Electromagnetic Field Evaluations Inside a Body-Tissue-Simulating Cylinder Phantom Excited by an Ideal First-Order Circularly Polarized Mode

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INTRODUCTION and OBJECTIVES: The RF field excitation homogeneity problem of MRI at high resonance frequencies is investigated on the basis of the simplest two-dimensional setup including a cylinder phantom with spatially constant but frequency-dependent material parameters and an impressed surface current distribution between the phantom's surface and a surrounding perfect electric conductor (PEC) shield. This simple arrangement has been chosen intentionally in order to reduce the set of parameters to a minimum and therefore maximize the physical insight, which allows quite general and helpful statements about the B1+ pattern quality for the widely used first-order circularly polarized (CP) excitation mode. The coefficient of variation (CoV) of the B1+ distribution is most suited as a figure of merit for the homogeneity, since it normalizes the standard deviation to the mean value of the field pattern. Only two parameters of the arrangement in Fig. 1 have been varied – the excitation frequency ranging from 30 MHz up to 450 MHz and the diameter of the phantom ranging from a few centimeters up to 40 cm, which covers more or less every MR imaging scenario. A characteristic B1+ pattern will be introduced, which indicates the transition between a regime with the well-known central brightening and another one without.

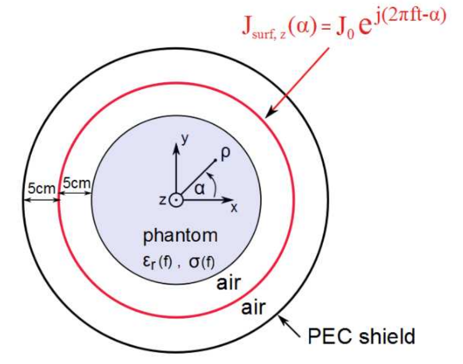

Fig. 1: Ideal 2-D setup including the cylinder phantom w/ frequency-dependent material parameters and varying diameter, the active sheet with impressed surface current (J_0 = 1 A/m) distribution 5 cm away from the phantom's surface, and the PEC shield with a further 5 cm separation.

MATERIALS and METHODS: The electromagnetic field problem was solved numerically by the full-wave finite element method (FEM) solver COMSOL Multiphysics. As mentioned before, only the phantom diameter and the RF excitation frequency were varied. Due to the two-dimensionality of the problem (cf. Fig. 1), one simulation took less than 10 seconds, allowing us to reduce the step width to 10 mm and 5 MHz, respectively, yielding a reasonably smooth two-dimensional CoV contour plot, as given in Fig. 3. The mean value and standard deviation of the field pattern were calculated inside the whole 2-D phantom via the built-in MATLAB routines. For each frequency-domain FEM simulation, the phantom's material parameters were set as specified in the corresponding standard for the body-tissue-simulating liquid (BTSL) [1]. A corresponding plot is given in Fig. 2. Due to the rotational symmetry of the geometry and field excitation magnitude ($|J_{surf,\,z}|$) as shown in Fig. 1, the B1+ magnitude depends only on the radius coordinate ρ, thus a 1-D plot is sufficient (cf. Fig. 4).

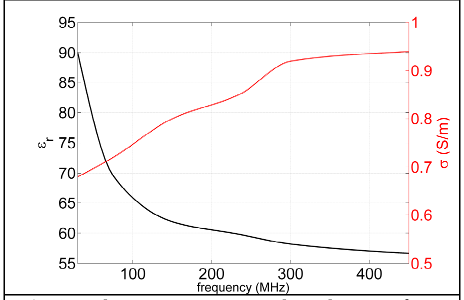

Fig. 2: Relative permittivity and conductivity for the standardized body-tissue-simulating liquid (BTSL) as a function of frequency [1].

RESULTS and DISCUSSION: The main result of this contribution has been condensed in the contour plot given in Fig. 3. The CoV of the B1+ magnitude inside the phantom is depicted by a discrete set of constant CoV contour lines for different MR frequencies (x-axis) and different diameters (y-axis). The CoV values along these lines range from 1 % up to 50 %. Quite often a CoV of 10 % is considered to be sufficient for most MRI applications [2]. For proton imaging at 3 Tesla, such a relatively low CoV is only ensured up to a diameter of 200 mm (cf. red dot in Fig. 3). Thus, in the case of whole-body imaging, the simple birdcage-based first-order CP mode is no longer sufficient if a CoV of less than or equal to 10 % is required. For ultra-high-field systems ($B_0 \geq 7$ T) such a 10-%-CoV is possible only for extremely small, and therefore non-practical, phantom diameters (cf. Fig. 3). For this inhomogeneous situation, an alternative upper limit for the usage of the simple birdcage mode is proposed. The corresponding B1+ pattern is shown in Fig. 4 (lower case), where the B1+ magnitude at the center of the phantom is equal to the mean value inside the whole phantom. This pattern with its typical characteristic can also be defined as the limiting distribution where the constructive interference at the center (also known as central brightening) is vanishing. The B1+ patterns of Fig. 4, which are normalized to the square root of the accepted power, show also a reduced mean value of the "center-equals-mean" pattern compared to the 10-%-CoV distribution. Consequently, more power is necessary for the case of a larger phantom.

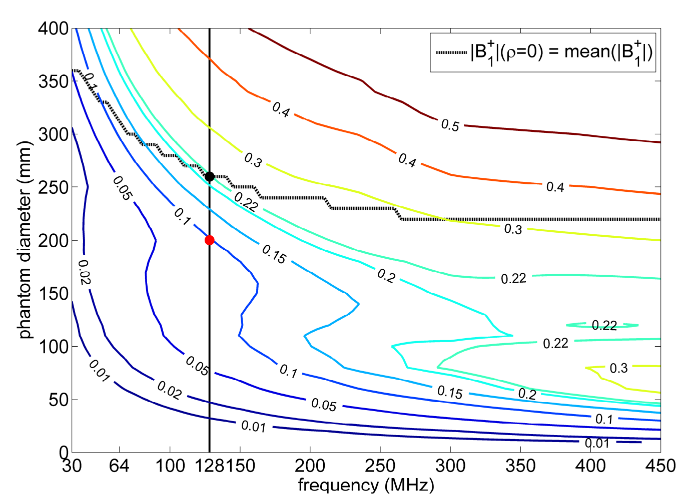

Fig. 3: Contour plot of the coefficient of variation (CoV) of the B1+ magnitude inside the phantom as a function of frequency (x-axis) and phantom diameter (y-axis) – with a border line between regimes w/ and w/o central brightening.

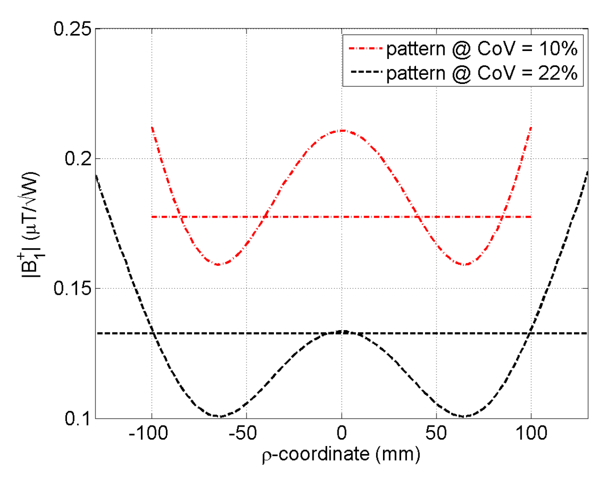

Fig. 4: B1+ distributions and corresponding mean value levels at 128 MHz for two phantom diameters, representing characteristic patterns: the 10-%-CoV distribution (top) and the "center-equals-mean" pattern (bottom), which marks the end of central brightening.

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