A principled approach to conductivity uncertainty analysis in electric field calculations

Uncertainty surrounding ohmic tissue conductivity impedes accurate calculation of the electric fields generated by non-invasive brain stimulation. We present an efficient and generic technique for uncertainty and sensitivity analyses, which quantifies the reliability of field estimates and identifies the most influential parameters. For this purpose, we employ a non-intrusive generalized polynomial chaos expansion to compactly approximate the multidimensional dependency of the field on the conductivities. We demonstrate that the proposed pipeline yields detailed insight into the uncertainty of field estimates for transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS), identifies the most relevant tissue conductivities, and highlights characteristic differences between stimulation methods. Specifically, we test the influence of conductivity variations on (i) the magnitude of the electric field generated at each gray matter location, (ii) its normal component relative to the cortical sheet, (iii) its overall magnitude (indexed by the 98th percentile), and (iv) its overall spatial distribution. We show that TMS fields are generally less affected by conductivity variations than tDCS fields. For both TMS and tDCS, conductivity uncertainty causes much higher uncertainty in the magnitude as compared to the direction and overall spatial distribution of the electric field. Whereas the TMS fields were predominantly influenced by gray and white matter conductivity, the tDCS fields were additionally dependent on skull and scalp conductivities. Comprehensive uncertainty analyses of complex systems achieved by the proposed technique are not possible with classical methods, such as Monte Carlo sampling, without extreme computational effort. In addition, our method has the advantages of directly yielding interpretable and intuitive output metrics and of being easily adaptable to new problems.

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