Electromagnetics in Medicine

Electromagnetic and thermal simulations find use in medical applications.

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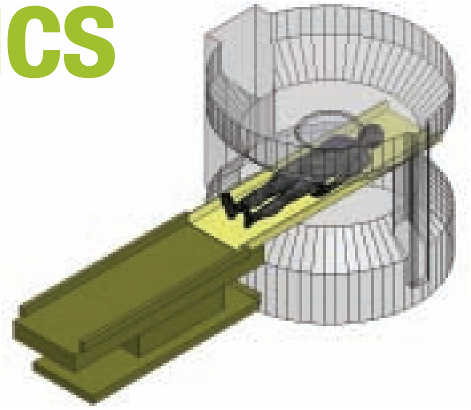
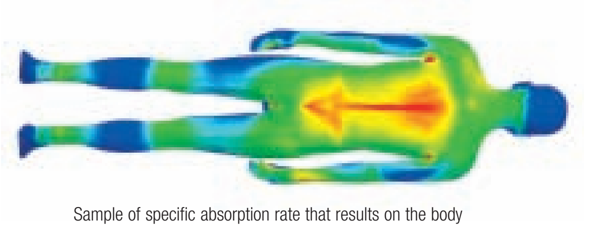


Model of the open MRI system, which combines an MRI model generated by Philips Healthcare with the ANSYS human body model

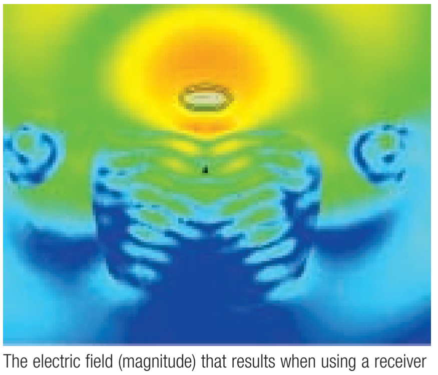
Electromagnetic fields are used more and more in advanced medical applications such as magnetic resonance imaging (MRI), implants and hyperthermia treatment. As the state of the art advances, devices are becoming more complex and simulation more indispensable in the product design phase. With simulation, a designer can study device functionality and address safety concerns without exposing a patient to harm or otherwise.

In the design of an open MRI system, for example, the details of the radio-frequency (RF) coils, a human body model, and the large volume of the entire examination room must all be included in an electromagnetic simulation model to determine the resulting field accurately. The finite element method found in HFSS (High-Frequency Structure Simulator) software, an electromagnetic field simulation tool new to the ANSYS portfolio, is well suited for this purpose as it uses small mesh elements where refinement is needed and larger mesh elements elsewhere. The human body model available through ANSYS comprises 300 objects that, detailed down to the millimeter, represent organs, bones and muscles. Frequency-dependent electromagnetic material parameters are also included in the model.

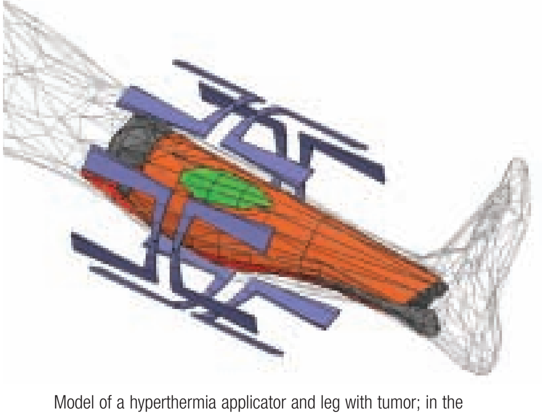
The RF coil design requires optimization for appropriate image quality: The coils need to resonate at 42.6 MHz for a 1 tesla system and produce a rotating magnetic field that is strong and smooth in the region of interest but minimizes undesired field components. If the field varies strongly, some parts of the image will appear to be overexposed, while other areas will remain too dark, both of which are detrimental for contrast. Once the specifications related to image quality are satisfied, the designer needs to make sure that specific absorption rate (SAR) safety regulations are met. SAR is a measure of how much RF power is absorbed by, and thus creates heat in, the body. When limits are exceeded in any part of the body, the patient can experience discomfort and tissue damage.



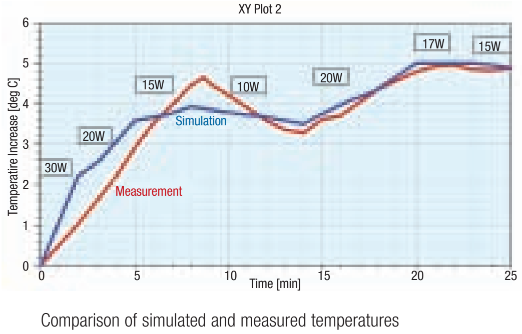
Sample of specific absorption rate that results on the body when using the open MRI system, as simulated using the HFSS electromagnetic field simulation tool



The electric field (magnitude) that results when using a receiver implanted in epidural space in conjunction with a wireless transmitter placed behind the back; the image shows a horizontal cross section of the torso and arms of a person, standing, using a wireless implant.



Model of a hyperthermia applicator and leg with tumor; in the image, some applicator and water cooling system components have been removed for clarity. The green object is the tumor.
Applicator design and tumor geometry provided by Duke University.



Comparison of simulated and measured temperatures in the tumor for a hyperthermia treatment case
Measured results provided by Duke University.

Simulation results from the open MRI case indicate hot spots under the armpits, a result that agrees with practical experience. Analysis also indicates resonant hot spots on the legs, even though they are not directly under the coils in the model. Given the frequency and material parameters of the body, the expected wavelength in the body is a little less than 1 meter, and resonances such as these are indeed possible. The SAR is not quite symmetric; this is expected, as the excitations are not symmetric either. Entire scan protocols can be simulated in the software by moving the body automatically through the scanner.

Another medical application in which human comfort is important is the design of wireless implants. Implants that require directly wired power supplies can be uncomfortable for the patient. But wireless power supplies that use low-frequency coupling require a bulky transmitter, reducing patient freedom. Wireless solutions that use higher frequencies can potentially provide both comfort and freedom. One design challenge is to transmit maximum power to the implant while also satisfying radiation and SAR regulations.

Simulations of wireless implants provide details that otherwise are not easily obtained for several transmitter and receiver locations. One important finding is that, in order to get accurate results, interior body components such as organs, bones and fat tissue must be included in the simulation model. If not, the results can easily be off by more than a factor two.

One final medical simulation example models an RF phased-array applicator for hyperthermia cancer treatments. In hyperthermia, a tumor is heated with RF power and held at an elevated temperature for some time, such as 15 minutes to 60 minutes. This weakens the tumor, which helps to make other therapies more effective. The challenge is to concentrate the hot spot in the tumor while minimally affecting healthy tissue.

The applicator consists of several dipole antennas printed on the surface of a cylindrical plastic shell that mounts around the patient's leg, the location of the tumor for this case. The chosen frequency for the device, 138 MHz, is a compromise between hot spot size and penetration depth. A higher frequency can provide a smaller hot spot, but it would be harder to penetrate deep into the tissue. Water cooling prevents skin heating during the procedure and is accounted for in the simulation model. A realistic tumor object, created using MRI data for this patient, is inserted into the leg of the human body model.

By using the electromagnetic simulation capabilities in HFSS software, the applicator and its settings are optimized to focus the hot spot in the tumor. Next, the power-loss information for every mesh element in the model is transferred automatically to the thermal simulation tool, ePhysics. The ePhysics product then computes temperature distribution as a function of time, taking into account thermal material properties as well as water cooling, blood perfusion, air convection and thermal radiation.

Blood perfusion refers to blood flow through capillary vessels in muscles and organs. This flow removes excess heat and must be included in hyperthermia simulations. To include all the details of the capillary blood vessels would be too complicated; therefore, a simpler model is used. It is assumed that a certain amount of blood enters a volume of tissue at a specified rate; it is also assumed that blood assumes the tissue's temperature and leaves the volume, taking a corresponding amount of heat with it. Perfusion for several tissue types can be found in literature [1] and is quantified in the simulation model as a temperature-dependent negative heat source. Overall, the simulation results proved to be very sensitive to blood perfusion.

The input power to the applicator is varied over time for both simulation and experiment. The outer layer of the tumor is assumed to have a higher perfusion rate than the core, as is consistent with literature. Deviations between simulation results and experimental data in the early stages are likely due to the fact that initial thermal conditions in the simulation did not exactly match those in the experiment.

With these simulations, modeling software progresses beyond device design into treatment planning. Finding the proper operating conditions through simulation relieves the patient from invasive experimental procedures. To efficiently optimize conditions for a variety of patients in a hospital environment, engineers must improve methods to translate MRI scan data into personalized human body models that are ready for simulation.

Electromagnetic and thermal simulations are well understood and used regularly for the design of medical equipment and procedures. The next breakthrough is expected when personalized human body models can be generated efficiently and doctors use simulation for treatment planning. ■

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References

[1] Erdmann, B; Lang, J; and Seebass, M. "Optimization of Temperature Distributions for Regional Hyperthermia Based on a Nonlinear Heat Transfer Model." *Ann. N. Y. Acad. Sci.*, Vol. 858, September 11, 1998, pp. 36–46.