A Comparison of FDTD-Solvers for Simulation of a ^{31}P Birdcage Coil at 1.5 T

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Introduction: The Finite-Difference Time-Domain (FDTD) method, introduced in 1966 by Yee [1], has since proven to be an efficient method for the simulation of a wide range of electromagnetic problems. As such, it is a valuable tool for MR researchers, as it can be used to assist in the RF coil building process, for coil performance evaluation, SAR estimation or simulated MR experiments. The wide range of available software packages, like XFdtd (Remcom, USA, State College, PA), Microwave Studio ("MWS", CST, Darmstadt, Germany) or SEMCAD (Schmid & Partner Engineering (SPEAG), Zürich, Switzerland), poses a challenge for exchanging and directly comparing simulation models and results. Different specialized additions to the FDTD method, like conformal surface treatments [2], modifications of the original algorithm (e.g., Finite Integration Technique “FIT” in MWS) and the use of proprietary algorithms and algorithm names for these modifications (e.g., Perfect Boundary Approximation “PBA” in MWS; XACT Accurate Cell Technology in XFdtd) give rise to the question of comparability of the results obtained by different software packages. This question is especially important if a coil builder plans to base the safe operation limits for a new coil on SAR values calculated by such a simulation. In order to explore this question we simulated a low-pass birdcage head coil for ^{31}P imaging at 1.5 T (RAPID Biomedical, Rimpar, Germany) in XFdtd, MWS and SEMCAD and compared the results. This evaluation was triggered when we were privately informed that simulations of the identical coil, performed by three independent professionals using the aforementioned programs, seemingly came to results differing by as much as 100%.

Methods: The eight-rung quadrature low-pass birdcage has a diameter of 265 mm and a leg length of 272 mm. A cylindrical phantom load (d=l=20 cm; ε=76; σ=0.33 S/m, ρ=1000 kg/m³) was placed in the coil center. The coil model was imported into each program via a CAD file to ensure identical geometry. Inside the phantom, a minimum mesh cell size of 2×2×4 mm^3 was enforced; fixed points at geometrical key features of the coil ensured an accurate representation. Conformal boundary approximations were enabled if available (MWS: “PBA”, XFdtd: “XACT”). All three simulations contained roughly 7 million mesh cells and similar mesh cell sizes. A convergence of -40 dB was used as steady-state criterion; the excitation was performed via a 50 Ω voltage source delivering a broadband pulse. The resulting fields were exported into MATLAB, scaled to 1 W of net transmitted power (that is after compensating for any coil mismatch) and finally re-gridded from the non-uniformly spaced mesh cells to a regular grid using a linear interpolation method to allow a comparison on the voxel level. The results of each program were compared to B_1^+ and |E| reference fields (Fig. 1) obtained by averaging over all three simulations.

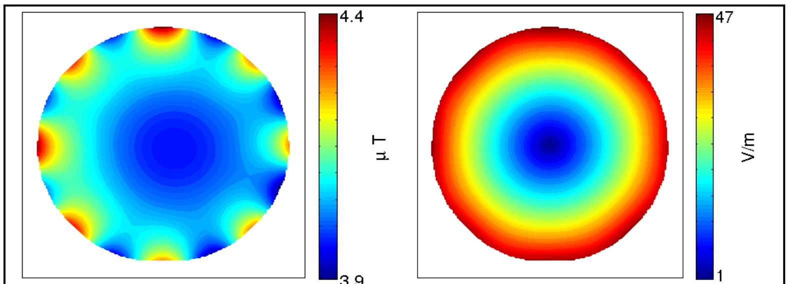

Figure 1: Center slice B_1^+ (left) and |E| (right) fields; averaged over all three simulations. Each single field pattern closely agrees with the shown average.

Results: The overall results (Table 1) show a very close agreement between the simulations. Slight differences in the frequency f_{res} of the CP mode can be attributed to coil inductance variations resulting from different FDTD meshes. The simulated field patterns agree closely throughout the whole phantom volume. The absolute per-voxel deviations of each $|B_1^+|$ and |E| field from the mean fields (Figure 1), averaged over the full volume, are 1.5% and 2.3%, respectively. Great care was taken to ensure the alignment of the data. Nevertheless, a residual positional mismatch due do the discrete nature of the problem and the different meshes cannot be avoided. This introduces artificial field deviations, especially in |E|, if the center voxels are not exactly aligned. SAR values are very similar as well, although the differences are higher due to the quadratic dependence on |E|.

	MWS	XFdtd	SEMCAD
Center B_1^+ /μT	3.95	3.88	3.99
Avg. SAR /W kg^{-1}	0.151	0.142	0.146
Vol. Avg. $\left\|B_1^+ - \overline{B_1^+}\right\| / \overline{B_1^+}$ /%	0.2	1.5	1.4
Vol. Avg. $\left\| \|E\| - \overline{\|E\|} \right\| / \overline{\|E\|}$ /%	1.8	2.3	1.4
f_{res} /MHz	24.57	23.97	24.08
$\|S_{11}\|$ at f_{res} /dB	-3.4	-3.3	-3.4

Table 1: Aggregate simulation results and comparison statistics

Discussion and conclusions: The simulation comparisons show that, apart from user interface preferences, the choice of simulation environment is mostly irrelevant regarding the similarity of the results. Although trivial in principle, care needs to be taken when scaling the obtained fields to the same power. First of all, naming conventions for different measures of power (incident, reflected and transmitted; real, reactive, complex…) are not consistent throughout the programs. Secondly, the scaling can be done with respect to, e.g., either incident-, transmitted or even dissipated power in the phantom load. While each of these procedures is valid, it is imperative to provide full details on how the calculation was done and additionally disclose all data required for scale conversion. For the user, it is not advisable to implicitly rely upon the automatic scaling features. Full field combination, post processing and scaling starting from the complex port signals should be performed manually at least once to ensure the automatically calculated results are as expected.

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[1] Yee, K.S., “Numerical solution of initial boundary value problems involving Maxwell’s equations in isotropic media,” *IEEE Trans. Antennas Propagat.*, Vol. 14, 1966, pp 302-307
[2] Yu, W., and R. Mittra, “A conformal finite difference time domain technique for modeling curved dielectric surfaces,” *IEEE Microwave Wireless Components Lett.*, Vol. 11, 2001, pp. 25-27