Working with Nulls, Reflections and Artifacts: Modified EM Mode Propagation in a Dielectric Waveguide at 21.1 T

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Introduction The effective propagation of electromagnetic (EM) waves inside a circular waveguide can be implemented in current MR systems for far field imaging despite the existence of nulls, reflections and artifacts intrinsic to expected propagation modes. Previously investigated in high field clinical imaging systems, traveling wave NMR can generate well resolved spectra acquired remotely as well as images with increased fields of view [1,2]. Different propagation modes can be emphasized or selected with changes to the waveguide diameter and/or wavelength of the propagating modes that alter the effective cut-off frequencies [3]. Additionally, several modes can be propagated at a distance by introducing dielectric materials (*e.g.*, high permittivity, low-loss ceramics) within the waveguide [4,5]. This work investigates materials and design modifications that impact waveguide cut-off and propagation for an ultra-high field MRI vertical system operating at 21.1 T, for which multiple TE, TM and hybrid/mixed modes are available at a Larmor frequency of 900 MHz. Optimizations of mode propagation for far field MRI are realized through alterations in **a) dielectric diameter**, **b) dielectric material** (including the sample of interest) and **c) propagation mode selection with filters**.

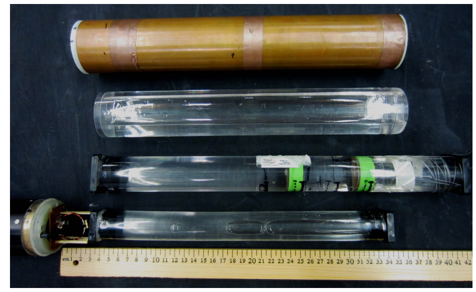
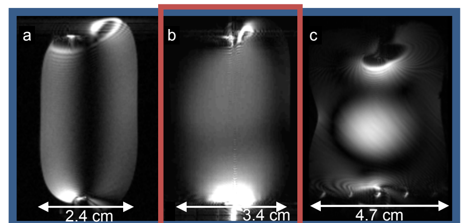


Fig. 1 21.1-T cylindrical waveguide with dielectric phantoms and orthogonal loop coil. Increasing diam. of sample tubes (bottom to top) shown with copper shield above. Image volume indicated by green tape.

Methods Common to all our experiments, excitation and reception were achieved using a single impedance-matched split 2.4-cm loop coil for both transmission and reception aligned so that its *B* field was orthogonal to the B_0 field of the vertical magnet (Fig 1). To support mode propagation, a partially filled waveguide setup was introduced with a concentric dielectric sample inserted into the copper cylinder over its entire length (25 cm) from the loop to the imaging volume defined by the gradients. Data were acquired using 2D and 3D FLASH sequences. **a) Dielectric diameter:** Three different sample diameters (4.7, 3.4 and 2.4 cm) were evaluated (Fig 1). For each, deionized water (ε_r = 80) was used as both the dielectric and the sample of interest while the copper cylinder was maintained at a 5.5-cm diameter. **b) Dielectric materials:** Three different dielectric materials were utilized: a high permittivity, low-loss calcium titanate slurry ($CaTiO_3$, Alfa Aesar, Ward Hill, MA, USA, ε_r = 110, tanδ = 0.02), a moderate permittivity, moderate-loss DI water (ε_r = 80, tanδ = 0.04), and a lower permittivity, high-loss saline solution (2.5-M NaCl in deionized water, ε_r = 55, tanδ = 5.4). In all cases, a DI phantom in a 50-mL centrifuge tube was used as the sample. **c) Mode selection with filters:** Filters were introduced into the concentric DI dielectric sample: a 7-tube, honeycomb arrangement of D_2O (ε_r = 80) and a solid ceramic disk of sintered $CaTiO_3$ (ε_r = 156). Filters were applied singly and in tandem at the entrance and exit of the imaging volume.



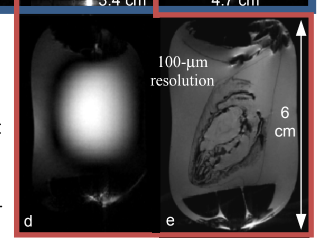


Fig. 2 Blue box: 2D GRE of DI phantoms with diameters (cm): a) 2.4, b) 3.4 & c) 4.7 using an orthogonal coil. Red box: D_2O filters applied to d) the same DI phantom as in (b) and e) a fixed mouse head immersed in a 0.9% saline bag immersed within the DI phantom. Note absence of artifacts related to gradient nonlinearities and altered mode pattern.

Results & Discussion **a) Dielectric diameter** (Figs 2a-c; blue box) has a significant impact on mode selection as shown by images acquired with the orthogonal coil. The smallest diameter (2a) shows a pure symmetric B_1 field, suggesting a $TE(M)_{01}$ mode, while the middle diameter (2b) displays a dominant TE_{11} mode, and the largest diameter (2c) displays a mixed hybrid mode. These changes altered the effective cutoff frequency of the waveguide. **b) Dielectric materials:** Fig 3 displays images of a DI-filled centrifuge tube using either DI or $CaTiO_3$ as the dielectric waveguide to demonstrate similarities (with some refinement) between the dielectrics. Notably, neither 2.5-M saline nor mineral oil used as dielectrics were capable of propagating modes within the cylindrical waveguide, underscoring the necessity of a high permittivity low loss dielectric insert. Subsequent imaging of dielectric samples with propagating waves (Fig 4) over a range of permittivities demonstrated the lack of mode penetration in samples with significantly lower dielectric coefficients. Though displaying similar modes as DI water, the $CaTiO_3$ dielectric demonstrated an improvement in the homogeneity of signal distribution as seen from flip angle map comparisons (not shown). Although used in this study as a convenient non-protonated dielectric for mode propagation, high permittivity low loss ceramics such as calcium titanate ($CaTiO_3$) have been used in their own right as dielectric resonators and absorbing pads for the improvement of B_1 homogeneity in high field systems [5,6]. **c) Filters** were placed at the entrance and exits of the imaging volume (Figs. 2d-e) to minimize artifacts from gradient non-linearity and reflections. D_2O filters, due to their geometric layout, effectively are "focusing" the nulls and reflections to result in purer modes that improve the RF homogeneity needed for imaging (red box). For example, this filter setup was able to significantly improve an image of a preserved excised mouse head at 100-µm isotropic resolution (Fig. 2e) without artifacts and avoiding multiple null patterns from hybrid modes. Likewise, $CaTiO_3$ filters also refined mode propagation, due in part to their permittivity but also their geometry.

Conclusions This work demonstrates that traveling wave NMR at ultra-high fields has potential for MRI studies through careful manipulation of excited modes. Alterations in dimension and dielectric materials within the waveguide setup as well as filter placement were added easily to an already available probe showing this implementation's simplicity for vertical systems. Of the variables analyzed, diameter of the dielectric had the most impact on mode selection. Dielectric waveguides composed of high permittivity, low-loss materials show promise for improved wave propagation, specifically improvements in *SNR* and RF field distribution. Furthermore, dielectric and geometric filters placed within the waveguide can be used to select modes within the imaging volume.

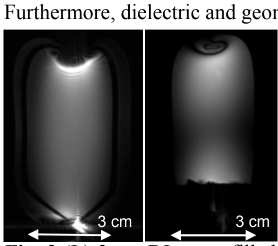


Fig. 3 (L) 3-cm DI water-filled centrifuge tube imaged in 3.4-cm DI dielectric; (R) DI tube imaged in $CaTiO_3$ dielectric.

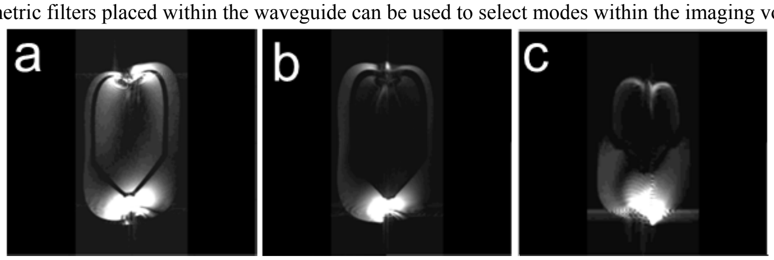


Fig. 4 Examination of mode propagation over a range of dielectric samples. Using the cylindrical waveguide and concentric 3.4-cm DI dielectric, different dielectrics were imaged in 3-cm centrifuge tubes centered within the gradients.
a) 110-mM saline, b) polyethylene glycol & c) 2.5-M saline. Note reduced RF penetration in lower permittivity materials of panels b) and c).

Acknowledgements & References

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