Interactive 3D Techniques for Computer Aided Diagnosis and Surgery Simulation Tools

Dr. Katja Bühler*, DI André Neubauer*, Dr. Markus Hadwiger*, MD Stefan Wolfsberger #, Dr. Rainer Wegenkittl+

* VRVis Research Center for Virtual Reality and Visualization, Vienna, Austria

Department of Neurosurgery, Medical University Vienna, Austria

+ Tiani Medragph AG, Vienna, Austria

1 Introduction

Visualization plays a crucial role in medical applications. Radiologists, especially, whose work is based on visualizing data acquired from different modalities, and surgeons, who need good visualizations for understanding a pathology and for planning an operation, have high demands on visualization algorithms. For these applications not only visual appearance, but also accuracy, speed, and simplicity of user interaction are of particular importance. While most commercially available diagnostic workstations provide a variety of good basic visualization techniques, there are still a lot of unsolved problems that arise in the daily work with such workstations. This includes topics like

- Real-time high quality direct volume visualization of large datasets, like e.g. a CTA of the lower limb.
- Design of transfer functions.
- Intelligent visualization of (segmented) data, that allows e.g. to focus on objects of interest without losing context information.
- Interactive perspective volume rendering and simulation of endoscopic views.

Computer aided diagnosis (CAD) aims to support radiologists in analyzing medical data with respect to pathologies. This includes, besides of a pure visualization of a data set, segmentation of objects of interest, fusion of data to combine information retrieved from different image modalities or to compare patient data over time, tools to perform measurements and quantifications, and other high level interpretation aids.

Requirements on CAD tools are extremely high with respect to accuracy and reliability. Economy of time becomes a more and more important factor since 3D imaging modalities produce a growing amount of data to be analyzed. Acceleration, intelligent automation, and improvement of user-friendliness of existing methods are many times as challenging as the development of new algorithms.

Most available high-level CAD tools are specialized on a specific task (analysis of a specific organ, detection of a specific pathology) and specific input data (CT, MR, US…) to be able to guarantee valuable results with minimal user interaction.

The success of a surgical procedure is in direct relation to experience and intuition of the surgeon. Computational tools like **computer-aided planning of operations, surgery simulation for training, and intra-operative surgery assistance** are mostly still at an experimental level and not yet well established in daily clinical routine.

Many tasks connected with the development of such tools can be accomplished by applying state of the art 3D computer graphics algorithms at high quality radiological data sets.

Nevertheless, there exists still a number of challenging open problems. A solution of many of these problems requires a high level of inter-disciplinarity:

- Advanced visualization techniques have to be combined with high-level physics-based simulation to get realistic images for surgery simulation.
- Quantization, manipulation, simulation and fast visualization very often requires a geometric reconstruction of volumetric structures.
- Augmented Reality allows the combination of intra-operative with pre-operative data and enables the surgeon to realize a pre-operative plan exactly. The combination of virtual reality, physics based simulation and the use of haptic feedback devices open new methods for realistic surgery training.
- Speed and accuracy of visualization, simulation and tracking play a crucial role having the necessary interactivity for surgery training and intra-operative use of the techniques in mind. A highly optimized software design and intelligent algorithms in combination with the expected development of the hardware will lead to more and more realistic simulations and visualizations.

This article aims at giving an overview on a selection of research projects of the Medical Visualization Group at VRVis Research Center, Vienna. The presented topics mirror some of recent developments in the fields medical visualization, computer aided diagnosis and surgery simulation, and give a good insight into emerging techniques. The focus lies on interactive 3D techniques, i.e.

- direct interactive and high quality 3D visualization of volumetric data sets (section 2) ,
- intelligent visualization of segmented data (section 2.3)
- flexible and fast rendering techniques for virtual endoscopy (section 2.1)
- time and memory efficient segmentation and registration (section 3)

Presented tools that combine several techniques in one high level CAD or surgery simulation tool resp. are

- the segmentation and analysis tools for 4D MRI and CT data of the myocardium (section 4),
- a virtual endoscopy application for simulation of endonasal transsphenoidal pituitary surgery (section 5).

2 High Quality Interactive Volume Visualization

Modern imaging modalities like Computed Tomography (CT), Magnetic Resonance Imaging (MRI), PET, SPECT, and 3D Ultrasound open a new dimension of possibilities for diagnosis and intervention planning.

Most modalities produce a stack of subsequent 2D slices, that might consist, e.g. in the case of a CTA of the lower limb, of up to 1600 high resolution images. This raw data is and will always be the ultimate material to be consulted whenever a diagnosis has to be done, but the representation of the whole dataset or regions of interest in three dimensional images can simplify diagnostic tasks and can give additional spatial information that might be difficult to retrieve consulting only the original slices. The possibility of interactive 3D exploration of the dataset and change of imaging parameters (e.g. colors, transparencies, and visualization modi) generates a set of diverse images of the dataset for the user and gives the radiologist a multilayered insight into the current status of the patient. Surgeons can preoperatively visualize a virtual version of the anatomy of a patient that is close to the intra-operative situation and allows for some surgeries a better planning of the intervention.

To be able to extract also spatial information from a stack of images, all images are combined into a single discrete 3D volume. Such a volume can be thought of as a simple three-dimensional array of cubic elements (voxels), each representing a unit of space. One voxel can be identified with a sample obtained at a single infinitesimally small point from a continuous three-dimensional signal (the human body) that can be partially reconstructed by interpolation.

Multi planar reconstruction (MPR) is a commonly available and wide spread visualization method for such volumetric datasets (Kanitsar et al., 2002). An MPR is simply the visualization of a set of connected *planar sections* through the reconstructed volume, and provides the possibility to analyze spatial dependencies of structures by connecting the information contained in all slices. Other planar visualization techniques like (rotated) curved planar reformation (CPR) allow for gaining more spatial insight into specific organs, but depict only planar sections extracted from the volume representing only one specific area (Kanitsar et al., 2003).

Volume rendering (Drebin et al., 1988;Levoy, 1988) is the generic term for a set of visualization techniques for three dimensional, i.e., volumetric, data. These techniques are in general classified into indirect volume rendering methods, which try to extract a (geometric) surface description from the volume data in a pre-processing step, and direct volume rendering methods that display directly the voxel data by evaluating an optical model which describes how the volume emits, reflects, scatters, absorbs and occludes light (Drebin et al., 1988).

Direct volume rendering techniques process always the whole information represented by the volume. Thus, they are extremely flexible with respect to changes of visualization parameters and allow e.g. a change of displayed iso-surfaces, i.e. surfaces connected to a certain threshold, on the fly. Especially for medical applications, speed, high quality of the visualization, and interactivity are essential characteristics. The computational power of customary PCs, including modern graphics hardware originally developed for computer games, reached in the last years a critical level allowing for the first time to provide direct volume rendering tools coming close to fulfil the three requirements listed above using low-price hardware.

2.1 Cell-Based First-Hit Ray Casting

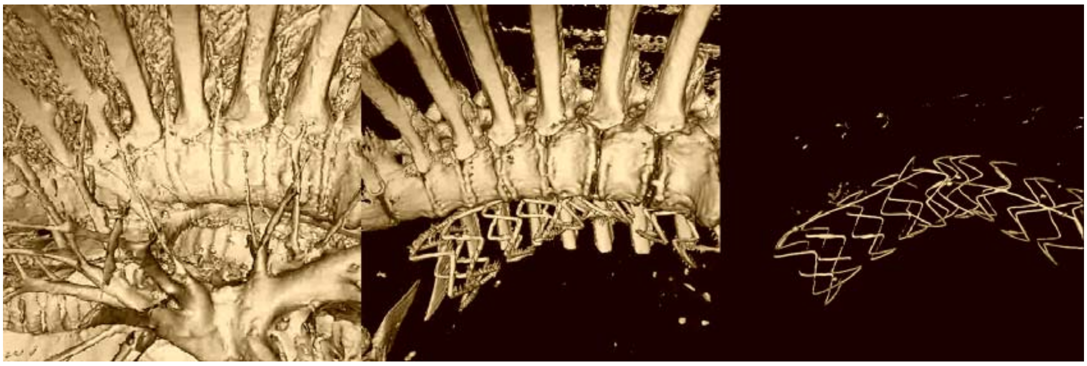


Figure 1 First hit ray casting with flexible iso-surfacing

Ray casting (Levoy, 1990) is a method for direct volume rendering, which can be seen as straightforward numerical evaluation of the rendering integral which sums up all optical effects such as colour and opacity along viewing rays cast into the volume. For each pixel in the generated image, a single ray is cast into the volume. At equispaced intervals along the ray (the sampling distance), the discrete volume data is resampled, usually using tri-linear interpolation. That is, for each resampling location, the scalar values of eight neighboring voxels are weighted according to their distance to the actual location for which a data value is needed. After resampling, the scalar data value is mapped to optical properties, which yields an RGBA value for this location within the volume that subsumes the corresponding emission and absorption coefficients. The volume rendering integral is approximated combining the computed sampled values in back-to-front or front-to-back order. Iso-surfacing, i.e. the display of a surface that corresponds to certain threshold, is a special case of ray casting.

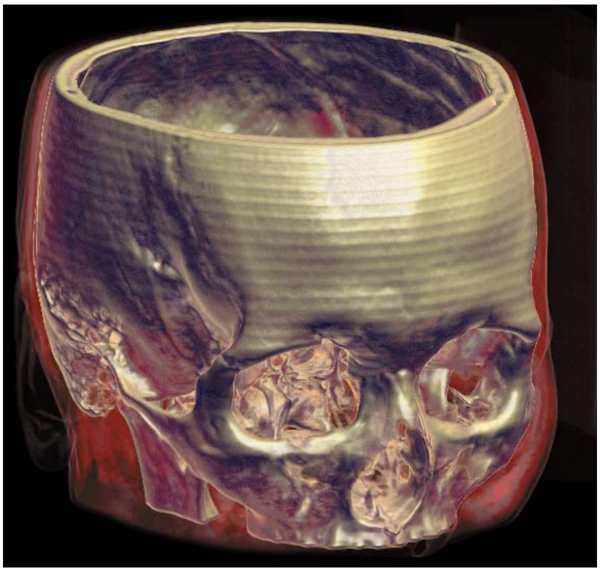
One application field for volume visualization via ray-casting is virtual endoscopy. Virtual endoscopy aims at simulating an endoscopic examination or intervention. Whereas real endoscopic examinations are very often connected with discomfort and pain, virtual endoscopy performs just on pre-acquired 3D data and has, besides of the data acquisition, no impact on the patient. Special solutions have been developed e.g. for laparoscopy, colonoscopy, bronchoscopy, angiography and specialized endoscopic interventions like described in section 5. An excellent overview on recent developments has been published by Bartz (Bartz, 2003).

Virtual endoscopy has special requirements on visualization, namely the simulation of the perspective and distorted view through an endoscope, and fast and flexible visualization of iso-surfaces, that represent in the dataset the boundary of the organ to be examined. Appropriate rendering speed is necessary to simulate the movement of the endoscope, i.e. to visualize in a realistic way changing views from inside the dataset. Interactive threshold adjustment helps to find the appropriate iso-surface that might not always be given by a known, fixed threshold, and depends on the focus of the examination.

Cell-based first-hit ray casting (Neubauer et al., 2002) is a relatively new technique for fast perspective volume visualization. This technique, based on the original ray-casting algorithm, performs fast iso-surfacing and supports interactive threshold adjustment (see Figure 1). It is accelerated by the reduction of average ray path lengths to only a few steps per pixel. The volume is divided into cubic sub volumes. Only such sub volumes that are intersected by an iso-surface are projected to the image plane. A local ray casting step within each sub volume is performed for all pixels covered by the projection. Cell-based first-hit ray casting is perfectly suited whenever fast perspective iso-surfacing is required. A detailed description of the algorithm can be found in (Neubauer et al., 2002).

The endoscopy project presented in section 5 is an example for a successful application of first hit ray casting. A specialized version and further improvements of the previously described cell-based first hit recasting algorithm has been developed for the efficient display of pre-segmented background objects (Neubauer et al., 2004a). Especially for intervention planning and intra operative support, the display of additional objects, like e.g. tumors and blood vessels, behind a transparent visualization of the wall of the investigated organ, can be of high interest to the surgeon and might reduce possible risks to the patient.

2.2 Interactive volume rendering based on consumer graphics hardware



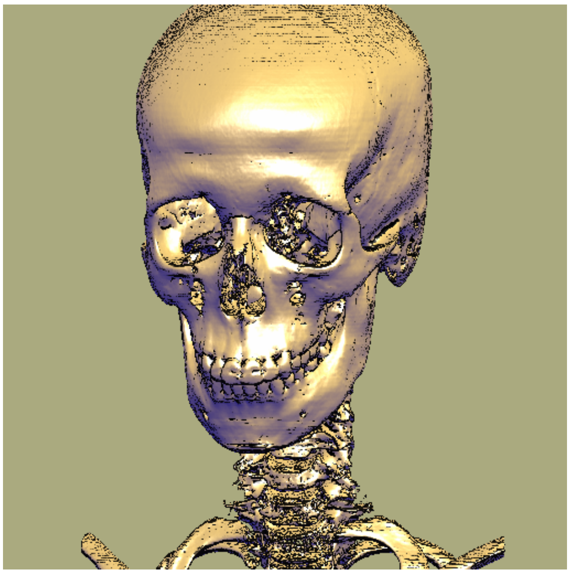


Figure 2: Different high quality direct volume renderings

Traditionally, volume rendering has high computational demands due to the enormous amount of data that needs to be processed. Most rendering methods in visualization and computer graphics are focusing either on image quality in order to produce “correct” images with non-interactive rendering times, or sacrifice quality in order to attain interactive or even real-time performance. However, the current evolution of desktop PC graphics hardware increasingly allows combining the quality of former off-line rendering approaches with highly interactive performance to get interactive and high quality rendering tools. In order to do so, new and customized algorithms have to be developed that take the specific structure of graphics hardware architectures into account.

For example, these algorithms allow using higher-order reconstruction filters, e.g., cubic instead of linear filters, for interactive volume rendering with higher image quality, and per-object optical properties such as colors, transfer functions, and rendering modes for higher flexibility and better perception of individual objects. Figure 2 (left image) shows an example for pure transfer function based direct volume rendering. Different rendering and compositing methods can also be combined using two level volume rendering on consumer graphics hardware. The concept of two level volume rendering is illustrated below.

Recently it has also become possible to compute non-photorealistic effects such as contours and ridge and valley lines interactively with high quality, and compute differential properties of surfaces embedded in volume data. The latter possibility allows computing high-quality surface curvature information, which could also be used to guide interactive segmentation, for example (Figure 2, right).

An excellent introduction and overview on the ongoing development with respect to hardware based volume rendering can be found in (Hadwiger, 2004)

2.3 Two Level Volume Rendering

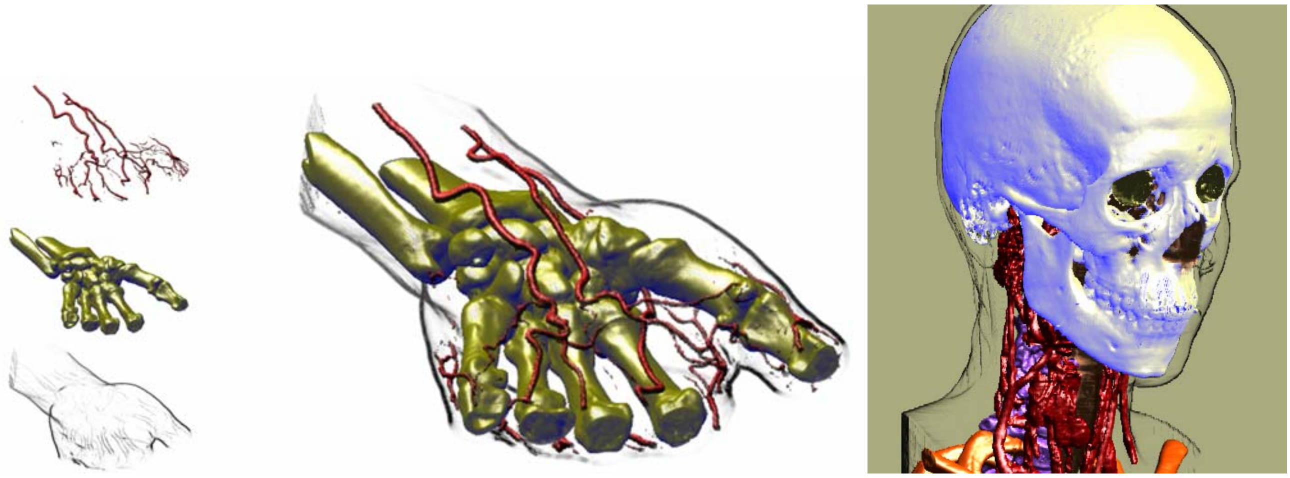


Figure 3: Examples for two level volume rendering

One of the most important goals in volume rendering is to be able to distinguish individual objects of interest that are contained in a single volumetric data set**.** This problem can be tackled with only a single global, possibly multi-dimensional, transfer function or non-photorealistic techniques. Nevertheless, it is often desired or even necessary to employ explicit segmentation information in order to visually separate and selectively display specific objects of interest.

The two-level approach for volume rendering (Mroz, 2002;Hadwiger, 2003) allows for choosing individual rendering techniques for each pre-segmented structure of a 3D data set. Selected structures are rendered locally on an object-by-object basis applying direct volume rendering, maximum intensity projection, surface rendering, value integration (x-ray-like images), or non-photorealistic rendering. Globally all results of subsequent object renderings are combined in a merging step.

The difference and also the big advantage of two level volume rendering compared to the traditional direct volume rendering lies in the possibility to apply the most suitable technique for depicting each object within the data, while keeping the amount of information contained in the image at a reasonable level. This is especially useful when inner structures should be visualized together with semi-transparent outer parts. We currently evaluate the potential of this technique for diagnosis, education and patient information. Especially if complex anatomic structures or a specific diagnosis have to be explained to persons inexperienced with the specific anatomy, like e.g. students or patients, two level volume rendering offers the possibility to focus on a specific organ without losing the context information necessary for orientation. Figure 3 shows good examples for such a *focus and context* visualization.

The necessary pre-segmentation of the structures to be visualized makes the technique only partly applicable for diagnosis in daily clinical routine, but we believe that the technique is well suited for education. The existing excellent but mostly hand drawn teaching material might be easily extended with high quality images of specific cases produced with the two level approach. A special implementation exploiting consumer graphics hardware allows rendering of the data interactively with high image quality (Hadwiger, 2003) and makes an interactive exploration of the data possible.

3 Algorithms for Computer Aided Diagnosis

3.1 Segmentation of volumetric structures

Segmentation of radiological datasets for diagnosis is a time consuming task in the daily routine of every radiologist. Localization of tumors, quantization of heart function, bone removal to simplify the examination of CTAs, segmenting and labeling of brain regions are some examples. Most 3D and 4D datasets are still processed manually on a slice-by-slice basis, i.e. by segmenting each 2D image of the stack separately. The increasing size of the datasets due to new high resolution acquisition techniques makes the traditional pure manual processing more and more difficult. Available modern segmentation techniques range from simple region growing approaches to sophisticated semi-automatic or automatic model based techniques that integrate previously acquired knowledge into the segmentation process.

While commonly available segmentation algorithms still work on 2D images, only a few recent developments face the challenge to develop true 3D and 4D segmentation algorithms, i.e. methods that segment the whole structure of interest in one single step.

An obvious approach is to extend existing 2D algorithms to higher dimensions, but the complexity of connected sub problems increases dramatically with each additional dimension. One simple example of increasing complexity is the extend of neighborhood of one element of the dataset – while in a plane image one single pixel has at most 8 neighbors to be checked or involved into computations of e.g. gradients, one volume element (voxel) has already 26, and a voxel of a 4D dataset has 80 neighbors! Thus, special care has to be taken to develop algorithms for multidimensional datasets that still allow for combining good performance with excellent quality of results.

Today, a high level of automation of the segmentation process is in many cases still equivalent to its specialization onto a specific task, like e.g. segmentation of the myocardium, vessels, liver, prostate, brain, or detection of specific tumors. Characteristics of the object to be segmented and the imaging modality have to be hard coded in the algorithm to guarantee a high level of user-independence and acceptable speed. Model based segmentation is one example for a highly specialized segmentation technique. The underlying model is based on a statistic description of variance of different instances of the same shape. Thus, individual models have to be built for each organ. An excellent example for model based techniques is proposed e.g. by Mitchell et al. (Mitchell et al., 2002).

The development of *universal and highly automatic* segmentation algorithms still fails with the complexity and variety of human bodies and the diverse characteristics of data produced by different imaging modalities. Only very few segmentation methods (e.g. simple thresholding, region growing) are all-purpose tools. Universally applicable segmentation methods still require user-interaction and post-processing to get reasonable results, but are fast and simple to apply.

The watershed algorithm is a classical algorithm in mathematical morphology originally described for 2D data sets. Structures and their borders are detected using a simple idea: The gradients of the image[1] can be interpreted as a height field similar to a landscape with ridges of mountains and valleys. Keeping this picture, the algorithm is equivalent to flood the landscape step by step with water up to a predefined level. The emerging basins correspond to the segmented objects and their borders.

In general, the algorithm is universally applicable to segmentation problems but works best in datasets with low noise and for structures with clear boundaries i.e., if surrounding tissue differs clearly from tissue of the object of interest, or if contrast agent is present.

The original watershed algorithm starts from local minima without taking specific objects of interest into account and suffers therefore from over segmentation. The *watershed from markers algorithm* introduces simple user interaction like marking regions of interest. This additional input restricts the algorithm to a specific area or object and reduces detection of false borders. Main drawback of the watershed algorithm is its tremendous memory consumption. Felkel et la. (Felkel et al., 2001) developed an extremely memory efficient and fast implementation of the watershed from markers algorithm that allowed to provide a 3D extension of the original version with acceptable performance even for large high-resolution datasets.

3.2 Registration of volumetric datasets

Nowadays, the variety of available imaging modalities allows investigating and considering different aspects of the patients' anatomy. Very often it is nor sufficient to investigate soft tissue anatomy (provided by MR), bone morphology (provided by CT) or functional information (provided by SPECT or PET).

To get a more complete image of the current situation or development of diseases of a patient for diagnosis or therapy planning, data of different imaging modalities or the same data taken at different time steps has to be put into direct relation to each other, i.e. matching of anatomical features of both datasets. This process is very often referred to as registration or image fusion.

The endoscopy tool described in section 5 is a good example for the application of registration algorithms. Diagnosis, pre-operative planning and the application of the virtual endoscopy tool require the fusion of CT and MRA data of the patients head and special regions of interest (in this case the area around the pituitary gland and the tumor).

Two main categories of registration methods are known, namely voxel based methods and marker based methods. Examples of such registration algorithms will be discussed in the following.

[1] The gradient information of an image/volume indicates for each pixel/voxel the direction and intensity of the most significant transition of gray values with respect to neighboring pixels or voxels.

Robust and Fast Registration of 3D Multi Modality Data Sets. Voxel based methods work fully automatic and are very robust, but show bigger errors in the registration result compared to marker based methods. The algorithm may fail if there is not enough information available e.g. in the case, when only a few slices of a volume have to be aligned.

Capek et al (Capek et al., 2001a) developed a fast and robust voxel based registration algorithm. The main focus of this work was to find an optimized function for the measurement of the quality of the registration, which influences the optimization strategy used for the search of a global optimum in a parametric space. The result is a very efficient implementation of the registration procedure that includes region of interest segmentation, a multi resolution strategy, and an incremental approach to volume resampling.

Simple user interaction has been added, that allows for doing by hand a pre-positioning of the dataset to be registered. A good initial position of the dataset accelerates the speed of the registration significantly, which is especially important if orientation, size, and scale of the datasets are quite different.

Multimodal Volume Registration Based on Markers. Extremely high accuracy of the registration result is required for planning and intra operative support of surgery in highly sensitive areas, e.g. like in any kind of neurosurgical procedure. Fully automatic registration algorithms supply already acceptable results, but the additional use of accurate, unambiguous landmarks ensures best matching of datasets.

Natural landmarks indicated by the user are one possible input for the algorithm. But manually selected as well as automatic detected natural landmarks are difficult to define and lack the necessary accuracy.

Artificial markers fixed relative to the patients' anatomy are one possibility to avoid ambiguities. At the University Hospital of Innsbruck a special external reference frame has been developed, containing twelve sphere shaped markers. Since the position of these markers is unambiguous, only one correct match for the data sets exists. The frame is fixated at the patient head by means of a "Vogele-Bale-Hohner (VBH) mouthpiece" during the data acquisition. The mouthpiece guarantees an exact positioning of the reference frame with respect to the cranial anatomy.

Capek et al. (Capek et al., 2001b) developed a registration algorithm that automatically detects the markers in the different data sets, finds the set of corresponding markers and calculates the transformation aligning one data set to the other. The algorithm is robust, even if some markers are missing or artifacts from image acquisition produce false markers.

4 High Level Diagnosis Tools - Segmentation and Analysis of the Myocardium

Computer-aided analysis of four-dimensional tomography data has become an important tool in modern cardiology. In order to examine the capability and health of a patient's cardiac system, CT or MRI scans are recorded at a number of time points evenly distributed over one cardiac cycle.

A key task for understanding the dynamics involved within a recorded cardiac cycle is to segment the acquired data to identify objects of interest in each volume of the sequence. The challenge lies especially in finding feasible algorithms for segmentation of the myocardium of the left ventricle in both 4D (3D + time) MRI and CT data sets. Further processing of the segmentation results with respect to specific questions, like e.g. thickness of the myocardial wall and blood ejection rate, and the visualization of the results of the analysis is needed in order to support the diagnostic process. Neubauer and Wegenkittl (Neubauer and Wegenkittl, 2003b; Neubauer and Wegenkittl, 2004; Neubauer and Wegenkittl, 2003a) developed such a segmentation and analysis tool that combines an innovative semi-automatic segmentation algorithm with state of the art tools for analysis.

4.1 Segmentation

Finding suitable techniques for segmenting the myocardium in a four-dimensional CT or MRI data-set has been, and still is, a major part of this ongoing project.

Image quality of cardiac CT data is in general quite good with respect to resolution and intensity contrast between myocardium and surrounding tissue which makes a slice by slice segmentation of the myocardium relatively easy. The algorithm described in (Neubauer and Wegenkittl, 2003a) focuses on an intelligent segmentation of the whole time depended data set.

Segmentation of cardiac MR images is often problematic due to poor image quality, which has various reasons: Patient movement, turbulent blood flow and physical and chemical disturbances of the imaging process lead to a number of artifacts which have to be compensated by the segmentation technique. The previously developed algorithm for CT data has been extended and improved by a preprocessing step to make it suitable also for MR data. (Neubauer and Wegenkittl, 2003b)

CT segmentation The currently implemented segmentation technique for CT data is skeleton-based, i.e., first a skeleton of the myocardium is identified. The myocardial boundaries are extracted in a second step.

For CT data, a rough sketch of the skeleton is initially drawn manually by the user on one slice. It is then automatically centered and propagated to all other slices. Propagation of the centre-line from the source slice to the destination slice is performed by copying the skeleton to the destination slice, identifying preliminary boundaries on the destination slice, centering the skeleton and finally performing a few maintenance measures to ensure that the skeleton can be further propagated in a stable way.

As soon as the centre-line has been propagated to all slices intersecting the myocardium, all 2D centre-lines are combined to a 3D skeleton. A connectivity volume is established by assigning to each voxel of the volume a value denonting the connectivity of the voxel to the 3D skeleton. The connectivity is high, if there exists a path from the voxel to the skeleton, which is short and traverses no significant gradients. Final segmentation is performed by thresholding in the connectivity volume.

MRI segmentation The segmentation of the myocardium from a MRI data set uses the same approach as above to propagate an initial centreline through the volume. But due to noise and poor resolution of the datasets pre-processing and a different segmentation technique is necessary to segment the myocardium in each slice. The segmentation starts with the user manually approximating the centre line (the skeleton) of the cross-section of the myocardium in an arbitrary slice by placing a poly-line onto the slice. Utilizing this user-defined skeleton, a pre-segmentation step identifies data gradients which are likely to represent parts of the boundary.

Next, a simple deformable boundary is initialized tightly enclosing the skeleton and iteratively refined ("inflated") to finally match the object contours. This progressive adaptation is achieved by applying a set of forces to the deformable model, which attract it towards the previously identified gradients, and at the same time enforce constraints which keep the boundary in the correct shape. Once the final contours have been found, the centre line of the segmented myocardial cross-section is calculated using skeletonization. This centre line is then copied to the next slice, slightly adapted to better fit the data and then used to initialize a new two-dimensional segmentation step.

Results. Both segmentation algorithms perform well and are faster compared to other fully automatic segmentation techniques. Although artefacts and big errors already introduced during manual initialization may lead to false result which have to be manually post-processed by the user, comparisons with data sets manually segmented by an expert proved the reliability of the technique.

4.2 The analysis tool

To provide a complete tool for analysis of the myocardium, analysis tools for measuring parameters including blood ejection rate and thickness of the myocardial wall have been added. Special care has been taken to guarantee an integrated and easy to learn workflow combined with intelligent visualization of image data and results. The software is commercially available as Plug-In of the Diagnostic Workstation JVision of Tiani Medgraph. Figure 4 shows a screenshot of the analysis tool.

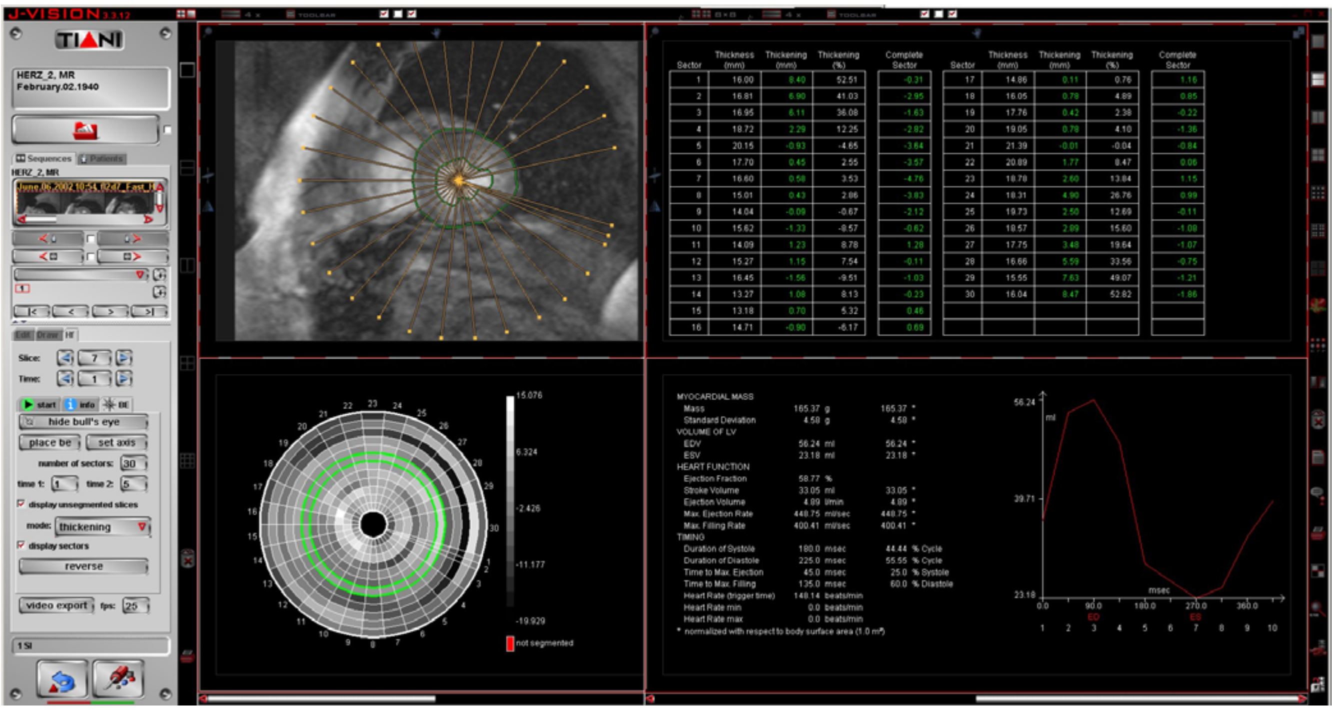


Figure 4: Screenshot of the tool for analysis of the myocardium.

5 Pre-operative Planning and Surgery Simulation - Endonasal Transsphenoidal Pituitary Surgery Simulation

Segmentation, registration and visualization are basic techniques for analysis and diagnosis of medical 3D datasets. The virtual simulation of a real surgery for training and/or planning purposes requires an intelligent and sophisticated combination of all these techniques.

Virtual endoscopy is constantly gaining importance in modern medicine. Apart from its application as a tool for diagnosis (e.g., virtual colonoscopy), virtual endoscopy is, within the medical community, increasingly recognized as a feasible tool for pre-operative surgical planning and training. New fields of application emerge with the increasing number and importance of minimally invasive medical procedures, usually performed using endoscopes.

5.1 Endonasal transsphenoidal surgery

An example is endonasal transsphenoidal surgery, often aimed at the removal of a tumor from the hypophysis: A rigid endoscope is inserted into the patient's nose and advanced into the sphenoid sinus, a cavity inside the human skull, separated from the pituitary gland only by the sellar floor, a bony structure which is usually very thin. In order to remove the tumor, the sellar-floor must be opened using a bone punch. Then the tumor is cut off the surrounding tissue and removed, again through the patient's nose.

This procedure is not free of danger for the patient and therefore requires the surgeon to be skilled and well trained. The internal carotid arteries and the optical nerve pass the pituitary gland along the far side of the sellar floor and are therefore not visible to the surgeon and endangered to be damaged by the punch.

5.2 The endoscopy tool

In cooperation with Tiani Medgraph and the Department of Neurosurgery, Medical University of Vienna the VRVis developed a tool for simulation, training and preoperative planning of transsphenoidal endonasal pituitary surgery (STEPS) (Neubauer et al., 2004b). It turned out that the use of virtual endoscopy can help to reduce dangers for the patient (Wolfsberger et al., 2004): One of the most important advantages of virtual endoscopy is the possibility to render the interior of the investigated cavity semi-transparently, with objects of interest in the background. Using virtual endoscopy as a training or navigation device and rendering the major blood vessels, the optical nerve, the pituitary gland and the tumour behind the translucent sellar floor can give the surgeon a good feeling of where to cut the sellar floor. Figure 5 shows a screenshot of the tool showing the simulated endocopic view including background objects and an MPR located at the current location of the endoscope showing original data and segmented objects.

Preparation. Data acquisition is the first step of the workflow. Radiological images of the patients head are generated performing computed tomography (CT), a computed tomography angiography (CTA) and magnetic resonance imaging (MRI) of the head. Fusion of all three datasets guarantees the optimal visualization of all objects of interest, namely internal carotid arteries, optical nerve, tumour, and pituitary gland. Segmentation of the mentioned objects is needed for later visualization as background objects in the simulated surgery.

Visualization. Two different optimized first-hit ray casting techniques (Neubauer et al., 2004a), see also section 2.1, are used to generate the virtual endoscopic view: The foreground (nasal airways and cranial sinuses) is rendered based on the CT scan of the patients head using a highly optimized standard first-hit ray-casting technique. Rendering of pre-segmented background objects (internal carotid arteries, optical nerve, tumour, pituitary gland) is performed using optimized cell-based first-hit ray casting.

Simulation of pituitary surgery. Using the developed software, the process of advancing the endoscope through the narrow nasal airways and finding the correct way to the sphenoid sinus can be trained as well as the most crucial part of the actual surgical operation, the opening of the sellar floor. For training purposes, it is important to model the degrees of freedom and constraints experienced when working with a rigid endoscope as accurately as possible. The trainee is confronted with similar challenges as in the real procedure and guided by haptic feedback. The most important parts of the user-application interface are provided by a force-feedback joystick.

STEPS is realized as a collection of three modules, embedded into the Java-based PACS JVision (Tiani Medgraph AG). Registration, segmentation and virtual endoscopy were each encapsulated into one module. A clinical evaluation has been performed within the scope of a medical dissertation of the Department of Neurosurgery, Medical University of Vienna (Forster, 2003).

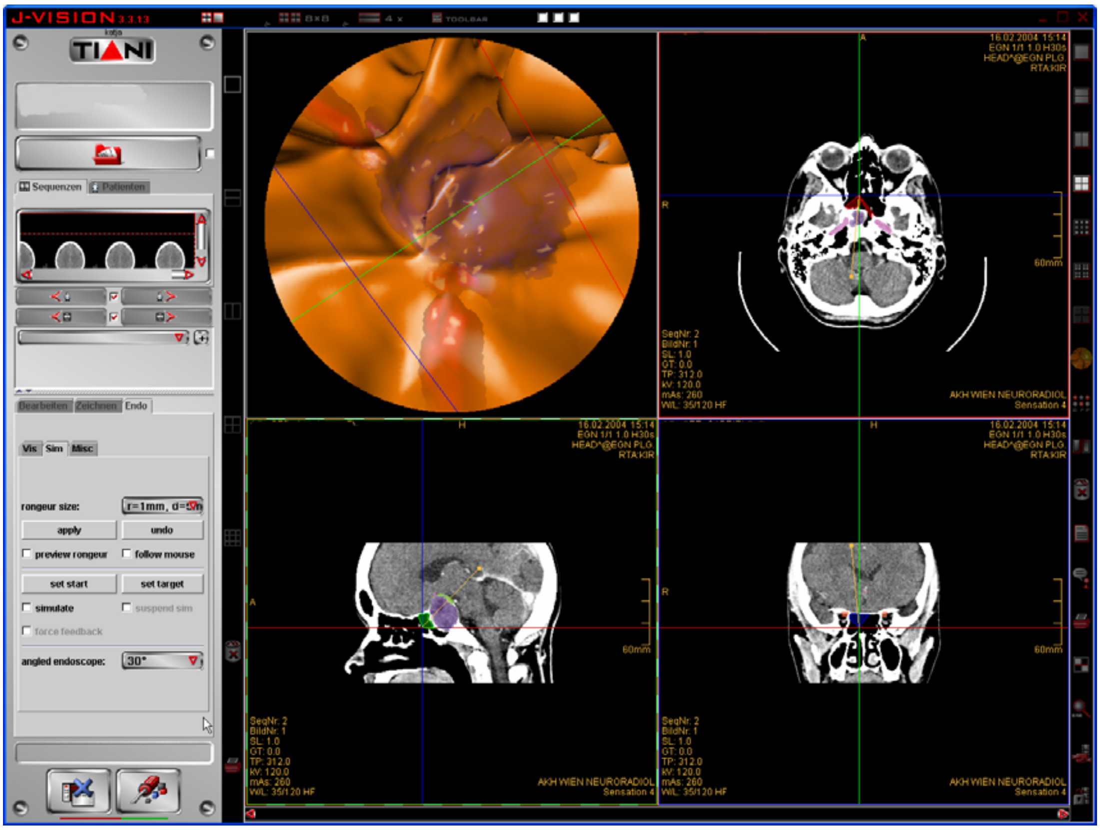


Figure 5: Screenshot of the tool for endonasal transsphenoidal pituitary surgery simulation

6 Summary

Research at VRVis is mainly directly application driven. In this spirit, the selection of research topics is motivated by real world problems of medical doctors. Aim of the presented projects was to identify deficits in the clinical routine and to provide applicable made-to-measure solutions for open problems. In this spirit, solutions have been developed in close cooperation with potential users and industrial partners and help to accelerate, optimize, and improve the workflow of radiologists and surgeons. Many challenges are left for further research, realistic simulation of deformation of soft tissue, powerful fast and automatic 3D segmentation techniques, and intelligent design tools for transfer functions. Our experience teaches us that many times closing the gap between theory and application is a challenge itself. The interaction with and the feedback from radiologists and surgeons is one of the essential requirements for the success of the developed tools.

7 Acknowledgments

We like to thank our industrial partner Tiani Medgraph AG, the Austrian Government and the City of Vienna for supporting our work in the framework of the KPlus Competence Centre Program. We also like to thank all our medical partners for their valuable feedback, provided datasets and transfer of medical knowledge.

Reference List

Bartz, D. *Virtual Endoscopy in Research and Clinical Practice.* Eurographics State of the Art Reports . 2003.

Capek, Martin, Mroz, Lukas, and Wegenkittl, Rainer. *Robust and Fast Medical Registration of 3D-Multi-Modality Data Sets.* Medicon , pp. 515-518. 2001a.

Capek, Martin, Wegenkittl, Rainer, König, Andreas, Jaschke, Werner, Sweeny, Reinhart, and Bale, Reto. *Multimodal Medical Volume Registration Based on Spherical Markers.* WSCG , pp. 17. 2001b.

Drebin, R. A., Carpenter, L., and Hanrahan, P. *Volume rendering.* Proceedings of Siggraph , pp. 65-74. 1988.

Felkel, Petr, Wegenkittl, Rainer, and Bruckschwaiger, Mario. *Implementation an Complexity of the Watershed-from-Markers Algorithm Computed as a Minimal Cost Forrest.* Eurographics . 2001.

Forster, Marie-Therese. *Virtuelle Endsoskopie in der transnasalen Transsphenoidalen Hypophysenchirurgie.* 2003. Universität Wien.

Hadwiger, Markus. *Two-level volume rendering on consumer graphics hardware.* IEEE Visualization . 2003.

Hadwiger, Markus. *VR on GPU.* Siggraph. Siggraph Course Notes . 2004.

Kanitsar, A., Fleischmann, D., Wegenkittl, Rainer, Felkel, Petr, and Gröller, Eduard. *CPR - Curved Planar Reformation.* IEEE Visualization . 2002.

Kanitsar, A., Wegenkittl, Rainer, Fleischmann, D., and Gröller, Eduard. *Advanced Curved Planar Reformation: Flattening of Vascular Structures.* IEEE Visualization . 2003.

Levoy,M., *Efficient ray tracing of volume data*. ACM Transactions on Graphics 9, pp. 245-261. 1990.

Levoy,M., *Display of surfaces from volume data*. IEEE Computer Graphics andApplications 8. 1988.

Mitchell,S., Bosch,J., Levieveldt,B., van der Geest,R., Reiber,J., Sonka,M., *3-D Active Appearance Models: Segmentation of Cardiac MR and Ultrasound Images*. IEEE Transactions on Medical Imaging 21, pp. 1167-1178. 2002.

Mroz, Lukas. *Two-level volume rendering.* 2002.

Neubauer, André, Forster, Marie-Therese, Wegenkittl, Rainer, Mroz, Lukas, and Bühler, Katja. *Interactive Display of Background Objects for Virtual Endsocopy Using Flexible First-Hit Ray Casting.* Proceedings of VisSym 2004 , pp. 301-310. 2004a.

Neubauer, André, Mroz, Lukas, Hauser, Helwig, and Wegenkittl, Rainer. *Cell-based First Hit Raycasting.* Proceedings of VisSym 2002 , pp. 77-86. 2002.

Neubauer, André and Wegenkittl, Rainer. *Analysis of Four-Dimensional Cardiac Data Sets Using Skeleton-Based Segmentation.* WSCG . 2003a.

Neubauer, André and Wegenkittl, Rainer. *Skeleton-Based Myocardium Segmentation.* Visualization and Data Analysis . 2004.

Neubauer, André and Wegenkittl, Rainer. *A Skeleton-Based Inflation Model for Myocardium Segmentation.* Vision Interface . 2003b.

Neubauer, André, Wolfsberger, Stefan, Forster, Marie-Therese, Mroz, Lukas, Wegenkittl, Rainer, and Bühler, Katja. *STEPS - An Application for Simulation of Transsphenoidal Endonasal Pituitary Surgery.* IEEE Visualization . 2004b.

Wolfsberger,S., Forster,M.-T., Donat,M., Neubauer,A., Bühler,K., Hainfellner,J., Knosp,E., *Virtual Endoscopy is a Useful Device for Training and Preoperative Planning of Transsphenoidal Endoscopic Pituitary Surgery*. Minimal Invasive Surgery 47, pp. 214-220. 2004.