Smart 3d visualizations in clinical applications

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Abstract. We discuss techniques for the visualization of medical volume data dedicated for their clinical use. We describe the need for rapid dynamic interaction facilities with such visualizations and discuss emphasis techniques in more detail. Another crucial aspect of medical visualization is the integration of 2d and 3d visualizations. In order to organize this discussion, we introduce 6 „Golden" rules for medical visualizations.

1 Introduction

Many tasks in medical applications can be supported with appropriate visualizations. In addition to visualizations from textbooks, computer-generated and highly interactive 3d visualizations are employed in medical education. In anatomy education, for example, the VOXELMAN [9-11] is used to allow the exploration of medical volume data with advanced cut and clip functions. The volume data was enriched by a sophisticated knowledge representation about anatomical taxonomy ("intelligent" voxels). The pioneering work of the VOXELMAN has inspired some of the ideas presented here. Another long-term effort has been carried out in surgery simulation by KÜHNAPFEL et al. [1, 12]. They developed the KISMET system which simulates bleeding and smoke caused by surgical devices besides a variety of other interactions between surgical devices and human tissue.

"Idealized" and clinical data. The discussion of appropriate visualizations has to consider the quality of the underlying data which differs strongly between the above-mentioned educational applications and applications for the routine clinical use. For educational purposes, idealized data, such as the Visible Human dataset of the National Library of Medicine are employed. The use of a cadaver dataset has several advantages: high radiation can be applied and motion artifacts for example from breathing do not occur. These datasets are carefully prepared and enriched with additional information. Such a time-consuming approach is not feasible for medical diagnosis and treatment planning. The underlying data have less quality (because they are acquired from living patients). This paper is focused on clinical applications and discusses visualization and interaction techniques that are designed to support diagnostic processes and treatment decisions, such as operability of a patient.

This paper is organized as follows: In Sect. 2 visualization techniques currently used for medical diagnosis and treatment planning are described. This section is followed by the brief Sect. 3 which names six "golden rules" for smart medical visualizations which are discussed in the remainder of this paper.

2 3d Visualizations for clinical applications

3d visualizations in medicine are based on radiological image data. Primarily CT (computed tomography) data,and MRI (Magnetic Resonance Imaging) are used. The traditional – film-based or soft-copy – "reading" of radiological image data represents a slice-by-slice inspection. Due to the growing resolution of image scanners this is no longer feasible as the only inspection method. As an example, CT data of the human thorax acquired with multislice image devices produce some 500 slices. Therefore, 3d visualizations, such as direct volume rendering, isosurface rendering, and maximum-intensity-projections (MIP) are becoming more commonly used. MIP images depict the brightest voxel along each line of sight and thus do not require any user interaction with respect to opacity settings ([3] gives an excellent overview on these basic techniques). Direct volume rendering and isosurface rendering, on the other hand, strongly depend on user settings. Predefined transfer functions for certain visualization tasks, such as highlighting bony structures in CT data, are used to reduce the interaction effort. Unfortunately, such predefined settings are not reliable for MR data (which do not exhibit a standardized intensity scale and are less homogeneous) and for the visual delineation of structures with similar intensity values.

If the diagnosis is confirmed, radiologists demonstrate the images to the referring physician in order to discuss the therapy. Furthermore, if an intervention is considered radiologists and surgeons discuss the strategy. Still, it is common to use static images, either slices from the original data or rendered images for this discussion. If interactive 3d visualizations are used at all, it is the radiologist who operates the system in order to show what is important. In order to understand the 3d reality of a particular patient's organ, it is desirable that interactive 3d visualizations are used and that the surgeon is in control to explore the data in order to answer his or her questions.

3 The six golden rules for the design of smart medical visualization

SHNEIDERMAN succeeded in convincing people of his 8 "golden rules" for user interface design [20]. Inspired by these we present 6 "golden rules" for the design of smart medical visualizations. "Smart" means that the visualizations are useful for clinical tasks which includes that they are recognizable and dedicated to a particular task. Moreover, smart medical visualizations are fast to generate and can be interactively explored. The following rules are based on our experience with the development and evaluation of clinical applications.

- Integrate 2d and 3d visualization with interaction facilities in both views
- Provide useful defaults for visualization parameters
- Provide dynamic interaction facilities
- Use model-based visualizations, for example for thin elongated structures
- Provide appropriate emphasis techniques
- Include anatomical context in the visualization of the relevant structures

The rest of the paper is devoted to the discussion of these 6 rules.

4 Integration of 2d and 3d visualizations

On the first glance it seems that smart medical visualizations should be 3d exclusively. The human body is a three-dimensional system; therapy planning and surgery simulation based on 3d visualizations are therefore more realistic than visualizations based on 2d slice visualizations. 3d visualizations with appropriate depth-cues (first of all shading) are intuitively comprehensible and seem to be superior. Despite of these obvious advantages, clinically relevant therapy planning systems contain 2d and 3d visualizations and interactive manipulations are allowed in both often with some kind of synchronization between the views.

The question arises whether 2d visualizations are only needed for conservative medical doctors not accustomed to the great benefit of 3d visualizations, so-to-say to be upward compatible to slice-based reading. Researchers in the field agree on real benefits of and needs for 2d visualizations, too.

In general, 2d-visualizations better support precise interaction. Precision is required, for example when measurements are derived, implants are placed in the geometric model of the patient and drilling procedures are planned. 2d visualizations are useful for these tasks because selection tasks which are part of the discussed tasks can be accomplished more precisely. Each voxel can be selected if the appropriate slice is chosen for the 2d visualization. 3d visualizations provide an overview; the “big” picture of the data. They are used, for example, to decide which range of slices is displayed in the respective 2d view in more detail. As a consequence, 2d and 3d visualizations allow for interactions in both views.

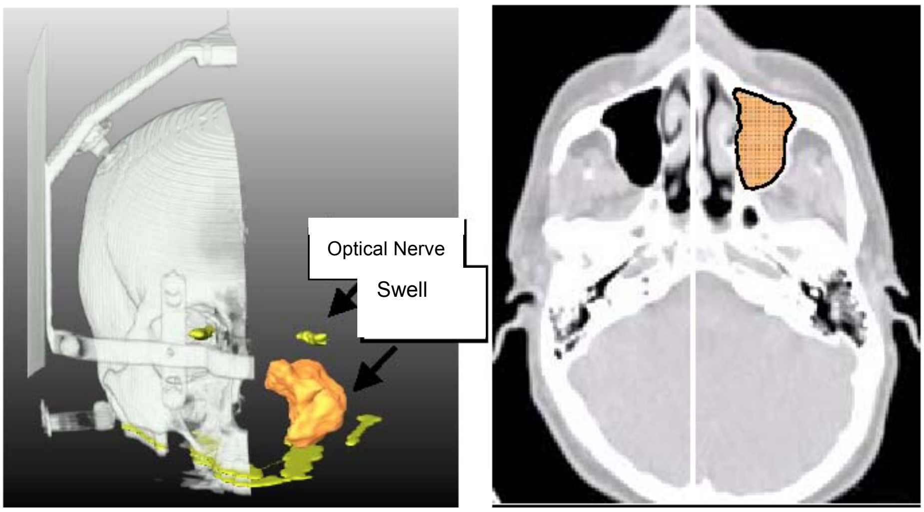

Fig. 1: The 3d visualization of a human head in CT data and the corresponding 2d visualization. The clipping plane is also included in the 2d visualization and can be manipulated in both views. The segmentation results are transparently overlaid to the original data in the 2d view. Radiological data kindly provided by University of Leipzig (Dr. Strauß).

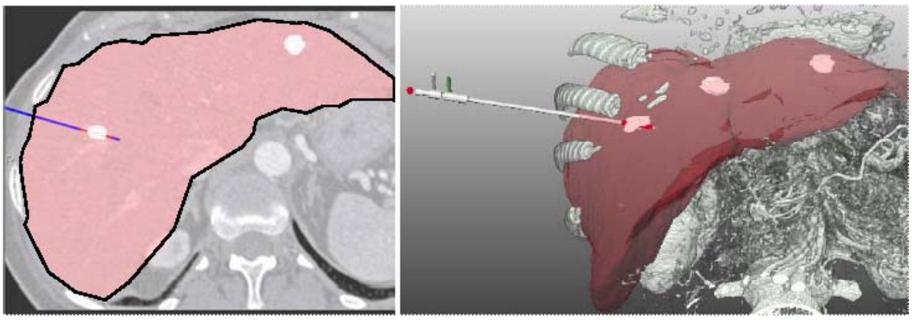

Fig. 2: Synchronized 2d and 3d visualizations of a CT liver data set with the segmented liver and three liver lesions (white). The visualization is used for the planning of a minimally-invasive therapy with a laser applicator. Radiological data kindly provided by the Technical University of Munich (Prof. Feussner)

While this general principle has been realized in several medical visualization systems, we have applied it consequently to all interactions frequently required for therapy planning ([16]). For example, 2d and 3d visualizations are employed for the placement of applicator devices used for minimally-invasive operations. The precise definition of the target point (the point where the applicator produces a maximum of energy to destroy the pathology around) is usually selected in 2d. The entry point (where the applicator penetrates the skin) might also be selected in a 2d visualization. Whether important structures are hurt by this access path, however, becomes more obvious in 3d visualizations (see Fig. 2). In a similar manner, 2d and 3d visualizations are combined for measurements, such as distances and angles for the quantitative analysis of spatial relations. Another frequent task in therapy planning is the specification of resection areas (those parts of the body which should be removed later in surgery). Resection specification can be accomplished in 2d (by drawing into selected slices and interpolating between them) and in 3d by moving surgical tools through the data which virtually remove tissue. Again, it is crucial to evaluate the virtual resection in the other view. If the resection area was specified in 2d, the 3d view shows its general shape – which is important to assess whether this shape can be resected. On the other hand, if the resection was specified in 3d, the 2d view is useful to asses the affected regions.

5 Provide useful defaults for visualization parameters

Visualizations, such as these presented in Figs. 1-2 are controlled by a variety of parameters. These include object colors, transparency values, the viewing direction as well as smoothness and quality parameters. It is essential that these parameters are available via the graphical user interface. However, it is tedious if they have to be specified again and again for individual objects. Hence, meaningful default values which can be accepted in the majority of the cases are crucial for the usability of such a system. How can these be specified? First it is important to classify objects, because such a classification provides a useful base for the assignment of default values. Examples of object classes are organs, bony structures, vascular structures and tumors. Organs are large structures: usually it is desirable to see details of the organ interior. Therefore, by default they are rendered semitransparently whereas lesions and vascular structures are not. Note, that different transparency values are useful for 2d and 3d visualizations. In 2d visualizations (Fig. 2, left) the original data should be visible to some extent. Therefore, even lesions and vascular structures are not displayed fully opaque. Large compact structures such as organs can be displayed with lower resolution compared to thin elongated structures.

Finally, and that is an aspect which was often discussed with medical doctors: the initial viewing direction should be a natural one, preferably the surgeon's view. The two images in Fig. 2 for example are generated without changing any visualization parameter. All colors and transparency values, the transfer functions for the volume rendering correspond to the default values. An individual user may have slightly different preferences. Therefore, it should be possible to customize visualizations by storing personalized default values. The benefit of well-selected default values are not only time-savings but also better quality and reproducibility of the resulting visualization.

6 Dynamic medical visualizations

The understanding of the complex spatial phenomena inside the human body requires the interactive manipulation of images. Dynamic visualizations – interactive visualizations with rapid feedback after continuous interaction – are particularly useful for this understanding because changes between images can be observed and need not to be interpreted (see [21] for a discussion of active and dynamic visualizations).

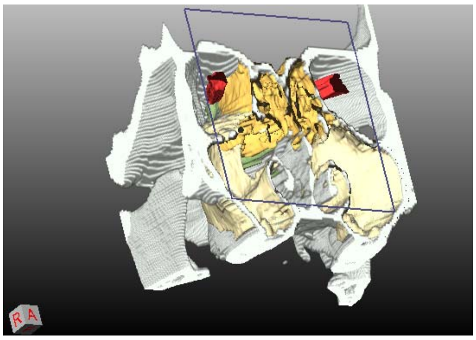

Fig. 3: Exploration of a CT data set of the human head. The continuous movement of the clipping plane is used to gain insight into the nasal cavities. The images were acquired to prepare surgery in this area. The spatial relations to critical structures, in particular the optical nerves, are essential. The cube in the lower left corner indicates the viewing direction. Radiological data kindly provided by University of Leipzig (Dr. Strauß).

There are several wide-spread interaction tasks in medical visualization which can be supported with dynamic interactions initiated with the pointing device on the image viewer (see Fig. 3). Clipping planes and clip boxes are translated and rotated in order to suppress parts of the underlying data. Radiologists are used to adapt brightness and contrast of volume rendered images by simply dragging the mouse (the *x*- and *y*-position of the mouse specify the parameters for the widely used ramp transfer functions). Again, the interaction can be initiated without moving the pointing device outside the visualization to some control element. Also, the traditional 2d slice view can be enhanced with dynamic interaction such that the displayed slice changes continuously as long as a certain combination of mouse buttons is pressed. This interaction is referred to as the cine-mode.

Another effective dynamic interaction facility is included in the VoxelMan (recall [9-11]). It is based on a sorting process of the object's relation to the skin. With a continuous mouse movement objects are hidden starting from those closer to the skin giving sight to more distant ones. Compared to the traditional interaction required to hide objects (select them individually and press some button to hide them) this is much faster and again allows to concentrate on the visualization.

7 Integration of anatomical context

Medical visualizations for sophisticated treatment planning procedures are based on prior image analysis. Examples are planning processes for total hip replacements [2, 8], facial surgery [4], neurosurgery [6] and liver surgery [19]. In the image analysis stage, important anatomical and pathological structures are identified and delineated (segmented). The segmented objects are usually visualized by means of surface rendering. With appropriate smoothing and shading this often yields easy-to-interpret visualizations.

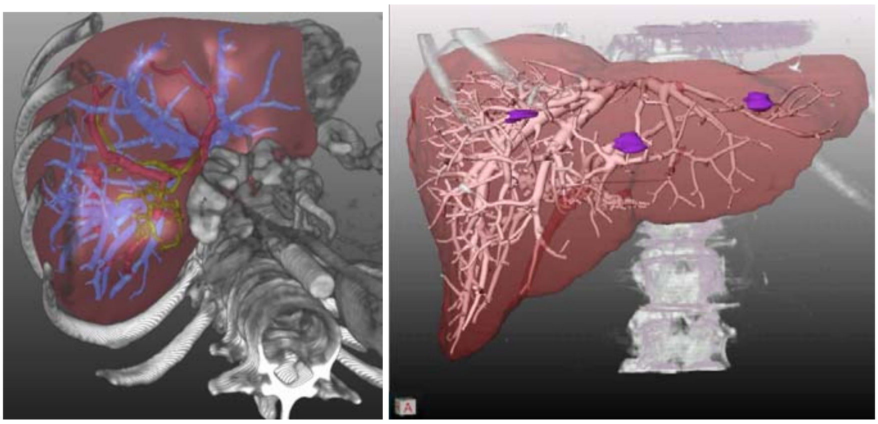

Fig. 4: Hybrid combination of the direct volume rendering of bony structures and surface rendering of intrahepatic structures (liver, vascular systems, tumors in the right view). The bony structures serve as anatomical context for the intrahepatic structures. Radiological data kindly provided by Medical School Hannover (Prof. Galanski).

Segmented objects might be selectively displayed or hidden to customize the visualization to the questions related to the therapeutic process at hand. However, the mere visualization of important structures is often insufficient. The lack of surrounding tissue, in particular of skeletal structures makes it very difficult to understand the current view. Therefore, medical doctors appreciate the visual integration of bony structures (usually displayed by means of volume rendering) and structures which are in the focus (see Fig. 4).

8 Model-based visualizations

Medical visualizations for clinical use have two fulfil two requirements:

1. they should strictly adhere to the underlying radiological data and
2. they should be easy to interpret.

Let us discuss these requirements with respect to vascular structures. These structures are often very thin, for example in the periphery of vascular trees. Due to the limited spatial resolution of CT and MR scanners these thin structures are often represented by only one or two voxels per slice. A straightforward visualization that fulfils the first requirement usually results in noisy visualizations due to the limited spatial resolution of radiological data. For example, it is very difficult, to assess the topology of a vascular tree based on such visualizations. This, however, is often crucial for surgery planning where risks of a procedure have to judged. As an example of this risk analysis it is important to recognize which branches of a vascular tree would be affected if a certain branch is cut. To support those questions, more abstract visualizations serve better. Therefore, several attempts have been made to reconstruct vascular structures based on a prior vessel skeletonization [5, 17]. In the skeletonization process, the medial axis inside the vessel as well as the minimum and maximum diameter for each skeleton voxel is derived (see [19] for details). This information can be used to visualize vascular trees by means of graphics primitives fitted along the skeleton path. As an example, we used truncated concatenated cones as the underlying primitives [7]. Special care was taken to provide smooth transitions of surface normals at branchings. Fig. 4 and Fig. 5 show examples of this vessel visualization method. This method has been developed and refined in fruitful discussions with radiologists and obviously is a good comprise between the desire to have precise *and* easy-to-interpret visualizations.

The degree of correspondence to the radiological data is adjustable by the number of cones that are generated. Cones can be generated between two subsequent voxels (highest level of correspondence) or only between branchings of the vascular tree (lowest level of correspondence). Also, the vessel diameter can adhere strictly to the values measured in the skeletonization process or be smoothed in order to reduce the effect of rounding errors (see Fig. 6). In summary, the degree of realism is adjustable with such model-based visualizations.

This method is based on the assumption that the cross-section of vascular structures is circular. This assumption, of course, is a simplification. It is not appropriate when vascular diseases should be diagnosed. However, for many therapy planning tasks it is crucial to understand the spatial relation between pathologic structures and adjacent vascular structures. In such cases these model-based visualizations are very helpful.[1] Similar model-based visualizations are used in the VOXELMAN (recall [9-11]) where B-spline shapes are fitted to selected points which represent nerves in some slices. These structures are so small that they appear in some slices and disappear in others.

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[1] Some details of the described visualization are inspired by medical doctors. The visualization method is regularly used for liver surgery planning.

Using the anatomical knowledge that the nerves are connected and using knowledge about their principal shape appropriate visualizations can be generated with the reconstruction process described in [14].

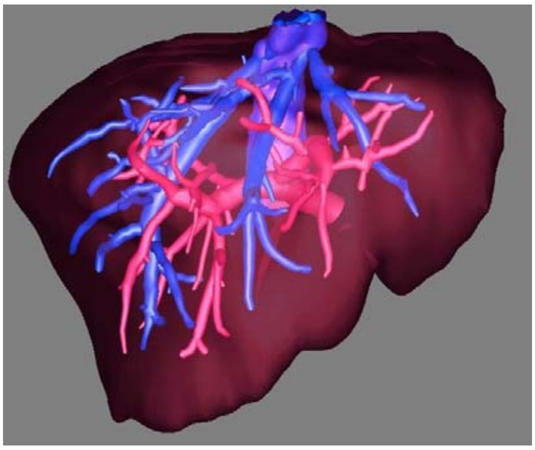

Fig. 5: High quality visualization of the intrahepatic vascular anatomy (hepatic and portal veins). Radiological data kindly provided by Medical School Hannover (Prof. Galanski).

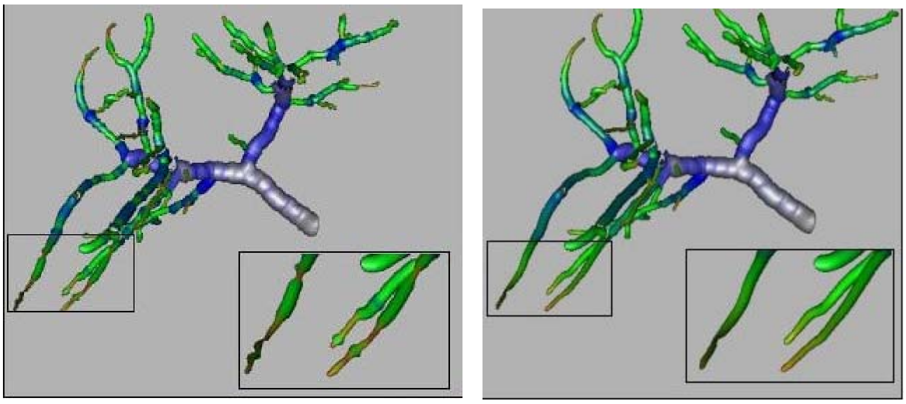

Fig. 6: Model-based vessel visualizations with different settings for the smoothing of the vessel diameter. The vessel diameter is color-coded. In the left image, no smoothing is applied which results in obvious discontinuities in the periphery. These discontinuities are due to the limited spatial resolution of the underlying data.

9 Emphasis in medical 3d visualizations

In therapy planning applications as well as in software for medical education it is often necessary to highlight an anatomic or pathologic structure. As an example, the user of such a system selects an object in a list via its name and the system should provide feedback emphasizing this object. Another obvious reason for the need of 3d emphasis techniques is due to the integration of 2d and 3d views (recall Sect. 4). After an object is selected in a 2d view it should be highlighted in the 3d view to support the connection between the two visualizations.

The emphasis of objects in 3d visualizations is difficult by its very nature. From the current viewing position objects might be too small to be recognizable or they might be occluded by other objects. In medical visualizations these problems are prevalent: objects are often concave, are at least partly occluded by others. Therefore simple emphasis techniques such as the use of a special colour for highlighted objects or blinking do not work well. Emphasis techniques therefore should ensure the visibility of the involved objects (see [18]). In principle, two strategies are possible to achieve visibility:

- the camera position might be changed to make the desired object visible or
- visualization parameters of occluding objects might be adapted to allow to look through them.

The first strategy, in general, cannot be recommended. A radical change of the camera position, not initiated by the user, is often not comfortable because the user has to interpret this change and perhaps dislikes the chosen perspective. Unnatural viewing directions may result. The change of visualization parameters, the second strategy, can be implemented by using transparency: occluding objects are rendered semitransparently to reveal objects behind. This is a viable approach, however showing apparent drawbacks. If several objects are in front of the object to be emphasized all occluding objects must be strongly transparent with the result that they are almost unrecognizable (see Fig. 7). As an alternative, fast silhouette generation algorithms might be used to enhance the visualization of the transparently rendered objects. For the sake of brevity, emphasis techniques could only be touched here. There is a variety of emphasis techniques suitable for medical visualization, including those based on the shadow generation for selected objects (see [15] for a review on such techniques).

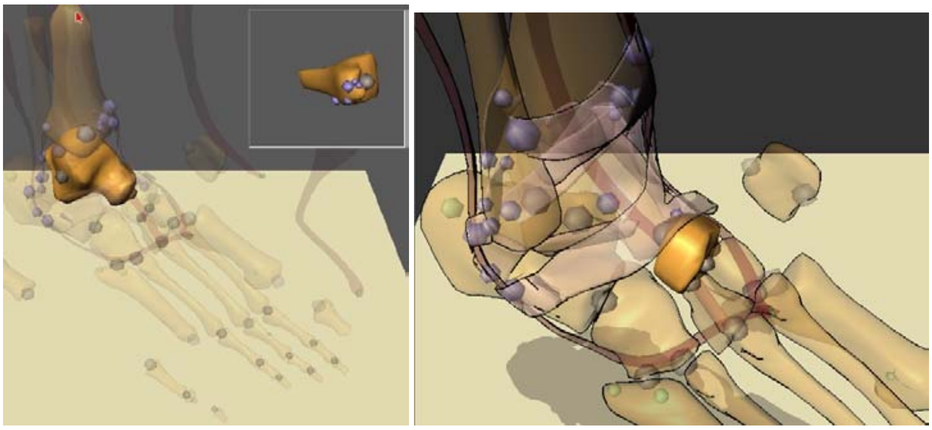

Fig. 7: Visualizations of bony structures and some muscles of the human foot as part of an educational system (the spheres represent docking positions to compose objects). A particular bone is emphasized using transparency of other objects (left). In the right view the shape of the transparent objects is emphasized with line drawing of their silhouette.

10 Concluding remarks

Smart medical visualizations integrate 2d and 3d visualizations with a bi-directional link in order to synchronize changes between both. 3d visualizations of the relevant anatomic and pathologic structures are integrated with the anatomic context which provides a reference. Appropriate visualization parameters depend on the category of the respective object; vascular structures should be rendered with other parameters than organs or pathologic lesions per default. A comprehensible visualization of thin elongated branching structures requires other parameters as large compact structures. Smart medical visualizations include predefined parameters for different categories. In particular for vascular structures a model-based reconstruction is useful for the visualization. Finally, smart medical visualizations are highly interactive. They support dynamic changes which are initiated with the pointing device on an image view.

Future Work. So far, non realistic renderings [22] have not been integrated in medical visualizations used in the clinical routine. With their ability to emphasize shape and structures, these algorithms are promising for such applications. Another wide area for future work is the incorporation of uncertainty visualization techniques. The image acquisition and image analysis steps which are carried out prior to visualization may produce imprecise or unreliable results. At least some of these “errors” might be estimated. For example, tumor segmentation is often imprecise because the lesions have similar intensity values to the surrounding tissue and apparently no gradient at their borders. Special visualization techniques should be developed to encode this uncertainty (see for example [13]). Finally, the development of emphasis techniques dedicated to the complex shapes in medical visualizations is an area where further research is needed. In particular, the appropriate technique should be automatically selected by the visualization system (taking into account object visibility, size and shape).

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References

[1] HK Çakmak, U Kühnapfel (2000). “Animation and Simulation Techniques for VR-Training Systems in Endoscopic Surgery”, *Eurographics Workshop on Animation and Simulation* (EGCAS '2000), Interlaken/Switzerland, pp. 173-185

[2] J Ehrhardt, H. Handels, T Malina, B Strathmann, W Plötz, SJ Pöppl (2001). “Atlas based Segmentation of Bone Structures to Support the Virtual Planning of Hip Operations”, *International Journal of Medical Informatics*, Vol. 64, pp. 439-447

[3] TT Elvins (1992). “A Survey of Algorithms for Volume Visualization”, *Computer Graphics*, Vol. 26 (3), pp. 194-201

[4] PC Everett, EB Seldin, M Troulis, LB Kaban, R Kikinis (2000). “A 3-D System for Planning and Simulating Minimally-Invasive Distraction Osteogenesis of the Facial Skeleton”, *Proc. of MICCAI*, Springer, LNCS Vol. 1935, pp. 1029-1039

[5] G Gerig, T Koller, G Székely, C Brechbühler, O Kübler (1993). “Symbolic Description of 3d structures applied to cerebral vessel tree obtained from MR angiography volume data”, *Proc. of Information Processing in Medical Imaging*, Springer, LNCS, Vol. 687: 94-111

[6] DT Gering, A Nabavi, R Kikinis et al. (1999). “An Integrated Visualization System for Surgical Planning and Guidance using Image Fusion and Interventional Imaging”, *Proc. of MICCAI*, Springer, LNCS Vol. 1679, pp. 809-819

[7] HK Hahn, B Preim, D Selle, HO Peitgen (2001). “Visualization and Interaction Techniques for the Exploration of Vascular Structures”, *IEEE Visualization* (San Diego, CA, Oct.), pp. 395-402

[8] H Handels, J Ehrhardt, B Strathmann, W Plötz, SJ Pöppl (2001). “An Orthopaedic Atlas for the 3D Operation Planning and the Virtual Construction of Endoprostheses”, *Computer Assisted Radiology and Surgery* (CARS 2001, Berlin), Elsevier, pp. 312-317

[9] KH Höhne, B Pflesser, A Pommert, M Riemer, T Schiemann, R Schubert, U Tiede (1995). “A new representation of knowledge concerning human anatomy and function”, *Nat. Med.*, Vol. 1 (6), pp. 506-511

[10] KH Höhne, B Pflesser, A Pommert et al. (2000). *VOXEL-MAN 3D Navigator: Inner Organs. Regional, Systemic and Radiological Anatomy*, Springer-Verlag Electronic Media, Heidelberg

[11] KH Höhne, A Petersik, B Pflesser et al. (2001). *VOXEL-MAN 3D Navigator: Brain and Skull. Regional, Functional and Radiological Anatomy*, Springer-Verlag Electronic Media, Heidelberg

[12] U Kühnapfel, HK Çakmak, H Maass (2000). “Endoscopic Surgery Training using Virtual Reality and deformable Tissue Simulation”, *Computers & Graphics*, Vol. 24, pp. 671-682, Elsevier

[13] AC Pang, CM Wittenbrink, SK Lodha (1997). “Approaches to Uncertainty Visualization”, *The Visual Computer*, Vol. 13 (8), pp. 370-390

[14] A Pommert, KH Höhne, B Pflesser et al. (2003). “Creating a high-resolution spatial/symbolic model of the inner organs based on the Visible Human”. In: *Yearbook of Medical Informatics 2003: Quality of Health Care: The Role of Informatics*, Schattauer, Stuttgart, pp. 530-537

[15] B Preim, F Ritter (2002). “Techniken zur Hervorhebung von Objekten in medizinischen 3d-Visualisierungen“, *Proc. of Simulation and Visualization 2002*, SCS, pp. 187-200

[16] B Preim, M Hindennach, W Spindler, A Schenk, A Littmann, HO Peitgen (2003). “Visualisierungs- und Interaktionstechniken für die Planung lokaler Therapien“, *Proc. of Simulation and Visualization 2003*, SCS, pp. 237-248

[17] A Puig, D Tost and I Navazo (1997). “An Interactive Cerebral Blood Vessel Exploration System”, *IEEE Visualization* (Phoenix, Arizona, October), pp. 433-436

[18] T Rist, E André (1992). “Incorporating Graphics Design and Realization into the Multimodal Presentation System WIP”, *Advanced Visual Interfaces (Proceedings of AVI '92, Rome, Italy)*, World Scientific Press, Singapore, pp. 193-207

[19] D Selle, B Preim, A Schenk, HO Peitgen (2002). “Analysis of Vasculature for Liver Surgery Planning “, *IEEE Transactions on Medical Imaging*, Vol. 21 (11), pp. 1344-1357

[20] B Shneiderman (1997). *Designing the User Interface*, Addison Wesley

[21] R Spence (2001). *Information Visualization*, Addison Wesley

[22] T Strothotte, S Schlechtweg (2002). *Non-Photorealistic Computer Graphics: Modeling, Rendering, and Animation*, Morgan Kaufmann, San Francisco