Improved RF control of the travelling wave MR using a multi-mode coaxial waveguide.

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Introduction

RF multi-transmit relies upon a tailored complex combination of B_1^+ fields to manipulate the total RF excitation field. The individual B_1^+ fields of the transmit elements can be seen as basis functions to construct a desired excitation pattern. An alternative concept is to use a superposition of modal fields of the closed waveguide formed by the cylindrical RF screen [1]. Such a concept connects naturally well with a multi-transmit travelling wave system. A sum of modal fields can span any B_1^+ field distribution based on the completeness of the infinite set of modes inside a closed waveguide. Thus, in terms of B_1^+ steering it is advantageous to excite as many modes as possible providing a larger set of orthogonal basis functions. Here we demonstrate a multi-transmit travelling wave setup with a coaxial feeding section [2] capable of supporting several modes for optimal RF shimming performance. Selective mode excitation is performed in the coaxial feeding section at a distant location from the sample. The cut-off frequencies of the higher order modes were tuned under 300 MHz by placing a circular array of densely packed water tubes along the RF screen. Such a dielectrically lined waveguide can support surface modes with similar field patterns and B_1^+ efficiency as normal volume waveguide modes but are less susceptible to RF attenuation [3, 4].

Methods and materials

With the coaxial feeding in place the scanner's bore is divided into two sections: a cylindrical waveguide section where the load is located and a coaxial feeding section with 8 antennas (stubs). See Fig. 1. Each stub was matched to 50 Ohm and coupling did not exceed 10 dB. EM field distributions in the phantom were simulated with using the FDTD method (SEMCAD, SPEAG, Zurich, Switzerland). For MR experiments the 8 channel coaxial feeding section and the phantom were placed in the bore of a 7T MR scanner. To demonstrate the effect of the increased number of modes present with water tubes in place, simulations as well as measurements were performed for 9 and all 32 tubes present. In the experiments the B_1^+ field patterns were measured with the AFI method (TR_1 = 50 ms, TR_2 = 250 ms). The B_1^+ phases were acquired with interleaved GRE measurements with two echo times (TE_1 = 3.89 ms, TE_2 = 4.89 ms) [5]. Cut-off frequencies of the several modes were estimated for the coaxial and cylindrical sections with and without the water tubes by solving analytically the 2D Helmholtz equation. From waveguide theory the first mode number *n* is the order of the complex exponential *exp{-jnφ}* which defines azimuthal dependence of the mode's EM field. The relative mode intensity in the given transverse field pattern can be calculated by Fourier transformation as the *exp{-jnφ}* functions form Fourier basis. We refer to this as the angular mode spectrum.

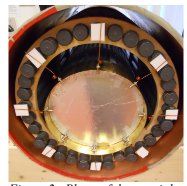

Figure 2. Photo of the coaxial feeding.

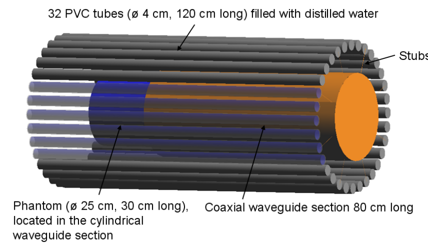

Figure 1. The set-up. Phantom contains 3 gr/l saline solution (er=80, cond=0.3 S/m). The coaxial waveguide is formed by the scanner's RF shield/ bore (ø 58 cm) and a hollow cylindrical inner conductor (ø 32 cm). Electrical permittivity of the tubes is 80. To perform mode excitation in the coaxial waveguide 8 transverse stubs were placed around the inner conductor.

Mode	No water tubes		Water tubes	
	Coax., MHz	Cyl., MHz	Coax., MHz	Cyl., MHz
TE11	**211**	**292**	50	**184**
TM01	1100	385	**260**	**211**
TE01/TM11	1100	610	**270**	**230**
TE21	420	485	**100**	**205**
TE31	620	677	**150**	**212**

Table 1. Cut-off frequencies of some lower order modes in the coaxial and cylindrical waveguide sections without and with water tubes.

Results and discussion

Cut-off frequencies evaluation showed that without water tubes only a single propagating TE_{11} mode is present in both the coaxial and cylindrical sections; higher order modes are evanescent. Inserting water tubes significantly increases the number of propagating modes in the coaxial and cylindrical sections (Table 1). The dielectric layer (water tubes) supports propagation of surface modes in both coaxial and coaxial waveguides (Fig. 3). Although most power is located in the tubes, a strong B_1^+ field can be generated in the load. These surface modes experience minimal attenuation and reflection while propagating from the coaxial into cylindrical waveguide. Measured B_1^+ fields of individual stubs correspond well to the simulations results (Fig. 4). Presence of more water tubes increases B_1^+ efficiency as well as the spatial diversity. This implies that a larger number of modes are being excited by a single channel. To demonstrate this we supplied the stubs with a phase modulation corresponding to a TE_{11} and TE_{31} mode respectively As can be seen from Fig. 5 (bottom row) our antenna geometry is able to selectively excite the desired mode patterns. The obtained B_1^+ fields for both mode excitations differ significantly for the 32 water tubes. In case of 9 water tubes almost no difference is observed suggesting that no 3rd order mode is present. In addition, the angular mode spectra from the simulations confirm that fewer modes are present in case of 9 water tubes compared to 32 tubes (Fig. 6, left and middle spectra). The presence of at least 5 different modes was also confirmed by the angular mode spectrum of the B_1^+ measurements for the 32 tubes (Fig 6, right spectrum). Thus, the higher angular spatial diversity supplies us an optimal control of the excitation field in the cylindrical section. Comparison of the relative intensities change for the 1 and 0 order modes with increasing distance from the coaxial sector shows much less attenuation of these modes in the cylindrical waveguide when more water tubes are present (Fig. 7) .

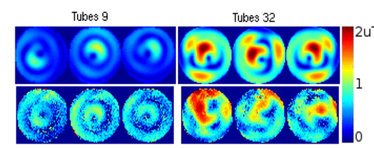

Figure 4. Simulated (top row) and measured (bottom row) B_1^+ fields of the three stabs, located at 0°, 45° and 90°.

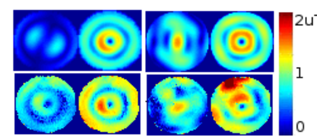

Figure 5. Simulated (top row) and measured (bottom row) B_1^+ fields of the TE_{11} and TE_{31} imposed modes with 9 and 32 water tubes.

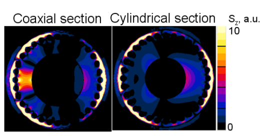

Figure 3. The transverse distributions of the z-component of the Poynting vector in the coaxial and cylindrical waveguides. The high intensity of the pointing vector at the surface of the scanner bore indicates that the most power is carried by surface modes.

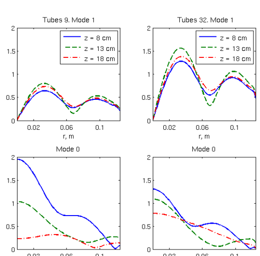

Figure 7. Estimated from the simulations Simulated relative intensities of 2 modes for 9 (left) and 32 (right) water tubes at the.

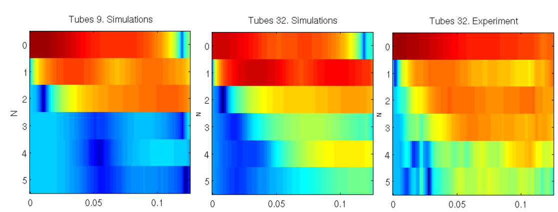

Figure 6. Spectral intensities of the first 5 modes (with patterns proportional to the product of N-order Bessel function ($J_N(kr)$) and complex exponential $e^{-jN\varphi}$, N =0..5) were calculated based on Fourier transform of B_1^+ fields along azimuthal angle φ in the cylindrical phantom: simulated in case of 9 water tubes (left) and simulated (middle) and measured (right) for 32 water tubes. On the vertical axis first mode number N is plotted, the horizontal axis represents the radial distance.

Conclusions We have demonstrated that with our waveguide design, a large number of distinct modal B_1^+ patterns can be selectively excited by an 8 channel coaxial feeding. The presence of more water tubes in both the feeding and imaging sections preserves B_1^+ control even at the distant locations from the feeding section. This confirms the advantage of using a multi-transmit travelling wave system based on surface modes rather than conventional volume modes, for optimal B_1^+ steering.

References [1] Brunner D.O. et. al., Proc. 18th ISMRM 2010; [2] Andreychenko A. et al., Proc. 17th ISMRM 2009; [3] Mahmoud S.F., "Electromagnetic waveguides", 1991: Peter Peregrinus Ltd.; [4]Van den Berg C.A.T. et al., Proc. 17th ISMRM 2009; [5] Van Lier et al., Proc. 18th ISMRM 2010.