Assessment of RF Safety of Transmit Coils at 7 Tesla by Experimental and Numerical Procedures

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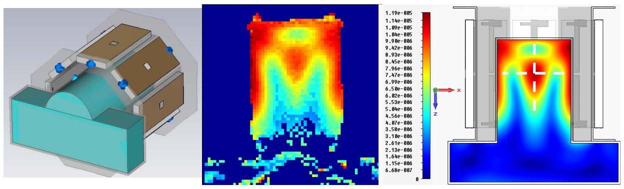
Introduction: To guarantee safe operation of RF transmit coils during MR examinations, the maximum permitted input power for the applied driving mode at which SAR limits specified in the guidelines [1] are not exceeded must be determined. Since techniques for direct measurement of SAR in vivo are not available, the safety assessment can be based on mathematical approximation methods. Whereas whole and partial body SAR can be estimated by the accepted power of the transmit coil and the exposed body mass, localized SAR demands RF simulations with detailed models for the underlying exposure scenario including the transmit coil and heterogeneous human bodies. This particularly applies to high-field MR, since the SAR may depend strongly on the local tissue distribution and the local SAR is often the most critical aspect concerning RF safety. Validation of the numerical results remains a critical issue, since adequate field measurements cannot be performed in vivo. Therefore, an iterative procedure for RF safety testing of transmit coils is proposed which incorporates validation of numerical results by field measurements in well-defined, canonical test scenarios

Materials & Methods: In order to rely on the simulated SAR distribution for the exposure scenario, the numerical model for the RF coil is validated in a first step by use of homogeneous phantoms filled with tissue-simulating liquid which model the exposed body region. With the proposed configurations, results from simulations and measurements can be directly compared and deviations can be taken as a measure of the uncertainty of the results obtained with the numerical coil model. Simulations were performed with the Finite-Integration Time-Domain Method (Microwave Studio, CST, Darmstadt, Germany). Dosimetric (SAR) and RF field probes (Dosimetric Assessment System, SPEAG, Zurich, Switzerland) were used for measurements. In order to check for possible effects from the magnet bore on coil properties, measurement of B_1^+ maps by the actual flip angle (AFI) method [2] and of the SAR distribution by MR thermometry are additionally performed with the same homogeneous phantoms. If good agreement between simulated and measured results is achieved, it can be assumed that the model of the transmit coil properly describes the implemented RF coil. Thus, in a next step simulations with heterogeneous body models [3, 4] are performed for the safety assessment, which should model all important details of the realistic exposure scenario as well as variations of exposure parameters, e.g. different body physique and body placement with respect to the RF coil.

Results: The proposed test procedure has been applied for safety tests of both local [5] and volume coils. Results are presented for two 7 T coils, an 8-channel head coil [6] and an 8-channel body coil [7]. Fig. 1 shows a comparison of measured and simulated B_1^+ maps in a central coronal plane inside a head and shoulder phantom for the head coil driven with a phase increment of 45° (CP^+ mode). The phantom is filled with head-simulating liquid (ε_r= 45.3, σ = 0.87 S/m). Simulated B_1^+ distribution agrees well with measured distribution. Calculation shows a higher maximum B_1^+ by only 5%. For a detailed validation of the numerical coil model, the magnitude of the electric |E| and magnetic field |H| is measured by field probes. For this purpose, the coil is driven in CP^+ mode at an input power of 34 W (CW). Comparison of measured and calculated field distributions shows good agreement (Fig. 2). The mean of the absolute normalized deviation of the magnetic and electric field in each point is 13% and 8%, respectively. Fig. 3 shows the voxel-based SAR distribution for a male and female head model. For both models the localized SAR is the most critical aspect and the resulting max. permitted accepted power of the coil array is 35.4 W and 33.8 W, respectively. Variation of the head's position inside the coil of Δx = -20 mm, Δy = -15 mm, and Δz = 30 mm results in a maximum variation of the localized SAR of -4% / +18%. Comparison of measured and calculated field distributions inside a body phantom (elliptical cylinder, minor/major diameter 19/29 cm, length 50 cm) is shown for the 8-channel body coil (Fig. 4). The deviation of the magnetic and electric field is 18% and 17%, respectively. For the exposure scenarios with the male and female body model, the limit for the localized SAR restricts the max. permitted power of the coil array to 30 W and 22 W, respectively. Here, an RF shim optimized for liver imaging was used (Fig. 5).



a) Measurement $B_{1\,max}^+$ = 11.3 μT

b) RF simulation $B_{1\,max}^+$ = 11.9 μT

Fig. 1: Comparison of measured and simulated B_1^+ map inside a head and shoulder phantom for an 8-channel head coil driven in CP^+ mode. **(a)** B_1^+ map acquired with the AFI sequence (250 μs pulse length and 1600 W peak power). **(b)** Simulated B_1^+ distribution in a corresponding plane.

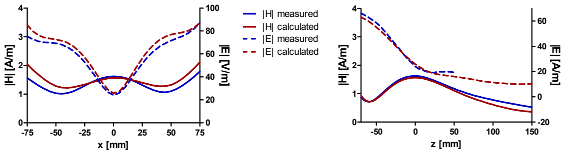
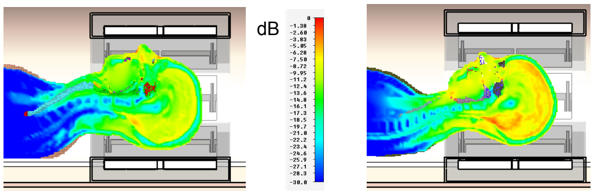


Fig. 2: Head coil: Measured and simulated electric |E| and magnetic field |H|. The measurement was performed along the dashed lines (x-axis: R-L, z-axis: H-F) in Fig. 1b.



0 dB = 1.28 W/kg

0 dB =0.811 W/kg

Fig. 3: Voxel-based SAR inside a male (left, 1.74 m, 70 kg) and female (right, 1.6 m, 58 kg) head model centered in a head coil for P_{acc} = 1W.

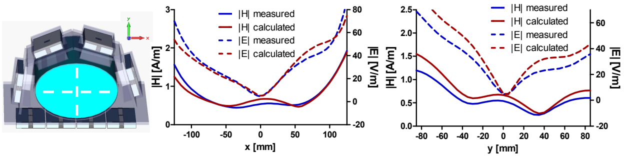
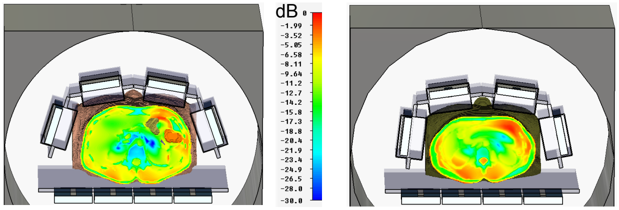


Fig. 4: Body coil: Measured and simulated electric |E| and magnetic field |H| for the CP^+ mode and input power of 31 W. The measurement was performed along the dashed lines shown in the left figure (x-axis: R-L, y-axis: A-P).



0 dB = 0.693 W/kg

0 dB = 0.506 W/kg

Fig. 5: Voxel-based SAR distribution inside the male (left) and the female (right) body model for the body coil with P_{acc} = 1W.

Conclusion: The proposed approach enables an accurate simulation-based safety assessment of transmit coils including suitable validation procedures. The procedure has been successfully applied for RF safety tests of various surface and volume transmit coils for 7 T MR systems. RF field probes enable a direct assessment of the magnetic and the electric field distribution and represent an additional and MR-independent validation in contrast to B_1^+ mapping and MR thermometry. For determination of an overall safety margin, deviations found in the validation procedures as well as SAR variations from subsequent parameter studies have to be taken into account.

References: [1] IEC International standard 60601-2-33; 2010. [2] Yarnykh VL, Magn Reson Med. Jan 2007;57(1):192-200. [3] Christ et al. Physics Med Biol 2010;55(2):N23-38. [4] Ackerman et al. Medinfo 1995;8:1195-1198. [5] Bitz AK, Proc. Intl. Soc. Mag. Reson. Med. (ISMRM) 16 (2008): 903. [6] Orzada et.al. Proc. ISMRM 17 (2009), 3010. [7] Orzada et.al. Proc. ISMRM 17 (2009), 2999.