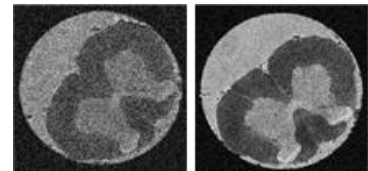


Fig. 2 - *Ex vivo* rat spinal cord image. Resolution: $(25\mu m)^3$. Left: solenoid. Right: ceramic.

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