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The Evaluation of Dielectric Resonators Containing H₂O or D₂O as RF Coils for High-Field MR Imaging and Spectroscopy

Han Wen^{*}, Farouc A. Jaffer[†], Timothy J. Denison, Stefan Duewell, A. Scott Chesnick, and Robert S. Balaban

Laboratory of Cardiac Energetics, National Heart, Lung and Blood Institute, 9000 Rockville Pike, Bethesda, Maryland 20892

Abstract

Electromagnetic resonators consisting of low-loss dielectric material and/or metallic boundaries are widely used in microwave technologies. These dielectric resonators usually have high Q factors and well-defined field distributions. Magnetic resonance imaging was shown as a way of visualizing the magnetic field distribution of the resonant modes of these resonators, if the dielectric body contains NMR sensitive nuclei. Dielectric resonators have also been proposed as RF coils for magnetic resonance experiments. The feasibility of this idea in high-field MR is discussed here. Specifically, the dielectric resonances of cylindrical water columns were characterized at 170.7 MHz (4 T ¹H Larmor frequency), and evaluated as NMR transmit and receive coils. The dielectric resonance of a cylindrical volume of D₂O was used to image a hand at 170.7 MHz. This study demonstrated that MRI is an effective way of visualizing the magnetic field in dielectric structures such as a water cylinder, and can potentially be generalized to solid-state dielectric devices. The possible applications of dielectric resonators other than simple cylindrical volumes in MRI and MR solution spectroscopy at high field strengths are also discussed.

INTRODUCTION

Low-loss dielectric materials are widely used in microwave technology to form part of or the main body of high-frequency electromagnetic resonators. In the presence of a time-varying electric field $E(t)$, a medium of dielectric constant ϵ has a dielectric current $j = [(\epsilon - 1)/4\pi]dE(t)/dt$. A volume of low-loss dielectric material exhibits electromagnetic resonances, because the material acts as both capacitors and inductors in the sense of a regular circuit. The first few resonant modes of a dielectric cylinder at the low end of the frequency spectrum are the TE_{01δ} mode, the HEM_{11δ} mode (transverse magnetic field in the equatorial plane), the TM_{01δ}, etc. (1). The influence of the transverse electric mode of a spherical water phantom on the RF field distribution has been observed in MRI at high fields (2), and the same phenomenon was also described in head imaging *in vivo* (3). Dielectric material has been used to change the boundary condition of high-pass bird-cage coils, resulting in improved B_1 uniformity in the transaxial plane (4). The idea of using dielectric resonators as RF coils has been proposed previously (5).

The resonant frequency of a particular resonant mode is determined by the shape and the size of the dielectric volume, and the electromagnetic wavelength in the material. For the first few modes, the resonant wavelength is on the same order as the size of the volume. Water has one

of the highest dielectric constants of fluids (approximately 78 up to gigahertz range). The wavelength in water is approximately 20 cm at the 4 T ^1H frequency of 170 MHz. When a water column on this scale is adjusted to resonate at precisely this frequency, the magnetic field distribution of the dielectric resonance can be visualized with MRI on a 4 T imager.

The oscillating magnetic field of the dielectric resonant modes can potentially be used for NMR experiments, in which case the dielectric resonator serves as the coil. Deuterium oxide (D_2O) has a similar dielectric constant as does water, but negligible proton density. It can therefore be used to construct such resonators for proton imaging without unnecessary signal from the resonator itself. Naturally, any other dielectric material that does not contain the nuclei of interest could also be used to make the resonator.

To assess the feasibility of using water or D_2O as the medium of an MR dielectric resonator, we used MRI to visualize the transverse magnetic field component of the resonances of a cylindrical water column, and measured their Q factors. To demonstrate that it is possible to use the first few modes of such simple dielectric bodies as RF coils (so called “water coils”) in MRT and MRS, we imaged a hand immersed in a cylindrical volume of D_2O , and obtained spectra of glucose and choline dissolved in D_2O . A more convenient configuration of an imaging coil, a water ring resonator, which permitted the sample to be placed in the middle of the ring, was also tested with a bottle of pure ethanol as the sample. We collected the image of the ethanol bottle and measured the signal-to-noise ratio as an indication of its efficiency.

EXPERIMENTAL METHODS

All imaging and spectroscopy experiments were conducted on a 4 T GE/Oxford one-meter-bore scanner, controlled by both a GE Signa console and an Omega console. Details of the imaging and spectroscopy experiments are presented in the text below.

A water dielectric resonator was made by filling a cylindrical fiberglass container with distilled water. The diameter of the cylinder was 24.8 cm. The bottom of the container was flat, the top was open. In all experiments, the cylinder was placed vertically. The resonant modes of the water column was detected with an HP-4195A network analyzer. Two small shielded loops (2 cm diameter) were connected to the transmit and receive ports of the network analyzer via 50 ohm coaxial cables. These loops were placed on the opposite sides of the water column 5 cm away from the water surface, and the transmission coefficient between them was measured with the network analyzer for a set frequency range. This transmission coefficient spectrum would display the resonant modes within the frequency range (6). The small size of the pickup loops and their placement were designed to minimize their perturbation on the resonant modes of the water column. The transmission coefficient spectrum was not significantly influenced by changing the positioning of the cables leading to the pickup loops.

By adjusting the amount of water in the cylinder, each resonant mode can be tuned to the frequency of 170.75 MHz (4 T ^1H frequency). To visualize the B_1 field of the resonant mode with MRI, a small coupling loop of 3 cm diameter was placed over the surface of the water column, as shown in Fig. 1. The coupling loop was connected to a standard matching circuit, and then to the T/R switch of the imager via a coaxial cable. The cylinder was placed vertically in the magnet, with its axis perpendicular to the axis of the main magnetic field. The three symmetric planes of the water column (transaxial and the two vertical planes perpendicular to each other) were then imaged to identify the resonant mode.

For a dielectric cylinder of radius a cm, length L cm, and relative dielectric constant ϵ_r , the resonant frequency of the $\text{TE}_{01\delta}$ mode is empirically given (1) as

$$f_{\text{MHz}} = \frac{3.4 \times 10^3}{a \sqrt{\epsilon_r}} \left(\frac{a}{L} + 3.45 \right). \quad [1]$$

This equation was used to predict the amount of water/D₂O needed to bring the TE_{01δ} mode of the water cylinder to 170.75 MHz. As shown below, the prediction was satisfactory.

In a more readily applicable configuration, a dielectric resonator in the form of an annular ring of water was used to image an ethanol phantom placed in the middle of the ring. The outer diameter of the water ring was 19.0 cm, the inner diameter was 8.5 cm, and the height of the ring was 16.9 cm. At this dimension, the TE_{01δ} mode of the ring was brought to 170.75 MHz. The diameter of the ethanol bottle was 6.5 cm. The ring was placed vertically at the center of the horizontal magnet. Images of the ethanol phantom were obtained.

To demonstrate the possibility of *in vivo* imaging with a dielectric material that does not contain the imaged nuclei, such as D₂O for proton imaging, the TE_{01δ} mode of a D₂O column was used to image a hand. The gloved hand was immersed in the central zone of the D₂O column. The D₂O resonator was driven with the coupling loop described above. The volume of D₂O was adjusted to bring the TE_{01δ} mode to 170.75 MHz.

RESULTS

The resonant spectrum of the cylindrical water column (24.8 cm diameter, 12 cm height) was obtained by measuring the transmission coefficient between two small probe loops placed near the column, as described under Experimental Methods. The transmission coefficient over the frequency range 0 to 500 MHz is shown in Fig. 2. The three resonances labeled 1, 2, and 3 were later identified as the TE_{01δ}, HEM_{11δ}, and a tilted TM_{01δ} modes, as shown below. The third mode was a hybrid of the HEM_{12δ} mode and the TM_{01δ} mode, which was likely caused by the asymmetric perturbation of the coupling circuit on the water body. From the transmission coefficient spectrum (Fig. 2), the *Q* factors of the three resonances were measured to be 57 for mode 1, 24 for mode 2, and 32 for mode 3. To test the significance of the radiation loss on the *Q* factors, the same water column was placed in the middle of the magnet bore (60 cm diameter and 210 cm in length); the *Q* factor of mode 1 then increased to 67. Thus, the radiated energy could account for a fraction of the total loss.

The *Q* factors were sensitive to the ion concentration in the water body. This was illustrated with a water cylinder of 19 cm diameter and 14 cm height for a series of ion concentrations. The *Q* factor of the TE_{01δ} mode at 161 MHz was measured. As shown in Fig. 3, concentrations on the order of several millimolar were sufficient to degrade the *Q* value significantly.

To visualize the magnetic field of each of the three resonances, the water volume was adjusted such that the resonant frequency moved to 170.75 MHz. The tuned column height for the resonances were 6.5 cm for mode 1, 12.2 cm for mode 2, and 25.0 cm for mode 3. The tuned height of mode 1 predicted by the empirical Eq. [1] was 6.3 cm, which agreed with the actual value within 3%.

After tuning, the water column was placed in the magnet, and three proton-density-weighted GRE images (TE = 4.8 ms, TR = 2 s) were taken in the three symmetry planes of the column. The images had 128 × 128 pixels over a 400 mm field of view; the slice thickness was 8 mm. They are shown in Fig. 4. The signal intensity of a pixel serves as an indicator of the magnitude of the transverse component of the magnetic field at that point. From the signal-intensity distributions of the three slices, the current and magnetic field distributions of the resonant

modes are sketched in Fig. 5. The resonances 1 and 2 were, thus, recognized as the $TE_{01\delta}$ and $HEM_{11\delta}$ modes, respectively. The three slices of the third resonance suggested a tilted $TM_{01\delta}$ mode. The tilting was likely caused by the asymmetric positioning of the coupling circuit relative to the symmetry planes of the water body itself.

When an annular ring of water was used to image a bottle of pure ethanol placed in the middle of the ring, as described under Experimental Methods, the cross-sectional image in Fig. 6a was obtained. The signal-to-noise ratio ($1.2 \times 2.3 \times 8$ mm pixel size) was 620:1. The uniform illumination of the bottle demonstrates the B_1 field homogeneity in the cross section. Figure 6b is an image of the same phantom with exactly the same imaging parameters, but using a shielded quadrature bird-cage coil of 18.3 cm inner diameter and 20 cm length. The signal-to-noise ratio was 90:1. Based on the reciprocity relation (6,7), the loss for the water ring resonator was lower than that for the conventional coil. The higher loss for the bird-cage coil was likely due to two factors: the RF currents were confined to the conductor strips and capacitors in the conventional coil, while fully distributed in the water ring resonator; the bird-cage coil was longer in the axial direction, its uniform B_1 region spanned a longer distance along the axis than the water ring.

In the above experiment, the water ring was placed vertically in the magnet bore, and the $TE_{01\delta}$ mode was used. If such a dielectric ring resonator is to be used for human head or body imaging, the ring should be placed in parallel with the magnet bore. In this case, the magnetic field of the $TE_{01\delta}$ mode is mostly parallel to the main magnetic field, and cannot be used for spin excitation. The two degenerate $HEM_{01\delta}$ modes should be used, and can be combined in quadrature to give a circularly polarized B_1 field. To demonstrate the feasibility of this arrangement, we constructed an annular ring of distilled water of 47 cm in length, 26.7 cm in outer diameter, and 24.8 cm in inner diameter. The two degenerate $HEM_{11\delta}$ modes occurred at 220 MHz, as shown in Fig. 7. Because of the lack of availability of material, we were not able to construct a larger ring that resonates at 170 MHz so that imaging experiments could be performed. It is reasonable to assume that a ring of a larger size would be able to work as a body coil at 170 MHz.

Finally, as an example of using dielectric resonators *in vivo*, a D_2O cylinder was chosen to image a hand. D_2O was used to avoid the bright signal from the resonator itself. The cylinder was 19.0 cm in diameter, and its height was adjusted to 17.3 cm to bring the resonant frequency of the $TE_{01\delta}$ mode to 170.75 MHz. The unloaded Q of this mode was 59, and the loaded Q value was 29. The factor of two change in the Q value suggests that the coil efficiency and sensitivity were limited by the unloaded Q of the D_2O column. Figure 8 is a slice from a multislice GRE image set of a hand collected with this resonator, with $0.78 \times 1.04 \times 5$ mm pixel size. The echo time was 11 ms, $TR = 1$ s, $NEX = 2$. The low signal-to-noise ratio of the image was likely caused by susceptibility effects from the irregular air space in the glove between the hand and the D_2O , as this effect becomes severe at 4 T for gradient-recalled-echo images. This imaging experiment suggests that for practical uses, lower-loss dielectric materials molded in hollow cylinders would be more suitable, as discussed above.

DISCUSSION

We have shown that MRI can be used to visualize the magnetic field distributions of dielectric resonators, if the body of the resonator contains magnetic nuclei, such as water. The field distributions of solid dielectric devices can potentially be measured with solid-state MRI, if NMR sensitive nuclei can be incorporated into the crystal structure. The field distributions of hollow resonators could also be imaged with MRI, if hyperpolarized gases fill the spaces.

The dielectric resonance phenomenon of water bodies on the scale of 20 cm is significant in the 100 MHz range (2,3). This phenomenon, on the one hand, may partially account for B_1 distribution distortions in high-field large-volume imaging experiments. On the other hand, it may be utilized to form RF resonators for transmission and/or reception. The advantage of a highly symmetric dielectric resonator comes from its fully distributed current paths and the zero or low charge accumulation on its surface, which has been the main cause of excessive capacitive losses and “hot spots” in RF coils. This was demonstrated with the imaging experiment of the ethanol bottle described under Results. Fully distributed currents also improve the B_1 uniformity when compared to the limited number of discrete current paths in coils made of normal circuit elements. In addition, dielectric resonators such as those discussed in this paper are simple in structure and potentially easier and less costly to make.

Dielectric resonators are well suited for high-frequency spectroscopy of solution samples. The solution volume itself may serve as the resonator, and, in the $TE_{01\delta}$ mode, the only loss is the unavoidable inductive loss of the B_1 field in the solution itself. The coupling scheme in this case can be two small, chemically inert, electrodes placed in the peripheral region of the solution. The absence of an external coil eliminates much of the losses and coil susceptibility effects encountered in spectroscopy experiments. This approach is not limited by the relatively low Q factors of the solutions, since the loss represented by the Q value is the inherent sample loss. Using this approach, we have detected spectra of glucose and choline solutions successfully at 4 T. The strong effect of the ionic components in the solutions on the Q value suggests that biological tissues do not possess well-defined resonances, and the human body itself is not adequate as a dielectric resonator for MR experiments. Nonetheless, dielectric resonance-related B_1 distortion and losses are significant at 4 T for human imaging (2).

We evaluated the first few resonant modes of dielectric cylinders and annular rings, which are the most likely candidates for MR coils. The $TE_{01\delta}$ and $HEM_{11\delta}$ modes of the dielectric rings possessed high transaxial B_1 homogeneity. The $HEM_{11\delta}$ resonance consists of two degenerate modes of orthogonal transverse B_1 field, which is ideal for generating circularly polarized excitation and quadrature detection. Thus, these modes would be quite suitable for most MRI and MRS applications.

These dielectric resonant structures can be very effective MR coils when made of materials of sufficiently high- ϵ and low-loss factors. We used water and D_2O as the initial material for their convenience. Water has an ϵ of 78 up to the gigahertz range. Mixtures of water and other fluids normally have lower dielectric constants. For RF coils used for imaging, the relatively high-loss factors of water or D_2O due to the electric dipolar relaxation are significant. The dielectric loss of water is represented by the ratio between the imaginary component (ϵ'') and the real component (ϵ') of its dielectric constant (8). As discussed in detail in Ref. (8), the complex dielectric constant of pure water is well described by the Debye equation. Under 1 atm pressure, the ratio ϵ'/ϵ'' is temperature dependent, and is about 85 between 10 and 20°C at 170 MHz. Since this ratio is the highest achievable Q factor of a water resonator, ignoring radiation losses and ion contamination, this limits the unloaded Q of the resonator to less than 100 at 170 MHz. As RF coils, good efficiency is not possible if the loaded Q value is not permitted to drop to around 10. If the loaded Q value reaches the range of 10, the spectral width of the resonance will not be negligible compared to the resonance separations, and, therefore, the perturbations introduced by the sample itself may significantly distort the B_1 field distribution. For MRS applications where the solution itself could be used as the resonator, the loss factor does not constitute a problem. However, for samples less than 3 cm in size, the lowest dielectric resonant frequency would be greater than 1 GHz, requiring very high magnetic field strengths. Other highly dielectric fluids such as BF_3 may have higher dielectric constants than water, but are usually hazardous and require great care in handling (BF_3 is extremely explosive). For these reasons, low-loss, high- ϵ , solid-state materials such as certain titanium oxide ceramics (9)

would be more desirable in the hundred megahertz to gigahertz range. When molded into the cylindrical resonators as described in this paper, they can become efficient quadrature RF coils.

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FIG. 1.

This diagram shows the setup of the imaging experiment of a water cylinder in the scanner. The cylindrical body was placed vertically in the magnet. A small loop was placed on top of the cylinder and inductively coupled to the water body. The coupling loop was connected to the T/R switch of the scanner via an impedance matching circuit and a coaxial cable. It was used to excite the different dielectric resonant modes of the water cylinder, and collect the signal from the water volume.

FIG. 2.

The dielectric resonant spectrum of a cylindrical water body, measured with two small shielded loops. The two loops were placed on the opposite sides of the water body, and the transmission coefficient between them was measured and plotted here. The first three resonances labeled 1, 2, 3 were imaged on a 4 T scanner to visualize their magnetic field distributions.

FIG. 3.

The Q factor of the $TE_{01\delta}$ mode of a cylindrical water dielectric resonator as a function of the dissolved NaCl concentration in it. The Q value was significantly influenced by the NaCl concentration.

FIG. 4.

Magnetic resonance images of the first three resonant modes of a cylindrical water body. The water cylinder was placed vertically in the magnet; its axis was perpendicular to the B_0 field. These images were acquired with a GRE sequence, $TE = 4.8$ ms and $TR = 2$ s, field of view = 40 cm, slice thickness = 8 mm, matrix size = 128×128 . (a–c) The transaxial (coronal relative to the scanner) and the two vertical (sagittal and transaxial relative to the scanner) slices of mode 1 ($TE_{01\delta}$). (d–f) The transaxial (coronal relative to the scanner) and the two vertical (sagittal and transaxial relative to the scanner) slices of mode 2 ($HEM_{11\delta}$). (g–i) The transaxial (coronal relative to the scanner) and the two vertical (sagittal and transaxial relative to the scanner) slices of mode 3. The B_1 distribution of this mode was similar to that of the $TM_{01\delta}$ mode, but did not have the expected axial symmetry. This was most likely due to the asymmetric perturbation introduced by the coupling circuit, which resulted in a hybrid mode between $TM_{01\delta}$ and $HEM_{12\delta}$.

FIG. 5. Schematic diagrams of the magnetic field and the electric currents in the first three dielectric resonant modes of the cylindrical water column, derived from their MR images shown in Fig. 4.

FIG. 6.

(a) This is a transaxial image of an ethanol bottle placed in the middle of an annular water ring. The $TE_{01\delta}$ mode of the water ring was used as the RF coil to collect this image. The inner bright circular region was the cross section of the ethanol bottle; the outer bright ring was the signal from the water resonator itself. The image was acquired with a GRE sequence of $TE = 5.5$ ms, $TR = 5$ s, field of view = 25 cm, matrix size = 128×256 , slice thickness = 8 mm. The uniformity of the B_1 field in this transplane of the water resonator was demonstrated by the uniformity of the signal from the ethanol bottle, (b) A cross-sectional slice of the same ethanol bottle imaged with a quadrature extremity coil. The signal-to-noise ratio of this image was compared to (a) as an indication of the efficiency of the water resonator.

FIG. 7.

The resonant spectrum of a water ring of 47 cm length, 25 cm diameter, and 1.9 cm thickness, measured from the transmission coefficient of two small shielded loops placed around the cylinder. The HEM_{11δ} mode was well defined.

FIG. 8.

This GRE image of a hand was obtained using the $TE_{01\delta}$ mode of a cylinder of D_2O on a 4 T scanner. The hand was emersed in the central region of the D_2O column. The imaging parameters were $TE = 11$ ms, $TR = 1$ s, $NEX = 2$, slice thickness = 5 mm, field of view = 20 cm, matrix size = 256×194 .