A numerical approach to the development of MRI radiofrequency coils

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Target Audience: Scientists and engineers in with an interest in radiofrequency (RF) coil design or electromagnetic simulation for MRI.

Purpose: To provide a guide to the steps involved in the simulation of RF coils and, in particular, the role of electromagnetic (EM) simulations in the development of novel designs and the creation of physically representative models. The use of Finite Element Method (FEM) software for EM field solutions will be described to illustrate the strengths and weaknesses of a simulation-based assessment of coil designs, though it is acknowledged that other numerical methods can be used; examples are given throughout with reference to COMSOL Multiphysics (COMSOL Inc., Sweden).

Outline of Content: The development of coil designs which provide optimal imaging capabilities for clinical use have to meet a range of criteria. The design process can be aided by a range of modelling software, typically prior to coil construction, through the assessment of expected performance and potential advantages over existing coils; simulations can identify design options with the best potential to fulfil the criteria without the cost of building a multiple prototypes. Performance criteria can include a homogeneous B_1^+ field for transmit designs or adequate SNR, appropriate spatial sensitivity and potential for parallel imaging in receive arrays. The potential for tissue heating is also widely assessed [1]. The simulation process itself comprises of several key stages:

(1) Physical Design - Appropriate 'geometry' is drawn to represent the physical shape and orientation of the coil elements with an appropriate loading object within a defined volume ('solution space'). Surfaces and edges are assigned mathematical conditions to represent physical boundaries; for example, a perfectly conducting boundary around a wire mimics the skin effect in conductors. Volumes can be assigned parameter values in accordance with their material properties (such as dielectric coefficients).

(2) EM Solution Method - Electromagnetic fields are defined by Maxwell's Equations; as it is not simple to solve these equations computationally, representative functions are used for $\boldsymbol{B}(r,t)$ and $\boldsymbol{E}(r,t)$. Such 'test' functions are designed to be correct over smaller regions into which the solution space is split (known as meshing, illustrated in Figure 1) and the solution of a matrix equation provides full field information [2].

(3) Performance Metrics - The resultant EM fields can then be used to calculate B_1^+ (Figure 1) and B_1^-, SNR and g-factor, quantifying the advantages of each coil arrangement [3]. The simulation can also be arranged to investigate the heating of tissue by calculating the Specific Absorption Rate (SAR). Further, boundary conditions can integrate the effect of tuning and matching circuits, allowing designers to provide approximate component values, reducing time commitments for coil construction.

(4) Iteration - The model is often created in a parameterised form. Here, certain user-defined constants – such as the length of the array or overlap of coil elements – are used to determine other dimensions – such as the width of the elements. These parameters can then be altered incrementally and the model re-solved to find the optimal combination of inputs to fulfil design specifications [4].

(5) Advantages of FEM and common pitfalls - FEM have advantages over other numerical solution methods used for EM modelling such as Finite Difference Time Domain (FDTD) methods. The flexibility of the FEM mesh enables fitting to complex geometries and therefore more accurate assignment of boundary conditions. Further, FEM are applicable to areas of physics outside of EM and some software packages allow for the interactive solution of multiple physical factors simultaneously (for instance, mechanical deformation and thermal heating). However, FEM – as a computational method – will introduce well recognised sources of error to any solution (i) discretisation of the solution space to create the mesh (ii) approximation of the fields over mesh elements and (iii) truncation errors in numerical solution. Modellers unfamiliar with FEM can also often assign unsuitable boundary conditions or mesh parameters and the creation of a parametric geometry can initially prove unintuitive.

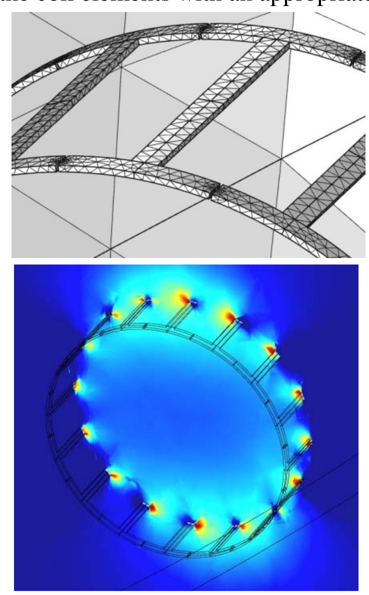

Figure 1 - (top) a meshed birdcage coil geometry and (bottom) the resultant B_1^+ field for coil driven in quadrature.

Summary: This poster summarises the key steps typically involved in radiofrequency simulations, with particular focus on the performance information which can be derived from results. These techniques are widely used in support of RF coil design to reduce the need for prototyping. The FEM solution method is detailed, with reference to its particular advantages and disadvantages.

References:

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