TORUS-SHAPED DIELECTRIC RESONATOR FOR 7T MUSCULOSKELETAL IMAGING

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Introduction Although in ordinary clinical scanners a body coil can be used to transmit the field into the body, at higher frequencies, for example 7T (300 MHz), a body coil is no longer efficient and preference is usually given to surface transmit arrays. Another solution for transmit at higher frequencies is a dielectric resonator [1]. At lower field strengths such a resonator will have large dimensions making it impractical. As frequency increases resonator dimensions decrease. In electron paramagnetic resonance cavity resonators are frequently used and sometimes filled with high permittivity materials to reduce their sizes. In this work we discuss the application of distilled water as a dielectric in a resonator coil for 7T musculoskeletal MRI. Experiments at 4T with cylindrical water columns and annular water rings have been reported in [2]. We investigate experimentally and numerically a water-filled torus, with a sample located in the middle. B_1^+-maps and in vivo results of a human calf are obtained with the torus as a transmit/receive coil.

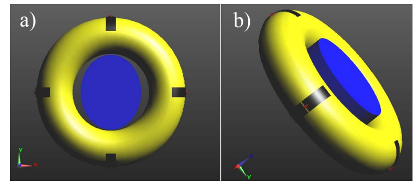

Figure 1: Simulation model. a) Top view. b) Perspective view.

Theory In a dielectric torus-shaped waveguide the same TE, TM and HEM (hybrid EM) modes can exist as in a dielectric cylinder. For our application we are interested in the TE_{01} mode. The cut-off frequency in MHz of this mode for a circular dielectric cylinder (radius r, relative permittivity ε_{r1}, permeability μ_0) in an infinite medium (ε_{r2}, μ_0) is [3]:

$$f_c = \frac{115}{r\sqrt{\varepsilon_{r1} - \varepsilon_{r2}}}$$

At 300 MHz the TE_{01} mode will propagate in a dielectric waveguide immersed in air and filled with water ($\varepsilon_r \approx 78$) if the radius is larger than 4.4 cm. For a torus a similar minimum radius is expected. At the center of the torus, the magnetic field lines from opposite sides add constructively if the circumference equals an integer number times the wavelength.

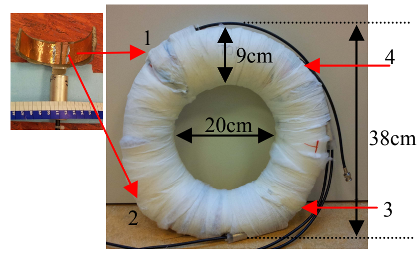

Figure 2: Experimental setup. Left: dipole antenna. Right: water-filled torus. The positions of the 4 dipole antennas are indicated by the arrows.

Materials and methods A torus (dimensions defined in *figure 3*) with ε_r=78 and conductivity σ=0.63 S/m (values of distilled water) was positioned with its rotational symmetry axis parallel to the static magnetic field direction. An elliptical phantom (major axis=18.5 cm, minor axis=15.0 cm, height=10.0 cm, ε_r=78 and σ=0.63 S/m) was placed at the center of the torus. The TE_{01} mode was excited by a dipole antenna wrapped around the outside of the torus (*figure 1*). The antenna was modeled by two perfect electrical conductors (6cm long, 2.5cm wide, separated by 2.5 mm) fed by a voltage source. Finite difference time domain simulations with harmonic excitation at 298.2 MHz were performed (SEMCAD, SPEAG, Zürich, Switzerland). For the experiment a torus (plastic wall, dimensions in *figure 2*) was filled with distilled water and four dipole antennas (copper tape, same dimensions as in simulations) were placed under angles of 90°. The experiments were performed on 7T MR scanners (Siemens Healthcare, Erlangen, Germany and Philips Healthcare, Cleveland, OH, USA). In a phantom (9×12×21 cm^3, ε_r=78, σ=0.63 S/m) B_1^+ maps per channel were obtained with a dual TR method (TR1/TR2=25ms/125ms) [4], using a 4 kW amplifier. In vivo results of the human calf were obtained with a multi transmit system using 4×1 kW amplifiers. A 2D gradient echo sequence (TR=200 ms, TE=3 ms, FA=90°, NSA=1, resolution=1x1x5 mm^3) was used.

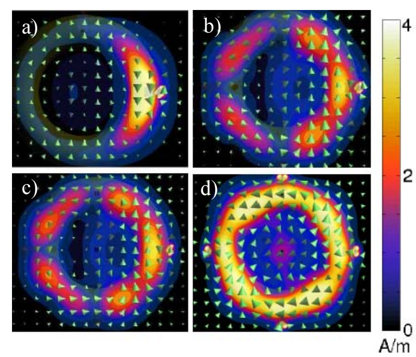

Figure 3: Simulation results for torus-shaped resonators. (a-c): right antenna transmitting. (d) all antennas transmitting (quad mode). RMS of H-field normalized to 1 W delivered power. a) r = 4.0 mm, outer diameter D = 37 cm. b) r = 4.5 cm, D = 37 cm. c) and d) r = 4.5 mm, D = 38 cm. The arrows indicate the real part of the H-vector (dB scaling).

Results *Figure 3a* shows the H-field in a torus with a cross-sectional radius of 4 mm at 298.2 MHz. The TE_{01} mode is evanescent since the frequency is below the cut-off frequency for this diameter. In a larger torus with a cross-sectional radius of 4.5 cm the TE_{01} mode propagates (*figure 3b*). Changing the circumference of the torus changes the standing wave patterns of the H-field in the torus (*figures 3b and 3c*). Transmitting with 4 antennas in quadrature mode results in the H-field pattern of *figure 3d*. In *figure 4* an experimentally obtained B_1^+ map for channel 1 is compared to the simulated B_1^+ map for the configuration of *figure 3c*. Experimentally about 10 μT was obtained in the phantom for one antenna with a 4 kW amplifier (50% power loss was taken into account in *figure 4a*). The patterns from the experiment resemble the simulation patterns, except close to the antenna. The efficiency in the simulation was not reached in the experiment. *Figure 5* shows in vivo results for the human calf. In the first images one channel was active; the last 2 images were obtained with all channels on, after phase shimming. The coronal image shows a good longitudinal coverage of the calf.

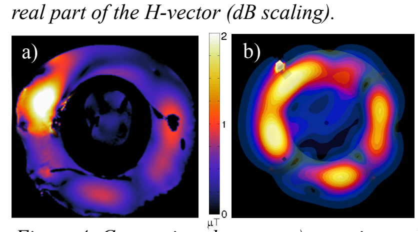

Figure 4: Comparison between a) experimental and b) simulated normalized B_1^+ maps.

Conclusion and discussion A torus-shaped dielectric (distilled water) resonator was introduced and a proof of concept was demonstrated for imaging at 7T. A TE_{01} mode propagated for a cross-sectional diameter of 4.5 cm. By using several antennas shimming was possible. Good resemblance was found between the experimental and simulated B_1^+ patterns. The setup could be optimized by selecting different dimensions and dielectric filling. Filling the torus with D_2O instead of ordinary distilled water would remove the signal of the resonator and hence a smaller field of view could be adopted. Moreover, other modes could be evoked by using different antenna types.

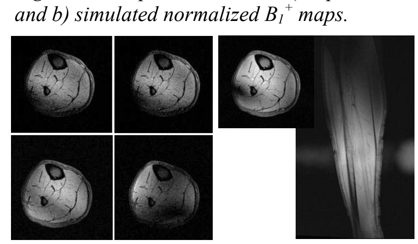

Figure 5: In vivo results (transverse and coronal) of the human calf. Left: images per channel. Right: transverse and coronal image for all 4 channels transmitting.

References [1] Webb (2011). Concepts in Magn Res Part A, **38A(4)**: 148-184. [2] Wen et al. (1996). Magn Reson, Ser B **110**: 117-123. [3] Yeh and Shimabukuro. The Essence of Dielectric Waveguides (2008). [4] Yarnykh (2007). Magn Reson Med **57**: 192-200.