Konrad-Zuse-Zentrum
für Informationstechnik Berlin

P. Deuflhard, H.-C. Hege, M. Seebass

Progress Towards a Combined
MRI / Hyperthermia System

Progress Towards a Combined MRI / Hyperthermia System

Peter Deuflhard*, Hans-Christian Hege, Martin Seebaß

Konrad-Zuse-Zentrum für Informationstechnik Berlin (ZIB)
Takustr. 7, 14195 Berlin, Germany
Email: {`deuflhard,hege,seebass`}`@zib.de`

Abstract

Regional hyperthermia, a clinical cancer therapy, is the main topic of the Sonderforschungsbereich "Hyperthermia: Scientific Methods and Clinical Applications" at Berlin. In recent years, technological improvements towards a better concentration of heat to the desired target region have been achieved. These include a rather sophisticated integrated software environment for therapy planning and a new hyperthermia applicator. In a next step, a detailed closed loop monitoring of the actual treatment is to be developed. For this purpose the hyperthermia applicator is combined with an MRI system, which will allow to check the positioning of the patients and to measure individual blood perfusion as well as the 3D temperature distribution.

The basic idea is to use temperature measurements directly for an on-line control of the whole treatment. In this intended setting, new fast feedback control algorithms will come into play.

Keywords: *hyperthermia, medical therapy planning, applicator design, interventional MRI*

1. Present Status of Hyperthermia Treatment Planning

Hyperthermia treatment planning has reached some first level of sophistication by the development of HyperPlan from ZIB – for a short survey see [1]. For a convenient use in hospitals the integrated software environment has been carefully designed and implemented (roughly 300.000 lines of code at present) [2]. Steps to be performed within HyperPlan are:

(a) Image acquisition – presently the input is in terms of 2D computer tomograms.
(b) Image segmentation – details of the individual patient's body must be segmented, which is still a challenging task.
(c) From the segmented 2D input a 3D grid patient is automatically generated, using dedicated tools for grid generation, parts of which have been especially designed.
(d) On this grid patient as a so-called coarse grid adaptive multilevel finite element methods are applied to solve both Maxwell's equations (in the radio wave regime) and the bioheat transfer equation (linear and non-linear). Details of these rather sophisticated recent numerical algorithms are given in [3,4].
(e) The compational results are displayed by means of modern visualization tools which also permit a flexible 3D interaction with the virtual models at each stage of the planning process.

The paradigm underlying the treatment planning system is as follows: map the essential features of an individual patient onto a virtual patient (s. Fig. 1), optimize the antenna parameters in the virtual situation, apply the thus obtained optimal parameters in the real situation.
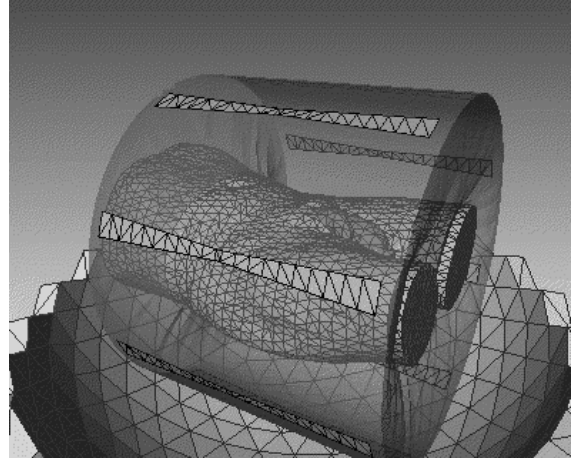
Fig.1a: Real patient during treatment.   Fig.1b: Virtual patient for therapy planning.

2. Technological Developments

Even though the partial differential equation model is in parts far from being perfect, it nevertheless already serves the purpose of giving a realistic assessment of the possibilities of hyperthermia treatment for an individual patient within a given applicator. In cases where HyperPlan predicted insufficient heat concentration in the tumor, temperature measurements along catheters have confirmed numerical simulations to an accuracy of 0.5 °C ! On this rather firm basis our virtual lab HyperPlan can be directly applied for the technological development process.

2.1. Design of New Applicators

The applicator shown in Fig.1 is the BSD Sigma 60 characterized by a circular cross section and a set of 8 antennas which are coupled in pairs ($k = 4$ channels). On the basis of earlier simulations by HyperPlan the new applicator BSD Sigma Eye has been developed, which is characterized by an eye-shaped cross section and a set of 24 antennas, once again coupled in pairs ($k=12$). Typical therapy planning times on a Sun UltraSPARC workstation are:

	old *(k=4)*	new *(k=12)*
segmentation	2-4 h *(semi-automatic)*	
grid generation	15 min	
electric field calculation	80 min	120 min
temperature calculation	2 min	20 min
temperature optimization	6 sec	1 min

With our present algorithm the CPU time for the finite element calculation of the electric field is proportional to k, whereas the temperature calculation is proportional to k^2. Additionally the new applicator leads to a reduction of the number of necessary nodes due to a smaller cross section. In passing we note that our Maxwell solver for the *E*-field calculation is presently also used in the design of specialized antennas for hyperthermia.

2.2 Frequency Studies

Within our virtual lab all kinds of parameter studies are, of course, easy to perform. In view of the MR frequency of 63 MHz at 1.5 Tesla (see Section 2.3) the question of how to choose the radio frequency once again deserves careful consideration. Recently *Paulsen* [5], on the basis of electrical power deposition calculations, has pointed out that frequencies beyond 100 MHz might be preferable. His numerical computations were done using an algorithm based on nodal tetrahedral finite elements for the magnetic field H – which may in rare, but unpredictable cases introduce unphysical spurious solutions. From this the electric field $E \sim rot\ H$ is obtained by differencing the linear tetrahedral elements – a procedure which loses one order of accuracy in terms of the mesh size.

Therefore, we performed numerical simulations to study the frequency dependence of the optimized temperature distributions for a set of virtual patients. Our first calculations clearly back the suggestions of Paulsen: frequencies around 200 MHz lead to better tumor heating together with a better suppression of hot spots in healthy tissue.

2.3 Combined MRI / Hyperthermia Systems

Combined systems using MR imaging and radio wave heating have been developed recently. Within Germany, a combined system including an open field MR device has been installed at the university hospital Großhadern, Munich, in the group of *Issels*. Another system, using conventional MRI, will be set up at the university hospital Charité, Berlin, in the group of *Felix* and *Wust*.
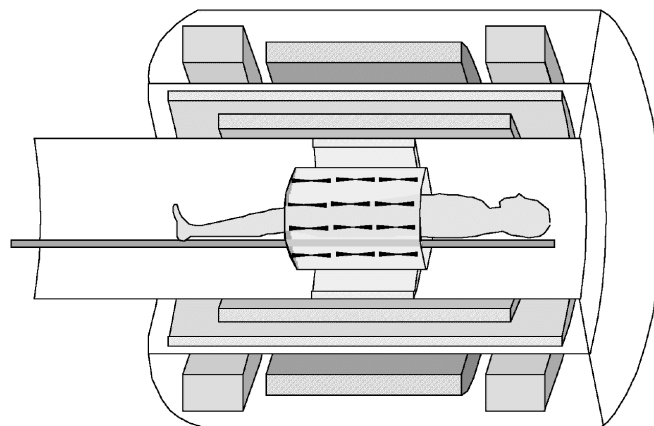

Fig. 2: Hyperthermia applicator combined with a conventional MR system.

One advantage of the conventional version is that stronger magnetic fields can be used (1.5 Tesla compared to 0.2 Tesla), which implies a better signal-to-noise ratio. Moreover the conventional setting leads to a more desirable homogeneous magnetic field. On the other hand, the open field system permits an easier access to patient and applicator, and is preferable in view of electromagnetic compatibility (EMC).

The main expectations connected with any such system are (a) an even more realistic mapping of individual patients onto virtual patients, since MRI is known to give a better resolution of soft tissue, and (b) the availability of additional information, which can be exploited for feedback control of the whole treatment for individual patients in situ. Relevant information obtainable from MRI is:

(a) *Patient positioning*: During a CT scan patients lie stretched on a couch, whereas during treatment they lie in a slightly bent position in a hammock.

(b) *Electric properties* of different tissues, which presently enter only as averages, can be measured during the treatment. Frankly speaking, however, sensitivity considerations seem to indicate that these coefficients do not enter crucially into the mathematical model.

(c) *Blood perfusion,* however, may be of crucial importance for the distribution of heat within the patient's body – ignoring up to now the local effects of strong blood vessels. MRI permits a rough measurement of this quantity as a function of position and local temperature.

(d) *3D temperature distribution*: The general experimental idea is to measure temperature dependent quantities via MR, such as the T1 relaxation time [6], diffusion [7], or the frequency shift of proton resonance [8] and deduce from these the temperature. The associated error tolerances are 2.0 ℃, 0.8 ℃, and 0.6 ℃, respectively. Currently we regard the latter method as the most promising one.

With fast measurements of that kind available, we plan to construct closed feedback loops: on-line measurement, on-line insertion of actual parameters into the mathematical models, computation of feedback control for optimal therapy, and, finally, adaptation of parameters in the real therapy. These feedback techniques should be able to improve both our therapy planning and our therapy for each individual patient during each treatment.

References

[1] Deuflhard P, Seebass M, Stalling D, Beck R, Hege H-C. *Hyperthermia Treatment Planning in Clinical Cancer Therapy: Modelling, Simulation, and Visualization.* In: Sydow A, ed. Procs. 15th IMACS World Congress, Vol. 3., Berlin: Wissenschaft und Technik Verlag, 1997: 9-17.

[2] http://www.zib.de/Visual/projects/hyperthermia/hyper/index.html

[3] Beck R, Deuflhard P, Hiptmair R, Wohlmuth B, Hoppe RHW. *Adaptive Multilevel Methods for Edge Element Discretizations of Maxwell's Equations.* Surv. Math. Ind. 1999; 8: 271-312.

[4] Deuflhard P, Seebass M: *Adaptive Multilevel FEM as Decisive Tools in the Clinical Cancer Therapy Hyperthermia.* In: Lai C-H, Bjørstad PE, Cross M, Widlund OO, eds. Domain Decomposition Methods in Sciences and Engineering. Bergen: Domain Decomposition Press, 1999: 403-414.

[5] Paulsen KD, Geimer S, Tang J, Boyse WE. *Optimization of Pelvic Heating Rate Distributions with Electromagnetic Phased Arrays.* J. Hyperthermia 1999; 15: 157-186.

[6] Delannoy J, LeBihan D, Hoult DI, Levin L. *Hyperthermia System Combined with a Magnetic Resonance Imaging Unit.* Med. Phys. 1990; 17: 855-860.

[7] Samulski TV, MacFall J, Zhang Y, Grant W, Charles C. *Non-invasive Thermometry Using Magnetic Resonance Diffusion Imaging: Potential for Application in Hyperthermic Oncology.* J. Hyperthermia 1992; 8: 819-829.

[8] De Poorter J, De Wagter C, De Deene Y, Thomsen C, Ståhlberg F, Achten E. *Noninvasive MRI Thermometry with the Proton Resonance Frequency (PRF) Method: In vivo Results in Human Muscle.* Magn. Reson. Med. 1995; 33: 74-81.