

Visualization and 3D-Interaction for Hyperthermia Treatment Planning

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Abstract

In regional hyperthermia extensive numerical simulations are required for optimizing individual cancer therapy treatments. To take full advantage of such simulations a therapy planning system is needed. In this paper we discuss a new hyperthermia planning system, focussing on its visualization and 3D-interaction functionality. Our software, called HyperPlan, assists the whole treatment planning process with state-of-the-art numerics and visual controlling techniques. Its flexible design allows it to be used in both hyperthermia research and clinical practice.

Introduction

Planning systems are well established in conventional radiotherapy. They have also proved to be essential for hyperthermia treatment planning. In this paper we deal with regional hyperthermia that employs radiofrequency waves to heat up the tumor region non-invasively. The goal is to locally achieve temperatures higher than 41C° without affecting healthy tissue. Numerical simulations can help to optimize an individual treatment and to facilitate the development of improved antennas and applicators.

The course of hyperthermia planning is as follows (compare Fig. 1). First a stack of tomographic images of the patient has to be segmented and classified. From this data a patient-specific tetrahedral finite-element grid is generated. Such a grid is required for the numerical simulation of the electromagnetic fields, as well as for the computation of the resulting power and temperature distributions. For both tasks adaptive multi-level finite-element methods [5, 2] are best suited. To achieve an optimal therapeutic effect the antenna parameters have to be optimized. Several numerical simulation steps have to be performed within the framework of a global optimization strategy [1]. The choice of clinical relevant parameters for optimization is discussed in [6].

Adequate visualization techniques are all-important throughout the whole planning process. In addition sophisticated user interaction is essential for many segmentation and grid generation tasks. For use in clinical practice all of these steps need to be integrated into a single easy-to-use treatment planning system.

Such a system, called *HyperPlan*, is currently being developed at ZIB. It is designed in a flexible, object-oriented manner. For maximal performance it can

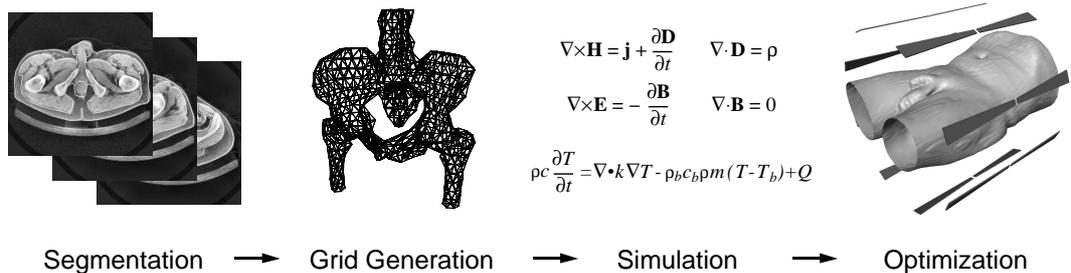


Figure 1: Schematic course of hyperthermia treatment planning.

take advantage of modern graphics hardware in several ways. Currently the system is primarily being used as an experimental environment by scientists involved in hyperthermia research at ZIB and the Rudolf-Virchow-Klinikum in Berlin. We intend to adapt the system for routine clinical use in future.

After giving a short overview of basic design issues we will discuss some of the visualization and interaction techniques employed in our system.

System Overview

A typical HyperPlan session begins with loading patient specific data, for instance tomographic images or a previously generated grid. Data objects are represented as icons in a *work area*. Each type of data object may be visualized using a number of different methods. These visualization methods are implemented by so-called *display modules*. Data icons provide a pop-up menu which allows to select suitable display modules to be linked to the data. In this way a graphical network is constructed in the work area, indicating which data is visualized by which module. The resulting three-dimensional scene may be viewed from multiple directions in different windows.

Display modules do not necessarily operate in a stand-alone fashion, but there may be dependencies between them. For example there are *overlay modules* which require some other module to provide a suitable planar background on which isolines or tissue boundaries can be drawn. These dependencies are also indicated in the work area.

The set of modules can easily be extended without recompiling. This is achieved by means of a resource file which informs the system about what data types can be displayed by which module and about further dependencies between modules. Loading and activation of modules is delayed until really needed by using a runtime loader. Modules which are not in use do not consume any system resources.

Data objects like tomographic images, contours, or tetrahedral grids may be manipulated interactively within corresponding *data editors*. An editor is activated by double-clicking a data icon in the work area. Editors enable the user for example to apply filters to tomographic images, to draw contours into images, or to invoke semi-automatic segmentation algorithms. They directly alter the data object for which they were invoked.

Some data manipulation tasks may also be performed automatically by a *com-*

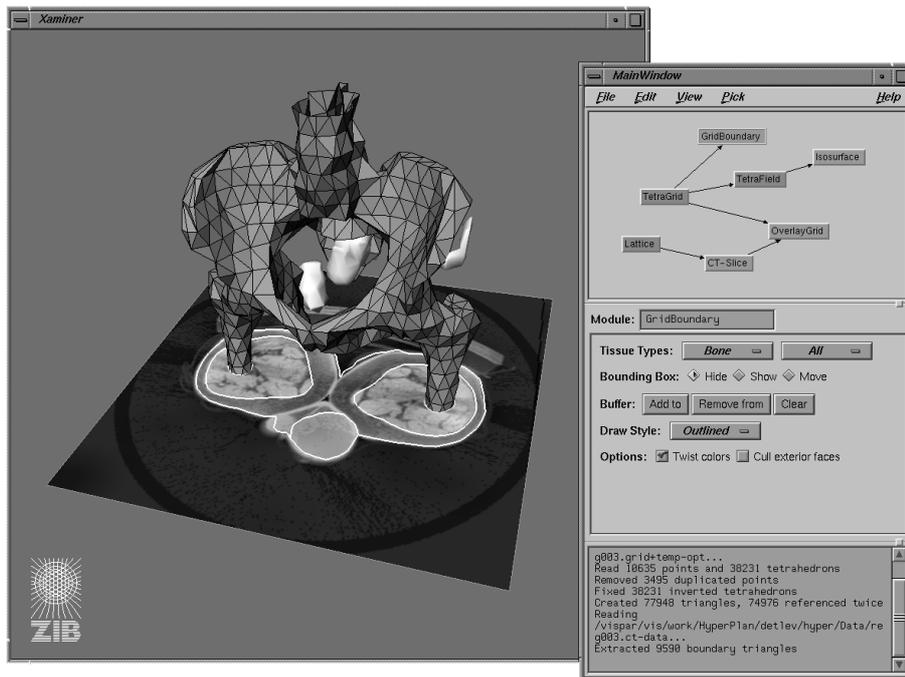


Figure 2: *Graphics window and work area in HyperPlan.*

putational module. Computational modules may be thought of as stream editors. They take a data object as input, perform some computation and generate a new data object which is represented as an icon in the work area. In contrast to data editors computational modules do not alter the original data. To the resulting data object another computational module may be attached. In this way a traditional dataflow chain can be established, like in AVS or Iris Explorer.

Visualization

During the treatment planning process several data entities of different modalities are encountered. It is important that all information available can be displayed in combination. Among other things this allows to judge how good a tetrahedral grid approximates the real anatomic situation, how a simulated field distribution depends on the underlying grid, or which tissue compartments are primarily affected by temperature hot spots. Adequate visualization techniques therefore hold a key position within the planning system.

External Geometry

Displaying geometric objects like the antennas or parts of the treatment room is often quite helpful for the therapist. It enables him to recognize and adjust the position of the treatment units relative to the patient. Our system builds upon the Open Inventor graphics toolkit [9]. This toolkit defines a powerful data format for geometric objects which allows us to load any kind of external geometry into the 3D-scene.

Tomographic Images

The most common way to view tomographic data is to take 2D-slices through the data volume. HyperPlan offers several methods to map data to gray scale values, like a simple clamped linear mapping or a contrast-limited histogram equalization technique. Slices are displayed either in a 2D-window of its own or in a 3D-window at the correct position with respect to all other geometries. The texture mapping capabilities of modern desktop graphics workstations allow to freely move and rotate the resulting scenes.

A more sophisticated method for visualizing tomographic data is direct volume rendering. Though computationally very expensive, direct volume rendering can be implemented at interactive rates by exploiting the 3D-texture mapping capabilities offered by some modern graphics hardware [3]. First for each voxel, color and opacity have to be computed. These values form a semi-transparent cloud-like tissue representation that can be loaded directly into the graphics subsystem as a 3D-texture map. This texture is applied to a number of parallel polygons, which are always oriented perpendicular to the camera's view direction. Typically 100 to 200 slices are taken through the volume. More slices improve image quality at the expense of rendering speed. For an example see Fig. 3a.

Segmentation Results

Currently we are using closed contours around tissue regions in subsequent CT-slices to build the patient-specific tetrahedral grid. The stack of contours or parts of it can be displayed in 3D-space. In addition the display of contours and CT-slices can be coupled, so that individual contours are always drawn into the corresponding tomographic image. Of course the direct volume rendering method discussed above may also be used to view segmentation results. To accomplish this the display can be restricted to parts of the CT-volume delimited by selected contours.

Tetrahedral Grid

A useful method to visualize the patient specific tetrahedral grids is to extract and display the boundary faces between neighbouring tissue compartments. Several draw styles are provided by HyperPlan including wire frame, shaded triangles or triangles with superimposed edges.

For a more detailed inspection of the grid individual tetrahedra may be selected and clipped off by 3D-interaction methods described below. In this way the user may "carve out" a way to interesting interior grid structures.

Electromagnetic Fields

The fundamental quantities in the simulation are electromagnetic vector fields. In this respect methods for visualizing vector fields are of particular importance in hyperthermia planning. In addition to a conventional "arrow style" visualization we incorporated a novel method capable to encode directional information at a much higher spatial resolution compared to traditional approaches, namely line-integral convolution (LIC) [4]. In this method a random texture is blurred along locally computed stream line segments defined by the vector field. From

the blurred image the directional structure of the field is clearly visible (Fig. 3d). The effect may be further improved by applying a gradient filter to the resulting image. The original LIC method is computationally quite expensive. Therefore we have developed and implemented an improved variant of LIC which reduces computation times by an order of magnitude compared to the original algorithm [8].

Power and Temperature Distribution

A number of different methods are available to visualize scalar quantities defined on the tetrahedral grid, like simulated power or temperature distributions. Among these methods are isolines, isosurfaces, arbitrarily oriented cutting planes (Fig. 3c), and a colorwash method, which may be applied to tomographic image slices. A direct volume rendering technique suitable for this kind of data is the splatting algorithm [7]. In contrast to the 3D-texture approach a transparent polygonal object (splat) is drawn for each vertex or group of vertices. Good results are obtained using a Gaussian shaped opacity distribution. Since splats can be positioned independently, there is no need to resample the data to a regular grid (see Fig. 3b).

We achieved the most meaningful visualization results by properly combining the methods described above, for example overlaying tissue boundaries on cutting planes or showing vector field arrows pinned to each vertex of a visible tetrahedron. The central idea is to present diverse visual information in a single 3-dimensional scene, thus revealing insights into their interrelations.

3D-Interaction

Because of the complexity implied by the combined visualization of all data relevant to the treatment planning, interaction techniques are especially important. Interaction becomes even more essential if the application is to be used by non-computer experts like physicians or medical assistants. A modern paradigm we have chosen to incorporate in HyperPlan is *direct interaction* with objects displayed in a 3-dimensional scene. For example to slice through a volumetric data set the user simply picks the cutting plane with the mouse and translates it along the plane normal. For choosing a different orientation a small trackball can be activated and displayed at the center of the slice. The trackball then can be picked and rotated using an ordinary mouse again. For analyzing the complex tetrahedral grids needed in numerical simulations, several selection schemes have been implemented. The user can pick and translate or resize a 3-dimensional selection box. Individual tetrahedra can be hidden and made visible by clicking on corresponding or neighbored faces.

Adequate interaction techniques are even more important for various segmentation and grid generation algorithms. Volume growing algorithms for example require the user to specify a seed point, for which a 3D-cursor seems to be best suited. Often user interaction is required to resolve ambiguities while connecting contours of different topology in neighbouring slices. Sometimes grids generated

automatically exhibit certain anomalies and defects which then have to be corrected interactively.

For some interaction tasks multidimensional input devices are more suitable than a traditional 2D-mouse. Currently we are using a spacemouse device, which turned out to be well suited for controlling a 3D-cursor as well as for navigating through the scene.

As in all medical applications special emphasis must be laid on the reliability of the displayed information. We tackle this problem by providing a set of tools for exact numerical data analysis, so-called *quantitative graphics tools*. They allow for example to query data values at arbitrary positions, or to plot any scalar quantity along an arbitrary line segment.

Conclusion

We have discussed several aspects of a new software system for hyperthermia planning, focussing on its visualization and interaction functionality. The system is built in an extensible, object-oriented fashion. Special efforts were made to guarantee a seamless integration of advanced numerical algorithms. The system has already proved to be very helpful as a scientific environment for mathematical simulations involved in hyperthermia planning as well as for medical research.

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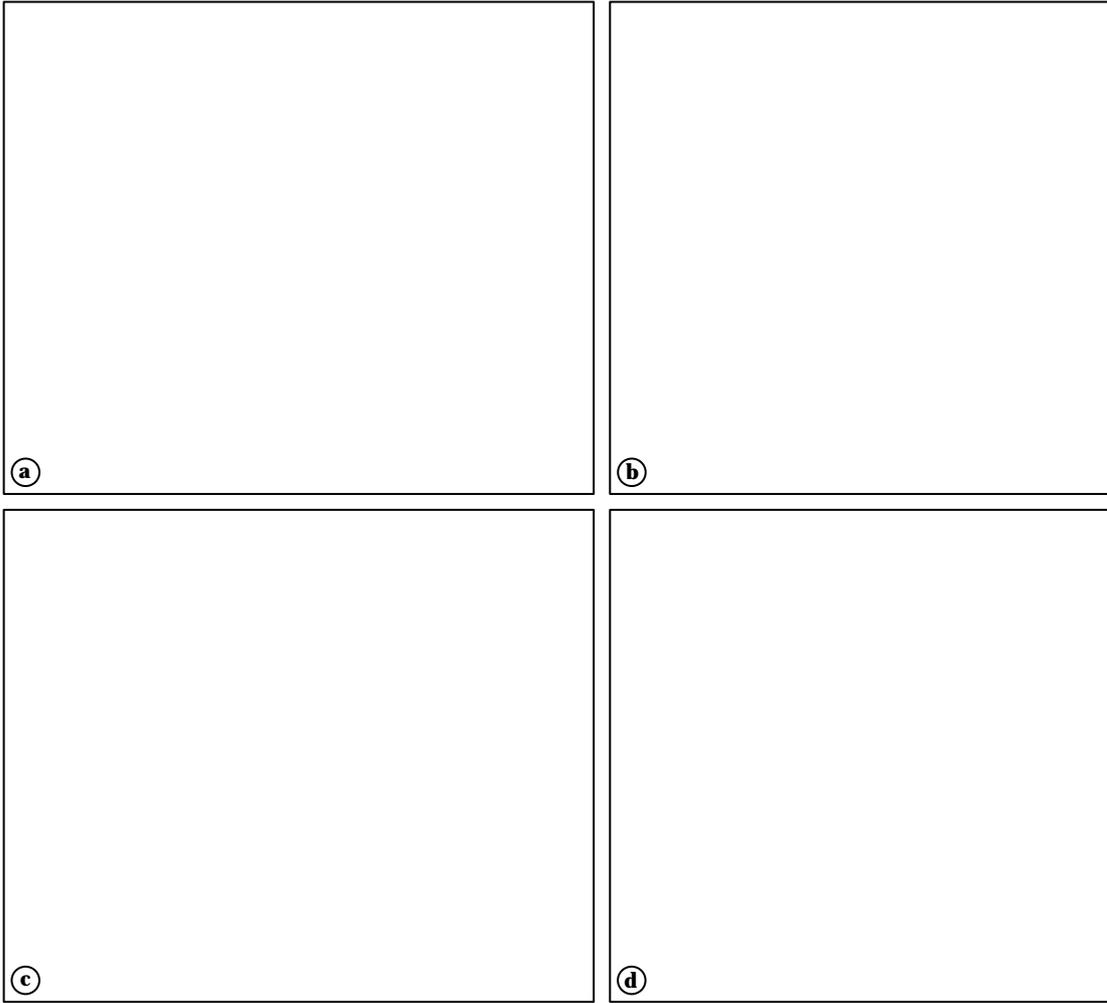


Figure 3: Visualization methods available in HyperPlan: a) volume rendering of a segmented CT-volume using a 3D-texture, b) splatting algorithm applied to a simulated temperature distribution, c) cutting plane showing simulated power distribution with overlaid tissue boundaries, d) line-integral convolution method used to visualize electrical field lines.

(color plates)