Reliable and robust RF safety assessment of transmit array coils at ultrahigh fields

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Target audience: Basic researchers interested in managing MR safety of transmit array coils at ultrahigh fields (UHF)

Purpose: Limiting local SAR during parallel transmission (pTX) MRI is required by safety standards like IEC 60601-2-33. Since the real-time determination of maximum local SAR is prone to model variations when relying on measured multi-channel driving voltages there is a need for a more reliable approach. A simulation based assessment of RF safety of pTX coils requires an elaborate estimation of upper limits of local SAR for all reasonable steering conditions and model assumptions. Limiting the forward power of each individual TX channel to the same value is the most simple and robust approach to reliably assure compliance with applicable safety standards. For these circumstances we propose a comprehensible estimation procedure to find an upper limit for the local SAR_{10g} from the power correlation matrix (Q-matrix) containing all the information about the local SAR of the system.

Methods:

Coil model: 8-channel decoupled loop array with external shield operating at 300 MHz (s. Fig.1).

Head models: 'Duke' and 'Ella' from the Virtual Family.

FDTD simulations: XFDTD 6.4 (Remcom Inc.), equidistant mesh (2mm), 8 million FDTD cells, CW excitation, 3D data sets of complex E, H and J field vector amplitudes were extracted for each port (8 driving/16 decoupling ports).

Co-simulation: 5-parameter matrices were calculated from port data to obtain tuning/matching/decoupling parameters within a subsequent co-simulation run. Tuning, matching and decoupling of coil elements was performed for the 'Duke' model by either using T-type matching circuits or decoupling capacitors. Intrinsic coil losses were included in the matching circuit by an additional resistor Rcoil = 5Ω resulting in realistic quality factor ratios. The same tuning/matching/decoupling/loss parameters were used for 'Ella'.

SAR calculation: For each voxel ϕ at position r and for 1V of feeding voltage (amplitude) of channel i(j) the 8×8 matrix Qϕ(r) = Jϕ(r) Eϕ(r) was calculated from all 3D field components. For a mass density ρ = 1g/cm³ the local SAR is given by cu Qϕ(r) = \|u\|^2/2000kg, where \|u\| is a dimensionless 8-component voltage vector. The transmitter forward power P_fwd is given by \|u\|^2volts^2/8Ω, where 8 is the open circuit voltage amplitude in volt and Z0 = 50Ω. To reduce computational efforts a data compression method similar to the 'Virtual Observation Points' (VOPs) was applied. With Qϕ(r) = Qϕ (v denotes the voxel at position r) the global maximum or 'worst case' (w.c.) of \|Qϕ\|\|u\| is given by the largest overall eigenvalue λ_max. (s. Fig.2). Then, the maximum local SAR for a given voltage vector \|u\| results to 2p maxSAR_{10g} < \lambda_{max}/R + max\{\|Q_{uop}\|\|u\|\|max\}. For R = 5 - 20 the number nvo pv of Q-matrices relevant for SAR calculation is typically < 300 reducing calculation effort by a factor of 10 to 100.

Calculation of upper limit of maxSAR_{10g} for fixed individual channel forward power: Qϕ(r) can be decomposed into Qϕ = Qϕ_max + Qϕ_min with Qϕ_max, min = \{Jϕ_max, min(r)Eϕ_max, min(r)\}. Then, assuming a fixed forward power for each individual channel, local SAR at voxel ivop is given by SAR_{10g} = max{maxSAR_{10g}(i)}_{i=1,nvo pv}. For R = 5 maxSAR_{10g} can easily be found by a successive one dimensional search. Although the phase settings for maxSAR_{10g} may differ, maxSAR_{10g} is always ≤ max{maxSAR_{10g}(i) + maxSAR_{10g}(i) \|maxSAR_{10g}(i)\}_{i=1,nvo pv} which is thus an upper limit of local SAR for all possible phase settings.

Butler matrix: A Butler matrix can be involved by transforming a given voltage vector \|u\| with the unitary matrix U^{\text{w.c.}} = \exp[2\pi i ch_{w.c.}/nchan]/\sqrt{nchan} with ch_{w.c.} = 1, ..., nchan.

Results and Discussion: For a forward power of 1W per channel, i.e. an overall forward power P_fwd of 8W, a maximum SAR_{10g} of about 13W/kg was obtained for both voxel models. For an individual VOP there may be large differences between 'Duke' and 'Ella' but the maximum values are almost the same (s. Fig.3). The corresponding 'worst case' local SAR values for P_fwd = 8W are 23.7 W/kg for 'Duke' and 20.2 W/kg for 'Ella', respectively. This reflects that in the 'worst case' much more than the average share of P_fwd/8 = 1W is fed to one particularly SAR critical channel. Compliance with the 20W/kg local SAR limit of IEC 60601-2-33 Ed.3 can be achieved by limiting the forward power to 1.5 W per channel, i.e. 12 W of overall forward power. Assuming an average head mass of 5 kg the head SAR limit of 3.2 W/kg is reached at 2W per channel or 16 W of total power. Hence, the power limit for safe operation of an array coil according to our model is only 25% below the volume SAR limit. This comfortable situation is worsened considerably, however, when using a Butler matrix in conjunction with this coil. Then, again at 1W per channel, the maximum SAR_{10g} is 20.3 W, i.e. about 1.5 times higher than the SAR_{10g} value of 13W/kg without Butler matrix.

Conclusion: We developed a procedure to find an upper limit for the local SAR_{10g} from the Q-matrix of transmit array coils. When applying this procedure to a 7T 8-channel transmit head coil the resulting local SAR related power limit is only 25% lower than the forward power limit for the head SAR which has to be obeyed anyway. This holds for both voxel models used ('Duke' and 'Ella') and thus allows the easy and safe use of the coil without substantial loss in performance. It appears questionable whether the remaining room for improvement justifies the effort of dedicated hardware, software and sequences for on-the-fly SAR calculations. This holds especially as such dedicated hard- and software is inaccessible and its correct performance cannot be tested or evaluated by the user. Care has to be taken when using a Butler matrix in conjunction with the array coil. Since a Butler matrix allows for coherent voltage superposition of all channels the local SAR can be > 1.5 times higher than without Butler matrix.

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