Maximum SAR Estimation of a Multiple Channel Travelling Wave System based on Waveguide Theory

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Introduction

Safety assessment of a high field (7T) multiple channel travelling wave RF setup [1] based on waveguide theory is presented. The multiple channel travelling wave setup poses unique challenges to numerical field simulation methods because of the large required memory, due to the dimensions, and the complex structure of the excited fields in the multimodal waveguide section. Therefore the system is divided into smaller subdomains [2,3]. Each of these subdomains can be treated separately with suitable methods [3,4], and joined together in a post-processing step. Since the resolution of the simulation can be increased in each of the smaller subdomains the result for the entire system becomes more accurate. The improved simulation results are used to determine a worst case scenario that is independent of the feeding geometry and the applied multi-channel RF pulse.

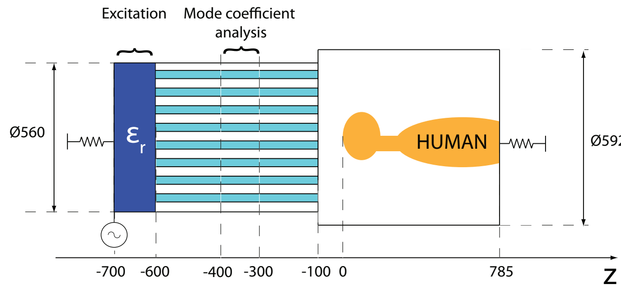

Fig. 1: 3D RF simulation setup, the resistance symbols stands for an absorbing boundary condition, the source symbol stands for a waveguide excitation.

Methods

Experimental Setup

The travelling wave multiple channel setup consists of a waveguide extension, a 2m long circular plastic tube covered with brass mesh, loaded with 52 PMMA rods filled with distilled water [1]. The waveguide extension can be divided into a 0.5m long excitation region and a 1.5m long piece of uniform waveguide region.

EM simulations & Post Processing

The division of the numerical domain into smaller subdomains is common practice for coil arrays, by splitting the system into a circuit region and EM region [2,3]. The EM region of travelling wave setups can be further divided into waveguide regions and a region where the EM-field couples to the human body, which is described below.

In a first step the 2D FEM eigenmode solver (COMSOL) was used to calculate the modes of the waveguide extension at 300 MHz that are capable to couple more than -60dB of power in the worst case, over the waveguide length of 1.5m. These modes can contribute to local SAR maxima, and therefore had to be considered in the analysis.

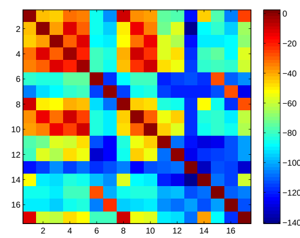

Fig. 2: S-matrix of the modes of the waveguide extension.

In a second step the 3D FDTD solver (SEMCAD) was used to simulate the field distributions in the human body. For the simulation setup, Fig. 1, the waveguide extension was cut after 0.5m. This length was chosen, such that only the propagating modes have a significant contribution to the EM-field in the 10cm middle piece of the waveguide extension. The waveguide extension is followed by the MR bore containing a human model, (Duke, Virtual Family, IT'IS). The simulation was excited using a 10cm piece of a circular homogeneous waveguide with corresponding excitation modes. The excitation mode was chosen, such that the coupling to a given propagating mode of the waveguide extension is maximal.

The EM fields from the 3D simulation were analyzed in MATLAB based on the modal fields in the waveguide extension. The forward and backward mode coefficients were calculated in the middle 10cm part of the waveguide extension for each simulation. The relation of these forward and backward wave coefficients can be expressed in a scattering matrix [S], whose ports correspond to the modes of the waveguide extension. The simulated EM field distributions can be transformed into fields that are excited by modes of the waveguide extension selectively, E_{mode}.

Safety Assessment

The worst-case SAR averaged over any 10 g of tissue was computed using the fields E_{mode}, normalized to 1W dissipated power in the entire human body. The radiation and conduction losses caused by the environment were not considered. Therefore, the resulting worst-case SAR is still conservative.

Imaging

Gradient echo images were acquired on a Philips Achieva 7T system, equipped with 8 independent RF amplifiers (Philips Healthcare, Cleveland, OH). Due to the lack of a power monitoring system, the maximum peak power of 8kW was assumed during the entire length of the pulse. The average output power was regulated by total RF duty cycle of the sequence.

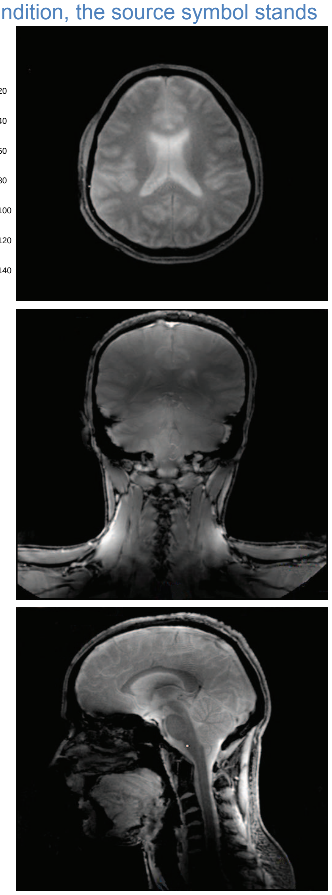

Fig. 3: MR-images, multiple channel travelling wave in transceive mode.

Results

It was found that 51 modes of the waveguide extension are able to couple more than -60dB over 1.5m of waveguide length. The first 17 of these modes are dominantly propagating. The expansion of the fields in the middle 10 cm piece of the waveguide extension with respect to the modal fields yielded a mean and maximal error of the fields of 0.6% and 10% with respect to the simulated fields. The scattering matrix at the reference plane of z=-0.1m is shown in Fig. 2. The worst case SAR normalized to 1W power loss in the human was found to be 2.2 W/kg, in the head. This results in a maximal average input power of 9 W, such that the local SAR limits in the head are not exceeded, [6]. In vivo MR images of three slices were acquired within the derived power limit, see Fig. 3.

Discussion & Outlook

A reliable safety assessment of a multiple channel high field travelling wave system was introduced, by splitting the system into a waveguide region and a EM field region. A worst case SAR was computed from field distribution in the human that can be excited by propagating waveguide modes of the waveguide extension. This worst case SAR cannot be exceeded by any combination of drive voltages and any positioning of excitation stubs and loops in the excitation region of the waveguide extension, for an average input power of less than 9 W. Future work will include a given positioning of excitation stubs and loops into the analysis, in order to provide less conservative worst case estimates. For this the presented approach will be analogously applied in order to separate the simulation of the feeding section from the rest of the system.

References

[1] Brunner et al, MRM 66:290–300, 2011 [2] Lemdiasov, DOI 10.1002/cmr.a:133-147, 2011 [3] Paska, ISMRM, p3038, 2009 [4] R.E. Collin, Field Theory of Guided Waves, McGraw-Hill, 1960 [5]: Marks, A General Waveguide Theory, NIS, 1992 [6] IEC 60601-2-33 ed3.0