# Exposure to Electromagnetic Waves from Mobile Phones

## Realistic Numerical Modeling of Head Tissues Exposure

The ever-rising diffusion of cellular phones has determined an increased concern for possible adverse effects of electromagnetic radiation on human health. Thermal effects have been investigated, via experimentation or computer simulation, by several research projects in the last decade. Concerning numerical modeling, the power absorption in a user's head is generally computed using discretized models built from medical images. The vast majority of such numerical studies have been conducted using the widely known Finite Difference Time Domain (FDTD) method, despite strong limitations of its accuracy due to material heterogeneity, variation in the discretization parameter (if the cartesian mesh is non-uniform) and poor definition of detailed structures of head tissues (staircasing effects). In this paper, we present the results of a multi-disciplinary project conducted at INRIA Sophia Antipolis between January 2003 and December 2004 that aimed at filling the gap between human head MR (Magnetic Resonance) images and the accurate numerical modeling of wave propagation in biological tissues using Discontinuous Galerkin Time Domain methods on unstructured tetrahedral meshes.

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The ever-rising diffusion of mobile phones has determined an increased concern for possible consequences of electromagnetic (EM) radiation on human health. As a matter of fact, when a cellular phone is in use, the transmitting antenna is placed very close to the user's head where a substantial part of the radiated power is absorbed. In the last decade, several research projects have been conducted in order to evaluate the possible biological effects resulting from human exposure to such an electromagnetic radiation. In this context, it is widely accepted that a distinction must be made between thermal and non-thermal biological effects.

Thermal biological effects of microwave radiation have been investigated both from the experimental and numerical viewpoints. Concerning numerical modeling, the power absorption in a user's head is generally computed using discretized models built from Magnetic Resonance images. The vast majority of such numerical studies have been conducted using the widely known Finite Difference Time Domain (FDTD) method due to Yee [1] for solving the time domain Maxwell equations. In this method, the computational domain is discretized using a structured cartesian grid, which can be directly derived from the structure of MR images. Due to the possible straightforward implementation of the algorithm and the availability of computational power, the FDTD method is currently the leading method for numerical assessment of human exposure to electromagnetic waves [2, 3]. However, limitations are seen, due to the rather difficult departure from the commonly used rectilinear grid and cell size limitations regarding detailed structures of head tissues as well as of a handset which might be essential for reliable compliance testing. So far, little attention has been put to the application of numerical methods able to deal with unstructured grids, i.e. Finite Element, Finite Volume or Discontinuous Galerkin Time Domain (respectively FETD, FVTD, DGTD) methods. This situation is essentially due to the lack of reliable automated tools for the unstructured discretization of human heads.

The Headexp project at INRIA[1)] aimed at filling the gap between human head MR images and the efficient and accurate numerical modeling of the interaction of electromagnetic waves emitted by mobile phones with biological tissues. This required the development of specific image analysis tools and automated unstructured mesh generation tools for the construction of realistic discretized human head models. In this effort, the numerical simulation of the propagation of electromagnetic waves throughout the head tissues called for unstructured mesh solvers able to take into account the heterogeneity of the electromagnetic characteristics (electrical conductivity and electrical permittivity) of the underlying media.

## From Medical Images to Numerical Simulation

Starting from MR data, the head tissues have to be segmented. Each voxel of the cartesian representation of the MR image is recognized as made (mainly) of a single material. After having decided the relevant number of different materials for the dosimetry analysis (each material having its own electromagnetic characteristics), the different tissues are segmented and the interfaces between tissues are meshed, using triangle facets. Different strategies can be used in order to obtain a smooth and accurate segmentation of head tissues and interface triangulations as well. A first strategy consists in using a Marching Cube algorithm [4] which leads to huge triangulations of interfaces between segmented subdomains. These triangulations can then be regularized, refined and decimated in order to obtain improved surface meshes, for example using a surface remeshing tool [5]. Another strategy consists in using a variant of Chew's algorithm [6], based on Delaunay triangulation restricted to the interface, which allows to control the size and aspect ratio of interfacial triangles [7]. Finally, another promising strategy deriving from a level-set approach has been tested [8]. The idea is to view segmentation as the definition of contours inside a volumic description of the material. This kind of method can have additional interesting features, like topology preservation for some parts of tissues (constrained spherical topology or minimal distance between interfaces). These topological properties can be important for the volumic meshing tools and in some cases for some qualitative aspects of the numerical model.

Starting from the triangular surface meshes of the interfaces between different materials, tetrahedral volumic meshes of the tissues are generated using quasi-automated tools [9]. The resulting meshes are fully unstructured and can lead to some small edges, which is a concern when an explicit time integration scheme is used for the numerical simulation (the stability condition is constrained by the smallest edge or element volume in the mesh). The exterior of the head must also be meshed, up to a certain distance, where an artificial absorbing boundary condition is imposed. For numerical simulations with a mobile phone model, the meshing process is a little more complex and requires the meshing of the phone (metallic box with apertures and a dipole model inside) and the volume between the head, the phone and the artificial far-field boundary. Examples of surface meshes of the brain, skull and skin are shown in figure 1.

`(Figure 1)`

## Discontinuous Galerkin Time Domain Methods

In this study, numerical dosimetry of mobile phone EM radiation, using the unstructured tetrahedral geometrical models of the head tissues discussed above, relies on Discontinuous Galerkin Time Domain (DGTD) methods developed in the Caiman project team at INRIA Sophia Antipolis.

The modeling of systems involving wave propagation in heterogeneous media has recently known a high interest in many application domains. Finite Difference Time Domain (FDTD) methods based on Yee's scheme [1] are still prominent. Nevertheless, many different types of methods have been proposed, like Finite Element Time Domain (FETD) methods, which are based on unstructured meshes and can deal with complex geometries. However, they induce heavy computations or lumping of mass matrices and significant works are still being devoted to the construction of edge elements allowing accurate and efficient mass lumping. Similarly, mimetic methods have proved properties for Maxwell equations which make them close to the classical edge elements in the unstructured case. At the same time, numerical methods have been adapted to handle coefficient discontinuities, which is rather natural for methods based on variational formulations.

Gathering many advantages, Discontinuous Galerkin Time Domain (DGTD) methods [10] can handle unstructured meshes, deal with discontinuous coefficients and solutions and get rid of differential operators (and finite element mass matrices) using Green's formula for the integration over control volumes. They can be seen as Finite Volume Time Domain (FVTD) methods, where the finite element approximation is piecewise constant inside elements. The different achievements of the FVTD methods are now being extended in the context of DGTD methods, which enjoy a renewed favor nowadays and are now used in a wide variety of applications as people (re)discover the abilities of these methods to handle complicated geometries, media and meshes, to achieve a high order of accuracy by simply choosing suitable basis functions, including spectral elements, to allow long-range time integrations and, last but not least, to remain highly parallelizable at the end.

As mentioned above, DGTD methods can be interpreted as high-order extensions of finite volume methods since they assume element-wise interpolation of the electric and magnetic field components and do not impose continuity of these quantities at element boundaries (i.e. triangular faces). Then, the integrals on element boundaries that appear in the variational formulation of the initial and boundary value problem for the time domain Maxwell equations are approximated using a numerical flux. In the $\mathbb{P}_k$-DGTD methods discussed in details in [11,12], we make use of centered fluxes which lead to energy conservation when an explicit leap-frog advancing-in-time scheme is used. Because of the discontinuity of fields through element faces, the corresponding finite element mass matrix is only block diagonal, which leads to the same kind of computational cost as for a standard explicit time integration scheme. When the fields are sought for as constants inside elements (one degree of freedom per field component and per element), the DGTD methods reduces to a centered Finite Volume Time Domain method $P_0$-DGTD version. We have also developed a $P_1$-DGTD version of the method, where the fields are sought for as at most first degree polynomials inside elements (four degrees of freedom per field component and per element). Higher order versions are under development.

## Results

We consider a geometric head model which consists of four tissues: the skin, the skull, the CSF (Cerebro Spinal Fluid) and the brain. At the selected frequency (1800 MHz), the minimal wavelength is obtained in the CSF (20,33 mm) while the maximal wavelength is 166,7 mm (in the air). A simplified mobile phone model (metallic box with a quarter-wave length antenna mounted on the top surface) is included and placed in vertical position close to the right ear. The temporal excitation is a Gaussian pulse modulated by a sinusoid with a central frequency of 1800 MHz and a total emitted power equal to 1 W. Two tetrahedral meshes have been constructed. The first one (M1) contains 311 259 vertices and 1 862 136 tetrahedra. In this mesh, the minimum and maximum sizes of edges are respectively equal to 0,650 mm and 8,055 mm. The second mesh (M2) contains 1 308 842 vertices and 7 894 172 tetrahedra. In this mesh, the minimum and maximum sizes of edges are respectively equal to 0,776 mm and 5,509 mm. Partial views of the surface mesh and positioning of the model mobile phone near the head are shown on figure 2.

`(Figure 2)`

The quantity of interest in the definition of international norms for the exposure to mobile phones is the Specific Absorption Rate (SAR), defined by

$$\mathrm{SAR} = \sigma \frac{|\vec{E}|^2}{\rho}$$

where $\sigma$ denotes the electrical conductivity, $\rho$ the density and $\vec{E}$ the electric file vector. The normalized SAR distributions (local SAR over maximum local SAR in log scale) on the skin, the skull and the brain are shown on figure 3 (mesh M1, $\mathbb{P}_0$-DGTD method), figure 4 (mesh M2, $\mathbb{P}_0$-DGTD method) and figure 5 (mesh M1, $\mathbb{P}_1$-DGTD method). On these figures, we note that the higher order $\mathbb{P}_1$-DGTD method yields a smoother solution although it is applied on the coarser mesh. However, from the point of view of computing times, the $\mathbb{P}_1$-DGTD is far more expensive (39 minutes for the calculation using mesh M1 and the $\mathbb{P}_0$-DGTD method and 6 hours and 48 minutes for the calculation using mesh M1 and the $\mathbb{P}_1$-DGTD method[2])). It is well known that $\mathbb{P}_k$-DGTD methods will be at their advantage for higher order interpolation ($k > 1$), leading accurate solutions on even coarser meshes.

`(Figures 3,4,5)`

## Ongoing and Future Works

This study currently proceeds in several directions. For what concerns geometrical modeling, the goal is to develop a quasi-automated tool that will allow the simultaneous extraction of surface meshes for several tissue interfaces and generation of volumic meshes using Delaunay refinement techniques. So far, this process is done in three main steps: extraction of the surface meshes, generation of volumic meshes of the tissues and assembly of the different volumic meshes to obtain the final geometrical model of the head tissues. Concerning numerical modeling, the development of high order $\mathbb{P}_k$-DGTD methods on tetrahedral meshes is underway.

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**Dr. Stéphane Lanteri** is a researcher in scientific computing at INRIA Sophia Antipolis. His research interests are concerned with the design of finite element methods for the numerical resolution of systems of PDEs modeling wave propagation (with applications to computational electromagnetics and computational geoseismics), and of numerical algorithms for high performance computing (domain decomposition algorithms, multigrid algorithms, parallel and distributed computing). He is the scientific coordinator of the HEADEXP collaborative research action dealing with the geometrical and finite element based numerical modeling of the interaction of electromagnetic fields with biological tissues.

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[1] http://www-sop.inria.fr/caiman/personnel/Stephane.Lanteri/headexp/headexp.html

[2] timings for calculations performed on a cluster of AMD Opteron/2,0 GHz nodes with Gigabit Ethernet interconnection

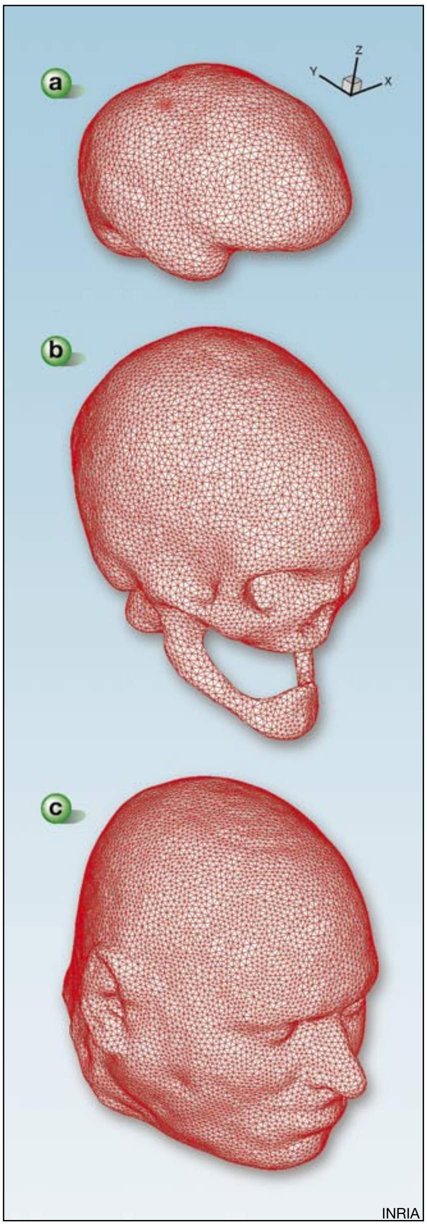

Figure 1 Surface meshes of the brain, skull and skin

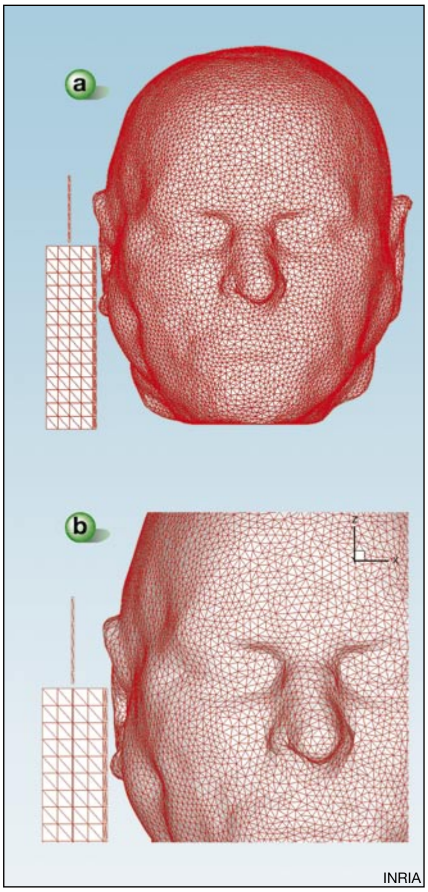

Figure 2 Positioning of the mobile phone

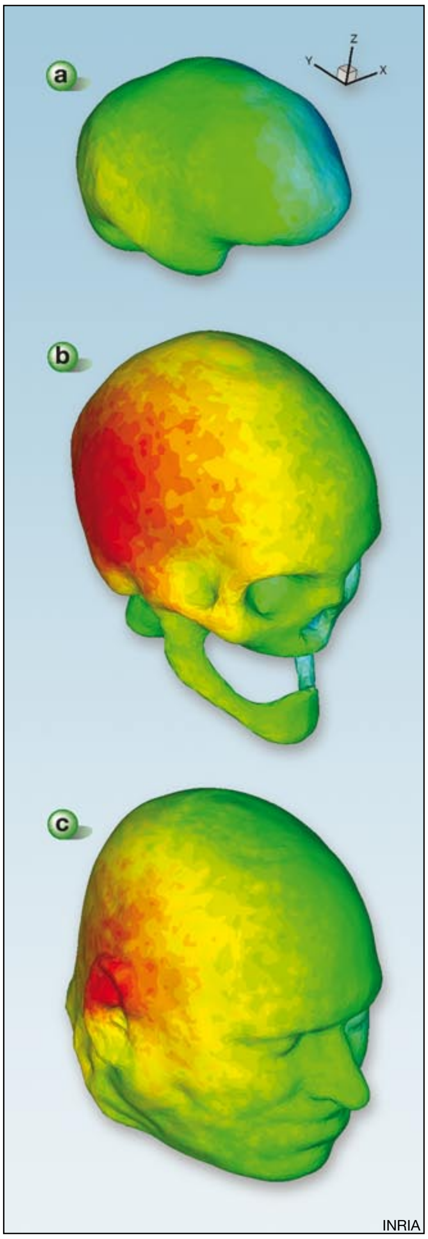

Figure 3 Normalized SAR (mesh M1, $\mathbb{P}_0$-DGTD

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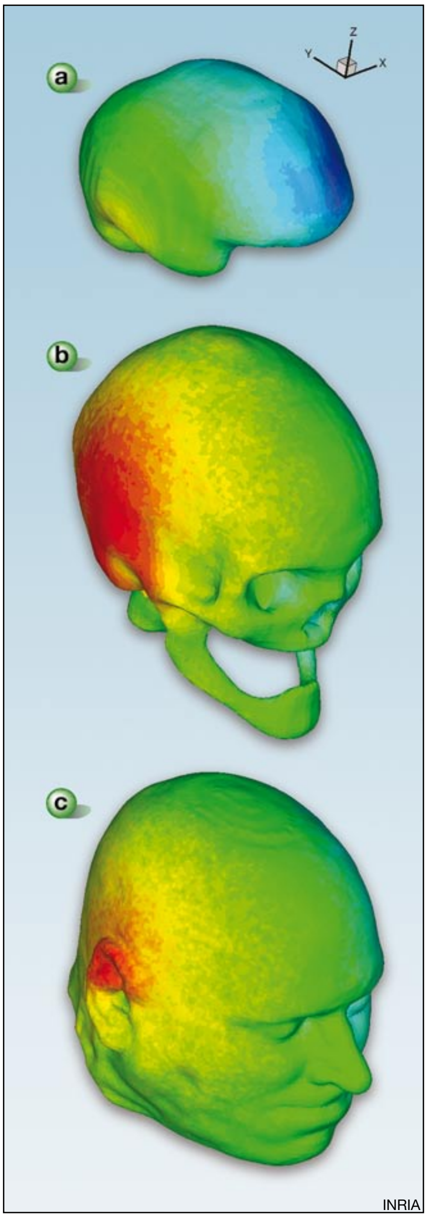

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Figure 4 Normalized SAR (mesh M2, $\mathbb{P}_0$-DGTD

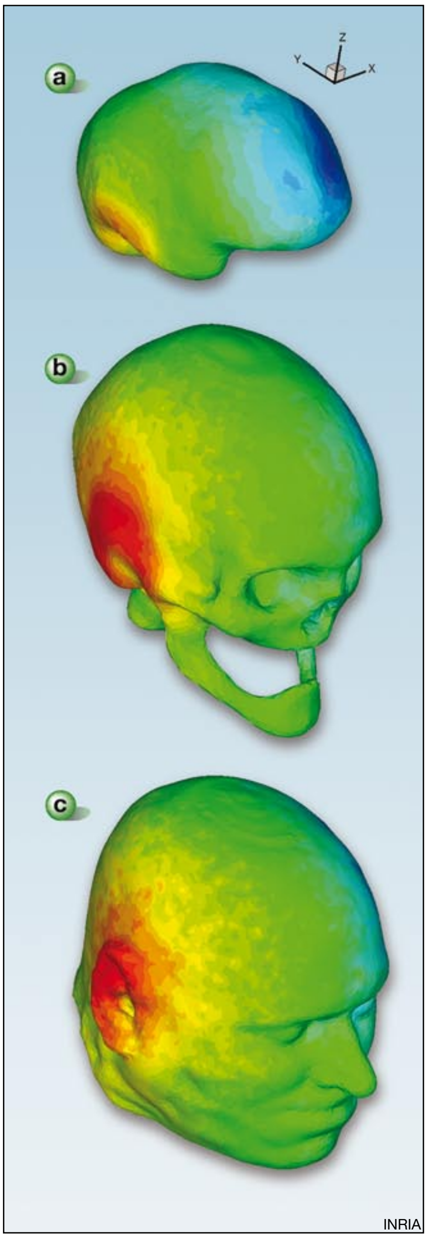

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Figure 5 Normalized SAR (mesh M1, $\mathbb{P}_1$-DGTD