Comprehensive analysis of parallel transmission local SAR errors introduced by an assumed uniform density distribution

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Target Audience: Researchers interested in SAR calculation, especially concerning multi-channel transmit arrays.

Purpose: The aim of this work was to investigate the error introduced in local SAR calculations by assuming a uniform tissue density of 1000 kg/m³. This assumption is often made when using in-house SAR averaging algorithms, since tissue density distributions are possibly not exportable from the electromagnetic solver of choice, also averaging becomes much simpler. In order to determine if this approach can be considered safe, we compared the calculated SAR matrices [1, 2] of a 7T 8-channel head array using the realistic and uniform density distributions for both 10g and 1g averaging volumes.

Methods: The investigated coil array consists of eight loop elements measuring 9x22 cm² and constructed of 5 mm width flat strip conductors. The elements are arranged on a cylindrical former with an outer diameter of 27 cm and loaded with the "Duke" model [3], which was truncated below the heart to ascertain proper coil loading. 3D field simulation was done in XFdtd (Remcom, State College, PA, USA) in conjunction with ADS (Agilent, Santa Clara, USA) for tuning to 297.2 MHz, matching and decoupling [4]. After exporting all simulation results and tissue properties, SAR post-processing was done in MATLAB (The MathWorks, Natick, MA, USA) using the SimOpTx toolbox (RSA, CMPBME, Vienna, Austria). After regridding of the simulation data to a 3 mm isotropic grid using an integral conservative algorithm ("SG" in [5]), SAR matrix averaging [6] was performed using both the real and uniform density distribution. The resulting averaging volume sizes, eigenvalue magnitudes, and eigenvector similarity via the hermitian inner product of corresponding eigenvectors [1] were compared. Additionally, a statistical analysis using 100 million random excitations was performed. Random vectors were distributed using a Latin Hypercube Sampling (LHS) scheme to ensure an even coverage of the 15-dimensional (8 amplitudes, 7 relative phases) parameter space. SAR calculation was carried out on a consumer grade GPU (NVIDIA GTX580), achieving a throughput of roughly 25,000 excitations per second for the model consisting of ~120,000 voxels. Averaging volumes containing more than 10% air were ignored in the SAR evaluation as per IEEE 1528.1. The analysis was restricted to voxels in the head and neck, as upper body regions show no appreciable local SAR hotspots using this coil geometry.

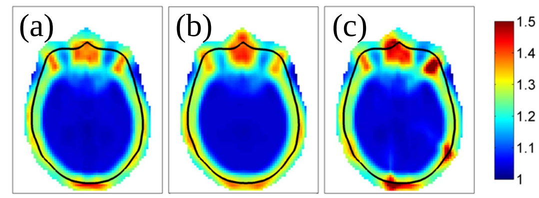

Fig 1: Largest eigenvalue ratio EV_{uni} / EV_{real} (a), averaging volume ratio V_{uni} / V_{real} (b) and local SAR ratio SAR_{uni} / SAR_{real} (c) of a random excitation for 10g volumes in an axial slice through the head are showing a strong agreement. Volumes outside the black line contain more than 10%. The agreement is similar for 1g averaging volumes.

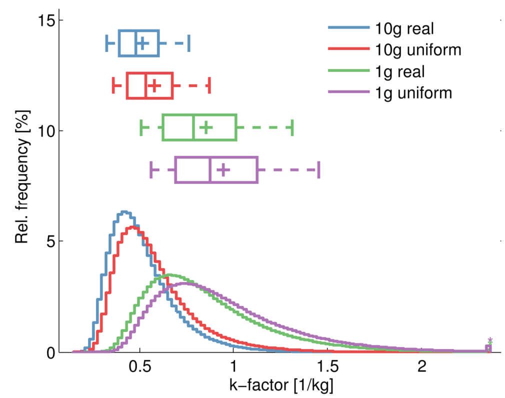

Fig 2: Normalized peak SAR distribution for all four cases investigated. Using the uniform density distribution results in higher local SAR on average.

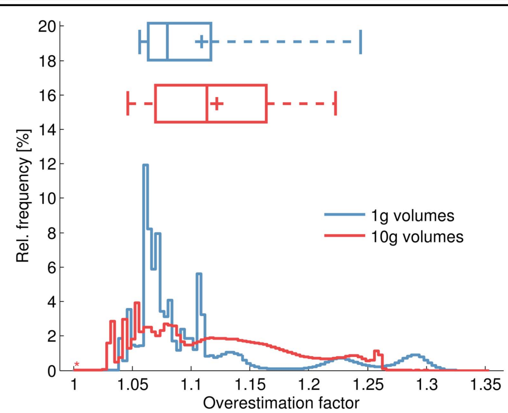

Fig 3: Peak SAR overestimation distribution caused by using the uniform density distribution. Underestimation of at most 0.5% occurs only for 17 of the 100 million random excitations in the 10g averaging case.

Results: Largest eigenvalue (EV), averaging volume (V) and peak SAR ratios between realistic and uniform density distributions are shown in Figure 1. The calculated eigenvalues of the SAR matrices are consistently larger when averaging using the uniform density distribution for both 10g and 1g averages, with the exception of small volumes in the neck. Eigenvector similarity was found to be very high, with less than 1% of voxels exhibiting a similarity below 0.99. The statistical results are shown in Figures 2 and 3. Average peak SAR overestimation is 10.9% and 12.2% for 1 g and 10 g averaging volumes, respectively.

Discussion: SAR is inversely proportional to tissue density, thus using an artificial density slightly lower than that of most tissues in the body results in higher SAR values on average. As the averaging volume difference between uniform and realistic density is small compared to the wavelength, there is an almost linear relationship between averaging volume and integrated power, with only a minor impact on the resulting SAR behavior as characterized by the SAR matrix eigenvectors. While it is computationally infeasible to compare SAR for the whole parameter space, the results of the statistical analysis together with the eigenvalue increase and eigenvector similarity allow the statement that SAR will be on average overestimated when assuming the uniform density. Underestimation might occur, but is highly unlikely and relatively small in magnitude. While the analysis was done for a head coil at 297.2 MHz, the results can likely be extrapolated to different body regions and lower frequencies. Care needs to be taken in averaging volumes around the lung, as the published density of inflated lung 394 kg/m³ [7] is far below 1000 kg/m³. The magnitude of local SAR error can be approximated by the averaging volume ratios.

Conclusion: Our results indicate that using a uniform density distribution for SAR calculation can be considered safe for the investigated coil. As SAR shows a high correlation to local tissue density distribution, these outcomes can likely be applied to other coil geometries and body regions. Definite proof of safety could be achieved by demonstrating SAR matrix dominance as in model compression schemes [2].

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