Below Cut-off Traveling Wave NMR at 16.4T: Interference of Propagating Modes in a High Dielectric-filled Waveguide

Alexey Tonyushkin[1], Gregor Adriany[2], Dinesh Deelchand[2], Michael Garwood[2], and Andrew J M Kiruluta[1]

[1]*Radiology Department, Massachusetts General Hospital, Harvard Medical School, Boston, MA*

[2]*Center for Magnetic Resonance Research, University of Minnesota Medical School, MN*

email: alexey@physics.harvard.edu, kiruluta@physics.harvard.edu

INTRODUCTION

Traveling wave NMR is a far-field imaging technique that relies on successful mode propagation in a waveguide utilizing the magnet bore of a scanner. This approach was originally experimentally demonstrated at 7 T [1], however, the main challenge for the traveling wave propagation in most conventional NMR scanners/spectrometers is the relatively small bore (a) to wavelength ratio (a/λ) even at ultra-high field strengths. For example, in a 7 T human-size MR system with the bore diameter of 60 cm and at a resonant frequency of 298 MHz (free space wavelength λ=100.6 cm), only a single mode (TE_{11}) will propagate in an unloaded bore. To date this is the only MR system with sufficient a/λ ratio for wave propagation within an unloaded bore of the scanner. The wavelength of the traveling excitation field scales inversely with the square root of permittivity (ε_r) and hence cut-off requirements can be met in a small bore scanner using a high enough dielectric in the bore [2]. Alternatively, a coaxial transmission line [3] enables TEM mode propagation without cut-off but requires a conductor to be placed in the middle of the bore thus restricting the imaging volume and the practicality of the approach. In this work, we utilize the first approach of partially filled dielectric waveguide [4] and demonstrate traveling wave NMR experiments in a 16.4 T (Varian) horizontal bore small animal NMR imaging system. Coupled with a simple transmit-receive loop coil (D=8 cm), the setup (see Fig. 1) utilizes a high dielectric (saline or deionized (Di) water) material within a cylindrical waveguide to achieve a traveling wave regime that allows the propagation of multiple TE or TM modes [5] including evanescent field coupling and imaging of an nearby phantom object (Fig. 4).

MATERIALS & METHODS

The system of interest has a magnet bore of 26 cm with a resonance frequency of 698 MHz (λ=43 cm). A gradient insert further reduces the usable diameter to 10 cm. Such system allows a single TE_{11} mode propagation if we have a uniform dielectric with at least ε_r=10 inside the bore. Depending on the probe (loop-coil) position with respect to the dielectric and matching, we expect single or multiple TE (M) modes propagating inside a high (ε_r=80) dielectric guide.

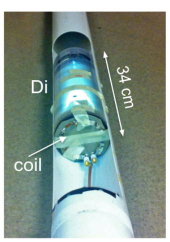
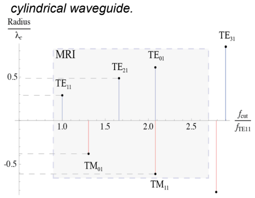


Figure 1. *Setup: a waveguide with acrylic tube filled with Di-water + loop-coil. Below: cut-off requirements in a cylindrical waveguide.*



RESULTS

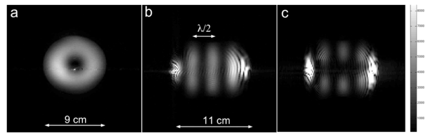
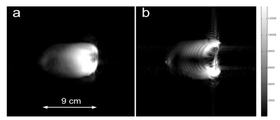


Figure 2. *MR images of Di-water phantom: axial (a), coronal off-axis (b) and on-axis (c). Dark spot in the center (a) and horizontal strip (c) is the null of TE_{01} mode. Vertical stripes (b, c) are interference fringes with period λ/2=3 cm. (Curved bright spots on the edges (b, c) and ringing are artifacts from gradient edges.)*



Parallel coil arrangement

Figure 3. *No interference effect: MR images of saline phantom, coronal off-axis (a) and on-axis (b). Saline conductivity strongly attenuates the reflected wave resulting in no interference fringes in this medium.*

The experimental results of imaging a dielectric tube (9x30 cm) filled with Di-water (GRE sequence with FOV=20x20 cm, TR/TE/θ = 100ms/2ms/60°, slice thickness of 5 mm for both axial and coronal slices) using a patched transmit-receive loop-coil as a probe for waveguide excitation are shown in Fig. 2. The dominant mode in the case of the loop-coil placed as shown in Fig. 1 is TE_{01}. In practice, we observed (coronal view) a standing wave pattern (Fig. 2 b, c) with three full fringes due to traveling wave reflection from the other (unmatched) end of a dielectric tube filled with Di-water. This result is remarkable, as for the first time in NMR, it shows interference effects with more than a single fringe within a FOV that utilizes whole length of the gradient insert (~11 cm).

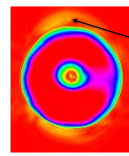
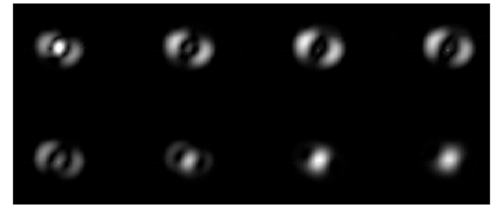


Figure 4. Evanescently imaged axial slice of a water filled tube placed next to dielectric wave guide



Orthogonal coil arrangement

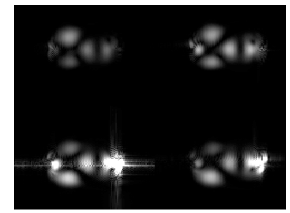
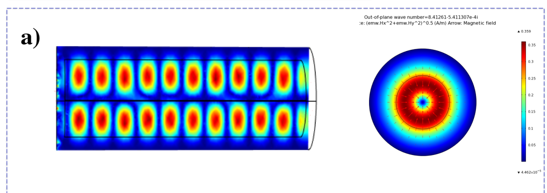
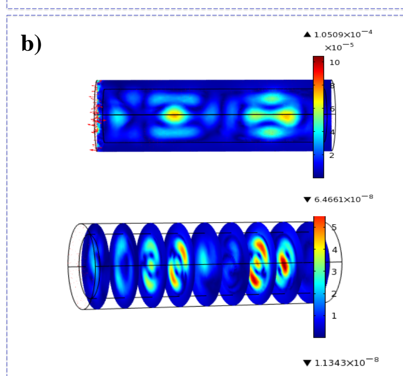


Figure 5. *Axial (top) and coronal (bottom) slices for orthogonal coil excitation show mixture of modes: TM_{11} and TE_{11} similar to Fig. 6 (b).*

SIMULATIONS





Propagation constants 1/k for various allowed TW modes (λ_{free}=43 cm, λ_ε=4.8 cm)

TE_{11} – 1/k=5cm
TE_{01} – 1/k=6cm
TE_{21} – 1/k=5.4cm

TM_{01} – 1/k=5cm
TM_{11} – 1/k=6cm

We simulated modes inside a waveguide with partial dielectric using an eigenmode solver in Comsol Multiphysics (Burlington, MA). A high-permittivity, low loss dielectric rod of DI water was placed concentrically within the cylindrical waveguide. We computed the distribution of B_1 field of dominated modes in such waveguide by using eigenmode solver as shown in Fig. 6. From the field pattern distributions, we confirmed that the waveguide supports single TE_{01} mode, as well as a mixture of modes depending on the waveguide excitation method employed and as validated by the experimental results.

Figure 6. *B1 field map of dominated modes in a partially filled dielectric waveguide: (coronal and axial) a) TE_{01} b) mixture of modes TM_{11} and TE_{11}; the arrows represent B_1 field (here and else where color bar has a relative scale).*

CONCLUSIONS

This is a first step in controlled NMR interference experiments [6], where more than a single RF wave can create interference fringes in 3D. While such demonstration is important, to advance further, we need to be able to eliminate standing waves from a single probe (loop coil) and to control the phase relationship between multiple excitation probes. A long tube with saline solution was shown, Fig. 3, to extinguish the standing wave pattern from any given single coil by dampening the reflected wave. The implications of our experiments for ultra-high field NMR include larger FOV and a possibility for new mechanisms of image encoding as well field inhomogeneity correction using conjugate imaging techniques [6].

REFERENCES

1. Brunner D.O. et al., Nature **457**: 994-999, 2009;
2. Brunner D.O. et al., MRM **66**:290–300, 2011;
3. Tang J. A. et al., Con. in Mag. Res. A **38A**: 253-267, 2011;
4. Tonyushkin A., Muniz J., Grant S., and Kiruluta AJM., to be submitted;
5. Tonyushkin A. and Kiruluta AJM, Proc. ISMRM **19**, p.1903, 2011;
6. Kiruluta A., JMR **182**: 308-314, 2006.