Traveling Wave MRI in a Vertical Bore 21.1-T System

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Introduction Traveling wave MRI relies on the propagation of time and spatially variant RF waves inside a scanner using a waveguide [1], namely the bore/shield of a scanner or a specially constructed metal enclosure. This technique has been developed and implemented at 7.0 T on clinical scanners [2]. At 7 T, only the lowest TE_{11} mode of the cylindrical waveguide can propagate in a hollow bore due to stringent cut-off wavelength requirements. However, with the higher fields of pre-clinical animal and vertical magnets, the typical diameter of the open bore is usually small compared to the free-space critical wavelength of the propagating mode in such a waveguide. Under these conditions, other modes of a cylindrical waveguide (hybrid, TM as well as higher order TE modes) are allowed, particularly through the use of high permittivity dielectrics [3-5]. An alternative solution to the cut-off problem is a coaxial waveguide [6], although at the price of a limited field of view (FOV) and heavy obstruction within the bore. In this work, a cylindrical waveguide capable of operating in the traveling wave regime (below the free space cut-off frequency) is demonstrated in a vertical 21.1-T ultra-wide bore magnet. Uniquely, aqueous samples provide the high permittivity required to modify the cut-off requirements of this transmission system. Coupled with a simple transceive loop coil, the arrangement yields a novel cylindrical waveguide filled partially with a concentric high dielectric sample capable of transmitting and receiving traveling waves in the far field. Further, the ease of construction and implementation of this setup permits for use in a variety of high field systems.

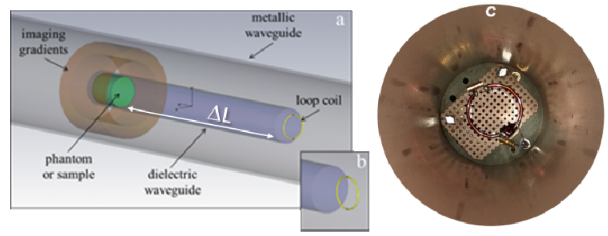


Fig 1: Schematic of a cylindrical waveguide for 21.1 T for (a) parallel and (b) orthogonal coil orientations. c) Tx/Rx loop coil near the bottom of the copper shield without dielectric rod. ΔL – offset of imaging volume from coil = 24 cm

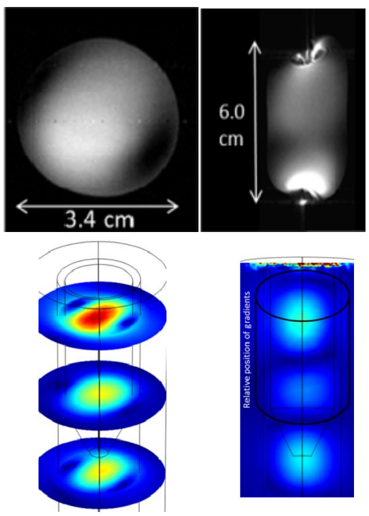


Fig 2: MR images (top) & corresponding simulated B_1 maps of TE_{11} mode (bottom) of DI phantom for the orthogonal coil configuration: a) axial 2D GRE; b) sagittal 2D GRE with signal distortion outside the linear region of the gradients. Dark regions in MRI represent nulls of TE_{11} mode.

Methods & Materials This effort focused on employing a vertical 21.1-T system with a clear bore of 10.5 cm, proton Larmor frequency of 900 MHz (33.3-cm free space wavelength) and critical wavelength λ_{cr}=18 cm for the TE_{11} mode. With the inclusion of gradients, the system provides an available diameter of 6.4 cm. The cylindrical waveguide (Fig.1) consists of concentric a copper shield (34-cm length and 5.4-cm diameter) and an acrylic tube (30-cm length and 3.4-cm diameter). For initial experiments and computational considerations, the inner acrylic tube was filled entirely with distilled water (DI; ε_r=80), which serves both as a high permittivity dielectric for the waveguide and as the sample of interest. For a non-conductive dielectric with ε_r=80, the lowest propagating traveling wave would have a spatial period of 3.8 cm along the *z*-axis. A simple, impedance matched pickup loop coil (2.4-cm diameter) was instituted to couple into the waveguide for both transmission and reception of propagating modes; this coil could be positioned such that its normal B field component was either parallel or orthogonal to the main B_0 field. Under these conditions, such a screened dielectric waveguide supports multiple propagation modes with λ_{cr}>4.4 cm. Mode selection is induced partially through coil orientation with respect to dielectric interfaces. Images were acquired using 2D and 3D gradient recalled echo sequences with minimum echo times (<5 ms) and moderate repetition times (>150 ms). Transmission power was set by maximizing the receive signal. To simulate propagation modes under these conditions, a finite element method (COMSOL Multiphysics, Burlington, MA) was employed to analyze the screened dielectric waveguide using a concentric non-conductive dielectric rod of ε_r=80 with varied conductivities within the imaging volume.

Results & Discussion Experimental images of DI water are shown in Fig 2. The traveling wave method provides a large FOV (~6 cm) along the *z*-axis limited by the physical length and 3D linearity of the imaging gradients. These phantom images were obtained with the orthogonal coil orientation and yield TE_{11} mode as expected from analytical and numerical simulations. To further demonstrate the capability of the technique, high-resolution 3D *ex vivo* images of a preserved mouse head immersed in 0.9% saline were acquired using a parallel coil (Fig. 3). Notably, the different dielectric of the tissue and saline as well as the presence of a conical centrifuge tube still generates a reasonable image with a null pattern similar to the TE_{01} mode, which is expected for parallel coil excitation. In practice, some mode asymmetry and multimode hybrid excitation for this cylindrical arrangement is apparent in MR images and simulations when no special mode filtering or selection is applied.

Conclusion Traveling wave MRI in an ultra-high field vertical MR system was achieved with an appropriate cylindrical waveguide and a high permittivity dielectric sample to enable propagation beyond cut-off for imaging in the far field. Theory and simulations corroborate the observed propagating mode structure. The applicability of the above methods relies on propagating wave properties, which are much more pronounced at ultra-high fields (due to smaller wavelengths) of small bore systems. While these systems potentially benefit most from this implementation, the impact and utilization of high dielectric materials/samples as an integral part of the waveguide may be significant for clinical MRI systems [7], particularly with continuing increases in B_0 field strength that are under construction and in planning.

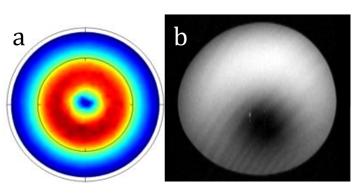
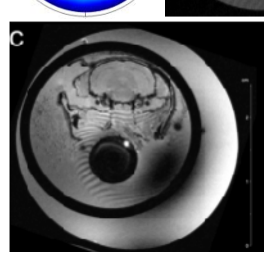


Fig 3: Axial slices of DI phantom within the screened dielectric waveguide with null pattern similar to TE_{01}: a) simulations, b) experiment (Tx/Rx loop coil in parallel orientation wrt B_0 field);



c) *Ex vivo* coronal partition from a 3D dataset of a fixed mouse head immersed in 0.9% saline within a centrifuge tube centered in the imaging volume. The 3D GRE image (100-µm isotropic resolution) was acquired using a concentric DI dielectric tube and parallel coil. TE01 mode dominance persists.

Acknowledgements: Experimental data were acquired at the National High Magnetic Field Laboratory, Tallahassee, FL, USA with funding from the NSF (DMR-0084173 and NHMFL User Collaborations Grant Program).

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