Traveling Wave Mode Transformation in a Waveguide with High Dielectric Medium for Ultra High Field MRI

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Introduction

Traveling waves inside a bore of a scanner can propagate as RF modes of cylindrical or coaxial waveguides. The traveling-wave (TW) concept may offer large FOV [1], new encoding mechanisms [1-3], and more comfortable environment for patients. Since MR scanners have cylindrical symmetry, the waveguides are ideally suited for far-field traveling waves MR experiments. For MR scanners, we can use both types of modes of cylindrical waveguide: TE and TM, however, only the lowest TE mode of cylindrical waveguide can propagate in a typical whole body 7.0 T scanner (60 cm bore) in empty bore due to stringent cut-off wavelength requirements. For practical MR imaging, this may not be the best mode because most of the B-field is wasted into the longitudinal component that does not result in spin flips. Fortunately for existing MR scanners, TM as well as higher order TE modes are allowed in high permittivity dielectrics [4,5], but B1 field map becomes complicated, which affects MR images. Previously, such mode excitation at high RF frequency was known in the context of dielectric resonances [6]. In this work we analyze the implications of dielectric media on the waveguide TW mode propagation by effective transformation to higher order waveguide modes.

Theory

At ultra-high field strength (>4T), the cut-off condition for the lowest waveguide mode propagation can be fulfilled provided that the bore is sufficiently large. For a 7T human system with the bore of 60 cm and the resonant frequency 298 MHz that corresponds to a free space wavelength of 100.6 cm and only a single TE_{11} can propagate inside the waveguide with no dielectric. If we insert a dielectric with a relative permittivity of $\varepsilon_r > 4$ we get the optimal condition for propagation of TE_{11} mode, which corresponds to a high value of wavenumber k_z, but other modes can also simultaneously propagate in such media depending on the excitation method.

The TE (TM) modes that provide sufficient B1 field uniformity are: TE_{11}, TM_{01}, TE_{21}, TM_{11} (Fig. 1), while most of the higher-index modes are impractical for imaging since they have high spatial variation of the B1 field.

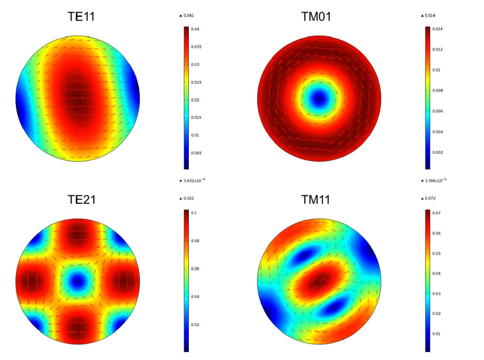

Figure 1: B1-field configuration of the first four modes of cylindrical waveguide: TE_{11}, TM_{01}, TE_{21} and TM_{11}. Arrows represent transverse magnetic field vectors; spatial magnitude of the field is depicted by the color and the arrow size. Each mode is normalized separately to cover full color range.

Methods and Results

We analytically and computationally (COMSOL Multiphysics) investigated stationary spatial distribution of magnetic field of traveling modes with and without a uniform dielectric phantoms placed inside the cylindrical waveguide that corresponds to a 60 cm diameter bore 7T system. In our 3D simulations we used a 3 m long empty cylindrical waveguide with a cylindrical uniform phantom (μ=1): diameter D=30 cm, length L=1 m, ε_r=10, 80; σ=0.78 S/m, 5.5e-6 S/m. The typical waveguide dimensions allow propagating only the lowest TE_{11} mode without dielectric insert. We investigated the field distribution in the dielectric phantom vs the relative permittivity and conductivity. The results (Fig. 2) show that unlike the empty bore where the B-field has mostly longitudinal components; there exist TM modes, where the magnetic field in the cylindrical phantom has only the transverse components. The observed field pattern implied that the field in such dielectric undergoes a mode transformation from TE to TM mode. This mode transformation is consistent with the modified boundary conditions of the dielectric cylinder. Depending on the diameter of the small cylinder and the relative permittivity we can obtain an effective transformation to the TM_{11} mode (Fig. 2, and 3a), which has a uniform transverse field profile in the central region and thus highly desirable for imaging application with traveling waves. At high (isotropic) ε_r multiple modes can propagate simultaneously, but with different dissipation rates (imaginary part of k_z) along z-axis. In practice, however, the usage of traveling modes is complicated due to the low penetration depth of the field at high RF frequency. Most of the biological tissues have a conductivity of around 1 S/m. Such a relatively high conductivity at 300 MHz results in a typical penetration depth of only a few cm. Therefore, in order to limit SAR, in human imaging studies the traveling wave method would best work in small FOV cases such as legs [7] and arms with some restriction (Fig. 3c).

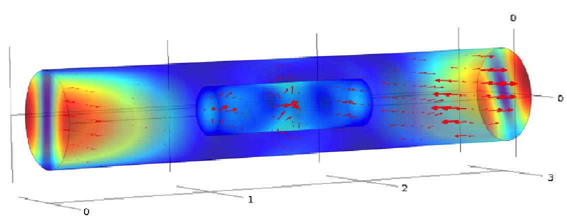

Figure 2: B-field distribution of the propagating mode in the cylindrical waveguide (D=60 cm). In the empty bore most of the field is concentrated in the longitudinal component of TE_{11}, while TM_{11} mode emerges inside a dielectric cylinder (ε_r=10, σ=5.5e-6 S/m, L=1m, D=30 cm).

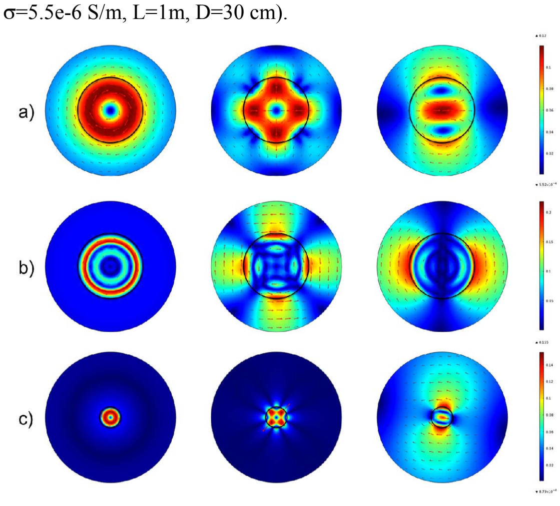

Figure 3: B1-field configuration of propagating modes in a waveguide (D=60 cm) with dielectric: D=30 cm, ε_r=10, σ=5.5e-6 S/m (a); D=30 cm, ε_r=80, σ=0.78 S/m (b); D=10 cm, ε_r=80, σ=0.78 S/m (c). The emergence of TM_{0n}, TE_{2n} and TM_{1n} modes in a sample is observed (from left to right). Higher ε_r (b), (c) offers larger variety of modes. Shallow field penetration occurs for high σ (b) and field penetration restores at smaller diameter (c).

Conclusion

Our analysis shows that for a Larmor frequency of 300 MHz in a 7.0 T whole-body scanner, traveling wave modes in dielectric samples within the range of biological tissues can be sufficient to support imaging of the body parts. The modes diversity depends on the tissue efficient diameter, relative permittivity, conductivity, and the Larmor frequency. The imaging contrast will depend on the particular modes that have been excited in the tissue. A more complicated case of heterogeneous axial symmetric dielectric can be also analyzed using effective permittivity with our approach of TW mode transformation.

References: [1] Brunner et al., Nature 2009, **457**: 994-999; [2] A. Kiruluta, JMR 2006, **182**: 308-314; [3] A. Kiruluta J. Phys D: Appl. Phys. 2007, **40**: 3043-3050; [4] J. Paska et al. Proc. ISMRM, 2010; [5] Brunner et al. Proc. ISMRM, 2010; [6] A. Kangarlu et al., J. Comp. Assist Tom. 1999, **23**: 821-831; [7] A. G. Webb et al., MRM 2010, **63**: 297–302.