From Image Data to Three-Dimensional Geometric Models
– Case Studies on the Impact of 3D Patient Models

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Image-guided diagnosis and therapy are widely used in medicine nowadays. Going one step further involves methods that allow physicians to further improve their diagnosis and to plan therapy or surgery by quantitative analysis and simulation. Fundamental requirements for this kind of quantitative medicine are methods for reliable creation of 3D patient models that faith-fully represent the individual anatomy. We demonstrate the impact of geometric patient models in medicine by presenting several case studies on work that is based on the 3D geometry recon-struction and visualization software amira®.

Keywords: *Image Segmentation, Geometry Reconstruction, Data Visualization, Therapy and Surgery Planning*

1. Introduction

Medicine is continuously pushing the limits of medical treatment through new insights as well as improved technology and methodology. Treatment is becoming more and more complex and requires a precision that can only be satisfied through detailed planning or even simulation.

Diagnosis, planning, and simulation rely on medical imaging of the individual patient. CT and MR scanners produce data in the form of high-resolution image stacks. However, it can be very difficult to interpret complex three-dimensional structures as well as spatial inter-relationships in a series of two-dimensional image slices. The scan data is inherently three-dimensional, and so the most natural way of looking at it is to computationally reconstruct the 3D structure and exploit all three dimensions for display and interaction with the data. The construction of explicit meshes representing the structures of interest becomes even more important if numerical simulations or quantification is involved.

3D visualization and data analysis technology has greatly improved over the last years, and software systems as well as 3D display devices are readily available. Looking at the appealing results of some researchers in the field, e.g. [6], the interest in true 3D visualization is continuously growing [1]. Visualization is not limited to viewing the 3D model on a 2D display such as an ordinary monitor, but it is possible to support the full spatial perception of the human visual system by supplying it with stereoscopic image pairs.

In this study, we demonstrate the importance and impact of three-dimensional visualization and geometry reconstruction techniques by showing results from three different applications: hyperthermia planning, facial surgery planning, and study of vascular networks. We briefly sketch each of the applications and discuss the different benefits of true three-dimensional visualization in each case. Finally, we conclude by summing up the benefits of 3D models and 3D viewing.

2. Methods and Tools

All projects described in this study have been carried out in cooperation with the Zuse Institute Berlin (ZIB), and have been implemented using the amira® software suite [2] that is developed by Indeed - Visual Concepts GmbH and TGS, Inc. in cooperation with ZIB.

amira® integrates the whole pipeline from reading in 3D medical images to geometry reconstruction and visualization into an intuitive and easy--to--use software system that supports many file formats, including DICOM import.

For immediate visual inspection of the volumetric data different visualization methods like slice--views, iso--surfaces, or direct volume rendering can be applied. Several digital filters can be used for further processing the data. Segmentation is the next step towards obtaining geometric models. A wide range of manual, interactive and automatic segmentation tools are incorporated into the amira® segmentation editor, e.g. thresholding, region--growing, intelligent scissors, and interpolation. Segmentation can be performed from different orientations and intermediate results can be visualized in a 3D viewer.

From the results of the segmentation triangulated surface models are generated, both manifold and non-manifold, representing different materials (tissues). These can be further processed (e.g. simplified or smoothed), visualized or exposed to quantitative measurements. Surface representations can then be transformed into tetrahedral grids for finite element simulations.

Furthermore, amira® offers excellent presentation support. Apart from generating snapshot images or direct MPEG movie export of animates 3D models, amira® can be used directly for viewing the medical content in full three dimensions on advanced stereoscopic display devices.

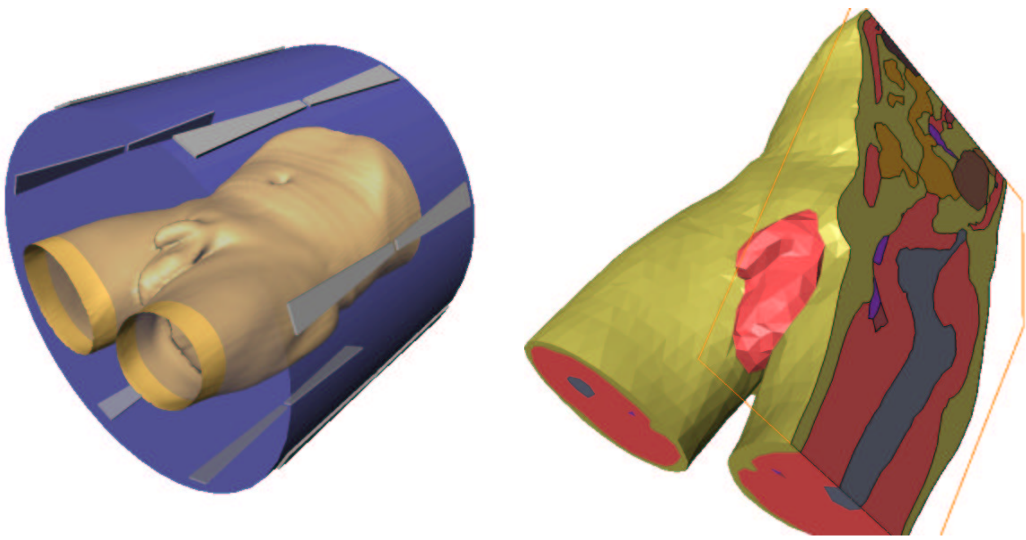

Fig. 1 Hyperthermia planning. Left: illustration of patient and applicator. Center: cut through the volumetric grid for heat transfer simulation.

3. Hyperthermia Treatment Planning

Hyperthermia cancer therapy weakens tumor cells by heating them by application of radio waves (microwaves) [3,5]. The applicator uses a number of radio antennas controlled in terms of the amplitude and phase of the emitted waves. The challenging task is to optimize these parameters to heat just the tumor region and as few of the surrounding healthy tissue as possible. This can be achieved by superposition of the electromagnetic waves from the individual antennas. Therefore, a model of the patient's bone and soft tissue needs to be generated in order to simulate the wave propagation, guided by the Maxwell Equations, followed by a heat transfer computation, based on blood perfusion within the patient's body. The different steps of generating and using this model involve segmentation and labeling of the image data, reconstruction and post-processing of surfaces, volumetric grid generation, finite element simulation, and multiple visualization techniques (cf. Figures 1,3).

The three-dimensional model of the hyperthermia patient also helps to comprehend the impact of the resulting temperature distribution on the patient. The doctor can visually check how good the target tissue is enclosed by the main hot spot. Furthermore, critical regions can be identified, such as important organs affected by secondary hot spots. Last, but not least, the 3D hot spot visualization is used for correct placement of cooling packs during the operation.

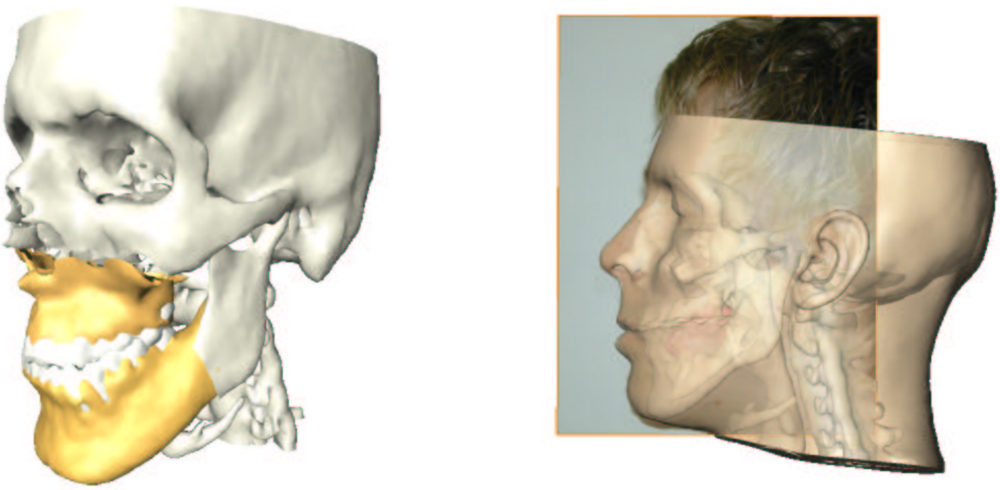

Fig. 2 Cranio-maxillofacial surgery planning. Left: interactive repositioning of the colored parts of the jaw bone model. Right: post-operative photograph of a patient, overlayed with the shape predicted by the soft tissue deformation simulation.

4. Cranio-Maxillofacial Surgery Planning

The second case that we study here is the repositioning of upper and/or lower jaw in cranio-maxillofacial surgery [7]. This operation requires the planning of the osteotomy lines and of the final position of both jaws. The surgeon must take into account the functional as well as the aesthetic impact of the operation. Therefore a 3D model of the jaw bones as well as of the facial soft tissue is generated from CT scan data. The surgeon defines the bone cutting lines (osteotomy lines), repositions the jaw bones interactively in the computer model, and checks the correspondence of upper and lower jaw in full three dimensions (cf. Figure 2). By running a complex finite element simulation, the deformation of the soft tissue can be predicted, yielding a qualitative 3D impression of the patient's face after the operation. The rightmost picture in Figure 2 shows a comparison of the predicted face with a post-operative photograph of the patient.

In addition to visually check the functional aspects of the jaw repositioning, the 3D model is used to predict the aesthetic aspect of the results, and to communicate these aspects to the patient. This is a very natural and convincing way of giving the patient an impression of how the surgery is going to affect his visual appearance. This task would be very hard to accomplish without the explicit 3D model of the face.

5. Study of Vascular Networks

Fig. 3 Hyperthermia planning: Direct visualization of simulation results (temperature, hot spots) on the patient

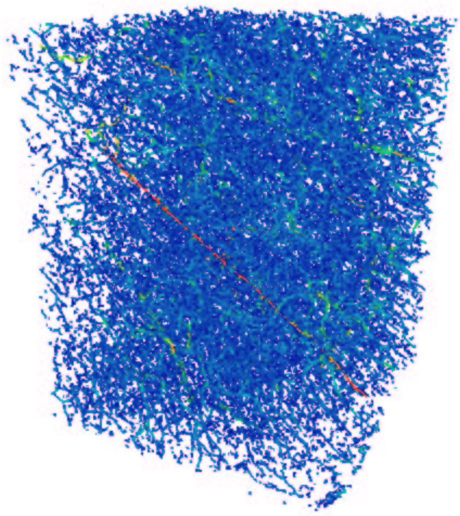

Fig. 4 Part of the capillary network in a $1mm^3$ cube of the human cortex, displayed as lines. Colors are used to encode the local vessel radii.

Another example for the use of 3D models is the work on capillary networks in the human cortex, for example in the context of stroke prevention research [4]. Here, researchers are interested in a statistical model of the blood flow and diffusion process in the cortex. In order to do so, the cortex tissue is scanned (e.g. by ultra-high resolution synchrotron based CT) and the capillary network is reconstructed. Then the volumetric representation is converted into a mathematical graph attributed with key parameters such as average segment length and diameter (see Figure 4). Based on such a representation, researchers can simulate blood flow and diffusion in this very complex network. Furthermore, the graph representation allows the user to interactively display and explore large parts of the network, to visually compare the vessel structure of individual patients, and to check the plausibility of the reconstruction and of the mathematical model. The graph representation can be re-converted into a surface representation for selected vessels for exploring details in the branching of the vessel tree.

6. Conclusions

We have sketched three medical applications of 3D visualization, data analysis, and geometry reconstruction. In each case, we have discussed the importance of true three-dimensional models and stereoscopic viewing, and we can summarize the observed benefits as follows:

- visual exploration of complex 3D structures
- truthful and natural display of spatial relationships
- visual communication of simulation results to experts or even non-experts (e.g. the patient)
- visual comparison of corresponding datasets
- visual plausibility control of reconstruction or simulation.

In this study we have only shown a small selection of the many different applications of modern 3D visualization. We believe that in the near future the 3D patient model will play the central role in medical research, and will as well become a crucial part of clinical routine.

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