A system for calibrated measurements of RF electromagnetic fields inside a clinical MR scanner

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Target Audience: Basic researchers and scientist relying on electromagnetic simulations for evaluation of RF safety

Purpose: Simulations are commonly used to evaluate the electromagnetic fields (EMF) and the specific absorption rate (SAR) experienced by patients during MR investigations. However, frequently the accuracy of such EMF simulations is either not questioned at all or at best tested by comparison to measured $|B_1^+|$ maps. For reliable SAR assessments, however, all E and B field components from a simulation have to be validated by measurements. Calibrated, time-domain field sensors with fiber optic readout allow reliable measurements of complex field amplitudes in an MR environment. Phantom experiments are best suited to assess the accuracy of EMF simulations with such sensor based measurements as only phantoms provide a controlled and well known environment.

Methods: An ASTM body phantom[1] filled with a tissue equivalent liquid based on TWEEN 20 [2] was equipped with 5 inner tubes for *internal* E and B field measurements (Fig 1a). In order to allow *external* field probe measurements as well, a gantry was designed for well-defined positioning of the sensors outside of the phantom. At 128 MHz the dielectric properties of the phantom liquid were measured to be ε= 62.7 and σ=0.81 S/m. For the in-situ calibration of the sensors an MR compatible TEM cell [3] was used with improved design with respect to field homogeneity, geometrical precision, and mechanical stability (Fig 1b). Running the cell as a Tx/Rx-MR-coil in the isocenter of a 3T MR scanner (Siemens Verio) and putting a 10 mm water filled polyethylene sphere in one compartment, the transmitter voltage V_{ref} required for a 90° flip angle using an 1ms block pulse can accurately be determined with a B_1-mapping sequence. With V_{ref} applied, $|B_1^+|$ = 5.872 µT inside the cell and the E field is given by $|\mathbf{E_1}| = |E_{1y}|$ = 3520 V/m [3]. As field probes we used a time-domain fiber optic E field sensor (OEFS–S1B, Seikoh Giken) and a home built B field loop connected via a time domain electro-optic transducer (PH-0655, Seiko Giken) and a 10 m optical fiber to the controller of the OEFS sensor system. B_{1x} and B_{1y} components were measured by rotating the loop in 90 degree steps around the z-axis, whereas all 3 field components of $\mathbf{E_1}$ could be measured by rotating the sensors in 120 degree steps around the z-axis [3]. From these measurements the complex amplitudes B_1^+ and B_1^-, as well as $|E_1| = \mathrm{sqrt}(E_{1x}^* E_{1x} + E_{1y}^* E_{1y} + E_{1z}^* E_{1z})$ can easily be derived. Both field sensors were calibrated immediately before each measurement with the calibration setup positioned on the patient table of the scanner together with the phantom (Fig. 1c). For comparison, EMF simulations of the phantom within the body coil of the scanner were performed using Microwave Studio (CST, Darmstadt, Germany).

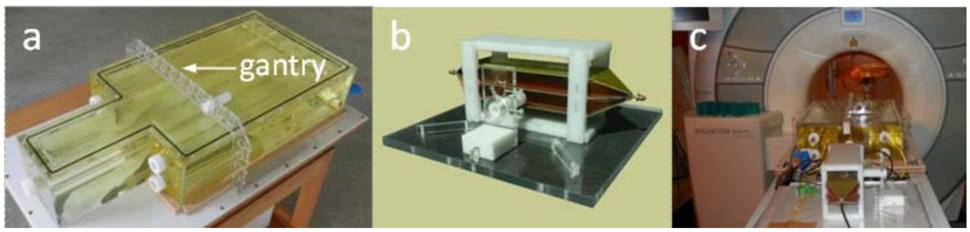

Figure 1: a) ASTM-like phantom with gantry for sensor positioning, b) MR compatible TEM cell with base plate and sensor mount, c) setup for calibrated E and B field measurement on the patient table.

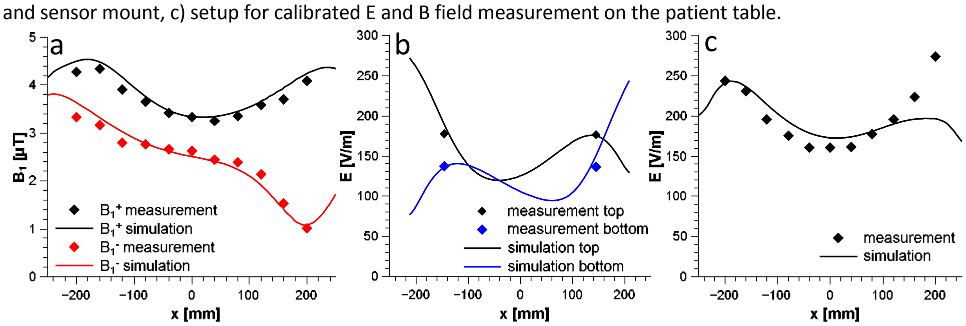

Figure 2: $|B_1^{\pm}|$ and $|E_1|$ field measurements and simulations (without any scaling) in an axial plane through the isocenter (z = 0), with the "head" end of the phantom at z = - 470 mm, using the body coil at a nominal power of 1 kW, a) external $|B_1^+|$ and $|B_1^-|$ on top of the phantom, b) internal $|E_1|$ in the tubes inside the phantom, c) external $|E_1|$ field on top of the phantom.

Results: External and internal time-domain $|\mathbf{E_1}|$ and $|B_1^+|$ field measurements for different phantom positions with respect to the isocenter of the scanner are shown in Fig. 2. External $|B_1^+|$ values measured on top of the phantom (using the gantry) confirm the absolute values from the simulation (Fig. 2a). The internal E fields measured at two different sensor positions are also predicted correctly by the simulations (Fig. 2b), but larger deviations exist for external $|E_1|$ field measurements (on top of the phantom). Especially at large off-axis positions towards the sides of the phantom (Fig. 2c) the real situation is not correctly mirrored by the numerical results.

Discussion: A system for calibrated measurements of all complex E and B field components in an MR environment was developed. It is based on fiber optic time-domain sensors which can be calibrated using an MR compatible TEM cell inside the MR scanner itself. Its functionality was demonstrated using an ASTM body phantom and the body coil of a clinical 3T scanner. The $|B_1^+|$ measured was in good agreement with simulations. The somewhat larger differences between measured and simulated $|\mathbf{E_1}|$ field on top of the phantom show that the $|\mathbf{E_1}|$ around the phantom is much more sensitive to the geometry and possibly the dielectric properties of the phantom container. These subtleties are obviously not correctly reflected in the numerical model, a finding which would have gone unnoticed if only $|B_1^+|$ maps had been acquired.

Conclusion: For a quantitative SAR assessment knowledge of all components of the EM field are required. Calibrated time domain field probes are suitable to get this data and evaluate the error margin of EM simulations in detail.

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References: [1] F2182–11, ASTM International, 2011. [2]. B. Loader et al, BEMS 2010. [3] T. Klepsch et al, Biomed Tech 2012; 57 (Suppl. 1), DOI: 10.1515/bmt-2012-4428.