Modeling-Based Optimization of Thermal Processing in Microwave Fixation

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The technology of microwave fixation has been identified as a highly promising (if not the only possible) way to lock the chemical state of the brain for post-sacrifice chemical analysis. This is a critical and challenging part of neurologic studies looking for cures for numerous disorders, including such degenerative diseases as Parkinson's and Alzheimer's [1-2]. Popular commercially available microwave fixation instruments use water jackets aiming to redistribute the electric field in the cavity in order to heat the animal's head uniformly. In such a configuration, however, the temperature field in the brain tissue is hardly controlled, whereas homogeneous thermal treatment is a requirement in this application. In this case, a significant fraction of the microwave power is absorbed by the water and thus wasted. Therefore, in order to rapidly heat a small volume occupied by the processed tissue (characterized by a lower loss factor), these systems need to use high microwave power (up to 5-10 kW). This suggests that existing equipment for microwave fixation is operationally cumbersome and energy inefficient, and thus motivates developing new efficient applicators for neurochemical studies.

In this paper, we report the results of initial exploration of an alternative microwave system design featuring a solid dielectic insert. The insert's shape and complex permittivity are determined for a given brain's material parameters and geometry so that the dissipated power distribution in the animal's head is as homogenious as possible. The corresponding optimization problem is formulated and solved with the use of a computational procedure using numerical data generated by a 3D model representing the microwave system.

We considered a fictional application, whose structure is conceptually similar to the GA5013 Microwave Animal Fixation System (Gerling Applied Engineering, Inc). The applicator consisted of a section of a single-mode rectangular waveguide, centrally connected with a cylindrical cavity of a diameter exceeding the wide wall of the

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waveguide. The animal was positioned so that the body was in the cavity, and the head in the waveguide. The head was surrounded by a rectangular dielectric insert; on the side facing the input of the system, the insert was covered by a cone for improving the matching of the loaded applicator with a microwave generator.

The entire system has been reproduced in a 3D parameterized model built for the full-wave conformal FDTD simulator *QuickWave 2014* [3]. Since the process of microwave fixation is very quick (less than 1s), we assume that the time of heat transfer is negligible and our computation can be reduced to determination of dissipated power. In the model, the animal's body and head are approximated by a cylinder and a truncated cone, and we utilize the value of complex permittivity for a mouse brain (gray tissue) as $\varepsilon_m = 46.9 - j7.2$ [4] at 2.45 GHz. To ensure high solution accuracy, the scenario in the model is discretized with a non-uniform mesh (with max cell sizes of 5 mm in air and 1.5 mm in the insert and in the animal), and thus the model contains roughly 560,000 cells.

Systematic computational tests were performed for varying insert's heights and widths as well as dielectric constants and loss factors. These parameters were found to significantly influence the dissipated power distribution. Thus, they were used as design variables in the optimization problem, aiming to reach maximum uniformity of dissipated power in the brain tissue.

For a uniformity metric, we used the relative standard deviation (RSD) of the dissipated power in all cells within the truncated cone representing the animal's head. (A low RSD indicates that the data set has little variation, meaning it tends to have a uniform distribution.) Several local minima were found after a series of random simulations in the space of four design variables. We then formed a sub-space around a minimum by reducing the bounds of the original space and, through a dedicated sensitivity analysis, determined and dropped from the following calculations the two least-influential design variables. In the final stage, the sequential quadratic programming was used to determine the complex permittivity and shape of the insert corresponding to the lowest RSD.

Application of this optimization procedure with the chosen ranges of the design variables (including the range of dielectric constant of the insert exceeding ε_m') produced parameters of the system in which the RSD was reduced from 120-135% (in non-optimized designs) to 23-27%. The achieved level appears to be the best for the chosen sub-space of the design variables; however, optimization in other sub-spaces (in particular with the dielectric constant being less than ε_m') may provide solutions with lower RSD.

The procedure appears to be suitable for homogenizing dissipated power in other microwave applicators with high rates of thermal processing.

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