Model-Based Visualization for Intervention Planning

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ABSTRACT

Computer support for intervention planning is a two-stage process: In a first stage, the relevant segmentation target structures are identified and delineated. In a second stage, image analysis results are employed for quantification and visualization in order to support a complex planning process. In the first stage, *model-based* segmentation techniques are often used to reduce the interaction effort and increase the reproducibility. There is a similar argument to employ model-based techniques for the visualization as well. With increasingly more visualization options, users have many parameters to adjust in order to generate expressive visualizations. This process is time-consuming and not reproducible. Although interactive 3d visualizations should be flexible and support individual planning tasks, appropriate selection of visualization techniques and presets for their parameters are strongly desirable. In this paper, we discuss examples for such a visualization support. We refer to model-based visualization to denote the selection and parameterization of visualization techniques based on á priori knowledge concerning the visual perception, the shape of classes of anatomical objects and the intervention planning task which has to be solved. Similar to model-based segmentation approaches, model-based visualizations need to be validated with respect to their accuracy.

1. INTRODUCTION

Surgical interventions, radiotherapies and other local therapies require a precise understanding of the patient’s anatomy. In particular, the location and extent of pathologic variations in relation to vital anatomic structures, such as major blood vessels, is essential to evaluate the resectability and to determine the surgical strategy.

Many surgical and other interventions are planned by means of CT or MRI data. Planning involves a systematic exploration of the slices of radiological data. In order to support the mental preparation of surgeons, more and more 3d visualizations are generated. Oblique MPR slices for instance allow to assess the local cross section of vascular structures and volume rendering is employed to get an overview which is essential for example in case of complex fractures or rare anatomic variants.

Intervention planning can be supported even better if image analysis results, such as segmentation information concerning the relevant objects, are available. For an efficient segmentation, *model-based segmentation* approaches are often exploited. Statistical models, such as Active Shape Models and Active Appearance Models, employ á priori knowledge with respect to the expected shape and grey value distributions [4], [5]. Active contour models are another class of model-based segmentation techniques. They fit deformable models to the segmentation target structure based on a flexible geometric representation such as B-Splines. The process of fitting the model to the target structure is guided by physical principles and constraints which restrict for example the curvature along the path (model assumptions) [17] [20] [26].

Based on image analysis results, visualization parameters can be locally adapted to individual objects or certain categories of anatomic structures, such as nerves or lymph nodes. Since visualizations should primarily provide insights into spatial relations, there is an argument for visualization techniques which "idealize" anatomic structures to some extent to render them more comprehensibly. As an example, the simultaneous visualization of two complex vascular trees based on segmentation results leads to visual clutter.

The design of "idealized" visualizations requires assumptions or à priori knowledge with respect to geometric properties. This gives rise to the term *model-based visualization.* More general, model-based visualization refers to the automatic selection of appropriate visualization techniques. There is a variety of sources which can be exploited to derive such automatic selections. Similar, to the model generation process in image segmentation, experience with the visualization of a variety of similar datasets is an essential source of information. In case of clinical applications, "idealized" visualizations must be shown to be "correct enough" to draw reliable conclusions. Therefore, we discuss the validation of model-based visualization techniques.

Conventional 3d visualization includes volume rendering and surface rendering where color and transparency are employed to selectively emphasize anatomic structures. These techniques have obvious limitations if a variety of different objects is relevant for a treatment decision and need to be displayed simultaneously. These limitations recently led to the development of so-called illustrative rendering techniques (Hadwiger et al. [11], Tietjen et al. [27]) which can be flexibly combined with conventional medical visualization techniques. These new techniques involve an increased flexibility on the one hand and an increased necessity to adjust parameters on the other hand. In clinical applications, presets are necessary to reduce the interaction effort. These presets must consider which techniques and which parameters of these techniques are appropriate for certain categories of anatomic structures. We regard this as another example of model-based visualization. Finally, emphasis techniques are useful for intervention planning to selectively emphasize relevant anatomic or pathologic structures. A wide variety of emphasis techniques exists [23]. The selection should again consider geometric properties and á priori knowledge of the objects. As an example, we discuss emphasis techniques which were developed to support the exploration of lymph nodes and nodules.

Organization. The remainder of this paper is organized as follows: In Sect. 2, we discuss model-based visualization of vascular structures. In Sect. 3, we describe the process of generating geometric models for illustrative visualization with a focus on silhouettes and feature lines. Illustration techniques, such as cut-away and ghostviews, and their application are discussed in Sect. 4. Finally, we present a general discussion of à priori knowledge for visualization purposes in Sect. 5.

2. MODEL-BASED VISUALIZATION OF VASCULAR STRUCTURES

For intervention planning, it is desirable that spatial relations can be correctly inferred from the visualization. In particular the topology of vascular trees is often essential to decide on the feasibility. Moreover, the curvature, the depth relations, and the diminution of the diameter towards the periphery should be depicted correctly. With conventional visualizations, such as Maximum Intensity Projection (MIP) or surface rendering, artifacts arise due to the limited resolution and inhomogeneities of contrast enhancement. Therefore, vascular structures should be reconstructed based on the radiological data of a patient and some model assumptions as to the shape of vasculature (Barrilot et al. [2], Gerig et al. [9]). The pioneering work of Barrilot et al. is probably the first dedicated effort to generate medical visualizations based on à priori knowledge and assumptions with respect to the shape of objects. Healthy vascular structures exhibit a roughly circular cross-section, they are connected with each other and their diameter shrinks from the root to the periphery. For many intervention planning tasks, healthy vascular structures can be assumed. The topology of vascular trees is essential in order to assess which portions are affected if the tree is damaged or cut at a particular position.

A variety of visualization techniques have been developed which use the skeleton and the local vessel diameter as input. Primarily graphics primitives, such as cylinders and truncated cones, were fitted to the skeleton and scaled according to the local vessel diameter (Masutani et al. [19], Hahn et al. [12]). A specialized variant of vessel visualization was described by Puig [24]. She considered typical elements (cylindrical, conic, stenosis, …) and branching structures in cerebral vasculature, tried to classify branchings accordingly and used this information to emphasize the corresponding branching type.

The explicit construction of a geometry however exhibits problems in particular at branchings were discontinuities arise at the joint of truncated cones or cylinders. A superior image quality can be achieved by means of implicit surfaces, where the shape of a vascular system is described by implicit equations. The resulting scalar fields are polygonized by means of a threshold. A special variant of implicit surfaces, convolution surfaces, allow to visualize skeletal structures, such as vascular trees, by applying a convolution filter to the skeletons. The use of convolution surfaces for medical visualization poses some problems with respect to accuracy; the depicted vascular structures should correctly convey the vessel diameter and the topology of vascular structures. Usually, convolution surfaces exhibit "unwanted effects", such as unwanted blending where two branches are incorrectly merged with each other due to the construction process. Oeltze et al. could show that an appropriate filter selection allows to effectively avoid that the resulting visualizations strongly deviate from the segmentation results on which they are based [21]. Two examples of this work are shown in Fig. 1.

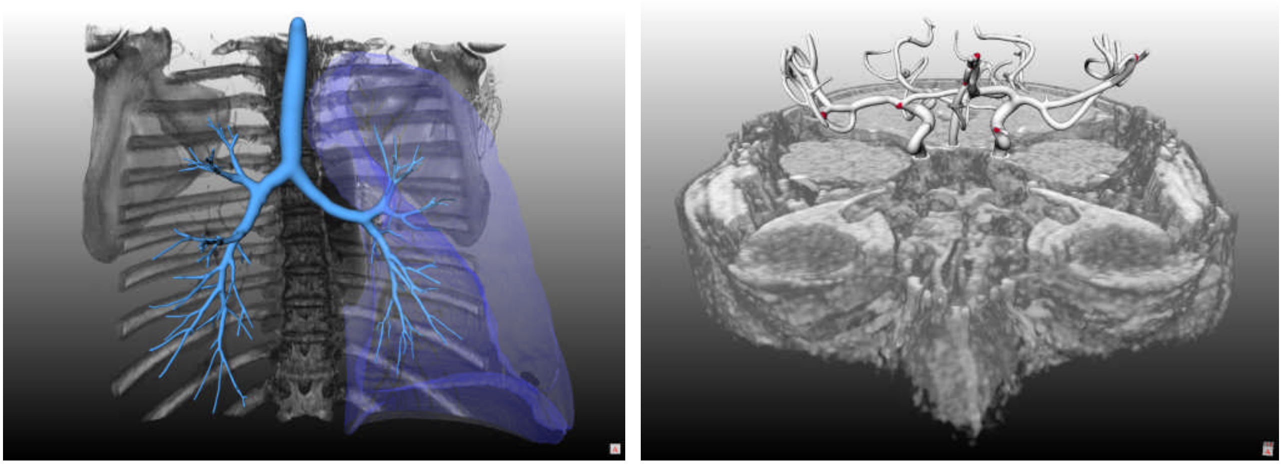

Fig. 1: Model-based visualization of vascular structures embedded in direct volume renderings of surrounding structures. Left: The bronchial tree is depicted. Right: a cerebral tree is shown.
Images are courtesy of Steffen Oeltze, University of Magdeburg.

2.1 Validation

Similar to new segmentation methods, new model-based visualization techniques should be carefully validated with respect to accuracy. This includes qualitative and quantitative comparisons with other methods. Quantitative comparisons are based on metrics which characterize distances between segmentation or visualization results or based on volume overlaps [29]. In particular, the comparison with a “gold-standard” is essential where the “gold standard” represents the solution which is regarded as “true” or at least as the most accurate result which could be generated. For image segmentation, the manual segmentation of medical experts is considered as gold-standard.

For model-based visualization, a separate validation is required to investigate whether the segmentation result is correctly displayed. For this purpose, it is reasonable to regard the isosurface rendering of the segmentation result as the gold-standard. Isosurface rendering should be accomplished with the Marching Cubes method [18], taking 0.5 as threshold, when “1” represents foreground voxels and “0” represents background voxels. Marching Cubes is based on linear interpolation along the edges where one vertex is below the threshold and one above. With respect to the metrics, distance metrics, such as mean distance and Hausdorff distance, are primarily relevant for assessing the accuracy of model-based visualization techniques.

As the major result of a quantitative validation, Oeltze et al. found that the deviation of “their” variant of convolution surfaces to an isosurface rendering of the segmentation result is on average below half the diagonal size of a voxel. Taking into account that half the diagonal size of a voxel is the uncertainty which is due to resolution of the data, this is an excellent result. Only for a very small fraction of the voxels the distance is up to 3 diagonal voxel sizes [22]. The validation was based on 10 abdominal CT datasets (patients with liver metastases) with different resolution and distances were computed for each vertex of the resulting polygonal mesh.

2.2 Discussion

Model-based visualization refers to the automatic selection of appropriate visualization techniques. With respect to the visualization of vascular structures this involves an assessment of the local vessel diameter in cross sectional areas.

If it turns out that the assumption of a circular cross section is strongly violated in several adjacent slices, any visualization technique which assumes this property is obviously not suitable. In such cases, a pathology is likely and an isosurface of the segmentation result is a better visualization option. Pathologies such as stenosis or aneurysms occur at small portions of a vascular system. A hybrid combination of isosurface rendering (in pathologic portions) and model-based rendering (in healthy portions) is probably the best choice to depict pathologic vascular systems.

There are some similarities between model-based vessel segmentation and visualization. Model-based image analysis techniques also assume connectedness of vascular structures and try to “bridge” over a few voxels which fail to fulfill a homogeneity criterion due to partial volume effects. An ellipsoidal cross-section is often assumed in vessel segmentation approaches [13]. In general, model assumptions in image segmentation must be less restrictive to cope with the variety of shapes and the imperfect quality of medical image data.

3. MODEL-BASED ILLUSTRATIVE RENDERING

Illustrative rendering refers to the use of lines and points as rendering primitives. Illustrative rendering in medical visualization is motivated by the illustrations in anatomy and surgery textbooks. Silhouette rendering, hatching styles and stippling are among the techniques which are used to render anatomic shapes more comprehensibly. After the pioneering work of Saito and Takahashi [25] dedicated therapy planning solutions have been developed. In particular for radiation treatment planning, illustrative rendering was used to show simultaneously dose distribution and anatomical structures (target structures and structures at risk) [14]. Illustrative rendering techniques are based on proven assumptions with respect to shape perception. Object boundaries are recognized faster and more precisely by depicting their silhouettes. Surface orientation is perceived more accurately (compared to shaded surfaces) if hatching lines along the main curvature directions are included [14] [28].

The potential of such visualization techniques for intervention planning can be easily shown. However, for practical use, the selection and parameterization of illustrative rendering techniques must be supported. Our experiments and informal user study reveal that silhouette rendering is useful for large structures, such as organs (see Fig. 2), but not for small structures such as small nodules [27].

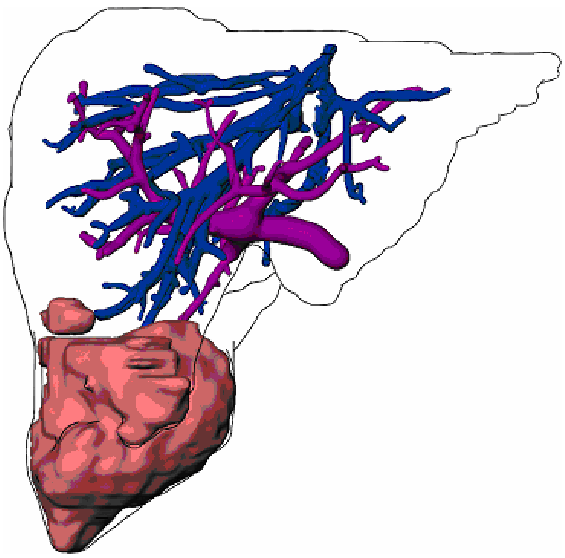

Fig. 2: Liver, intrahepatic vasculature as well as a tumor are depicted for intervention planning. Image is courtesy of Christian Tietjen, University of Magdeburg.

It is also necessary to investigate the prerequisites for illustrative rendering. A major problem with the automatic use of silhouette and hatching line generation is the smoothness of surfaces. Silhouettes emphasize not only the relevant features of a boundary but also noisy portions which might occur due to smaller segmentation errors or large slice distances. Hatching lines are usually generated by considering curvature directions. Noisy surfaces exhibit frequent strong changes of surface normals and curvatures. Therefore, the hatching directions suddenly change and lead to distracting visualizations. In summary, object shapes resulting from a segmentation process usually require a subsequent smoothing step to be adequate for illustrative rendering (see Fig. 3). Smoothing geometric models is a wide topic, similar to smoothing image data. Simple methods tend to remove not only noise but also relevant features. Advanced methods, such as those based on diffusion theory better retain relevant features. However, no single smoothing method is appropriate for all anatomic and pathologic structures. Pathologic structures, for example, should not shrink in the smoothing process, whereas this requirement is less crucial for large organs. Again, the suitable selection, combination and parameterization of smoothing techniques requires à priori knowledge with respect to the shapes to which they are applied. Smoothing techniques also alter the geometry and therefore, must be evaluated by measuring distances to “correct” visualizations.

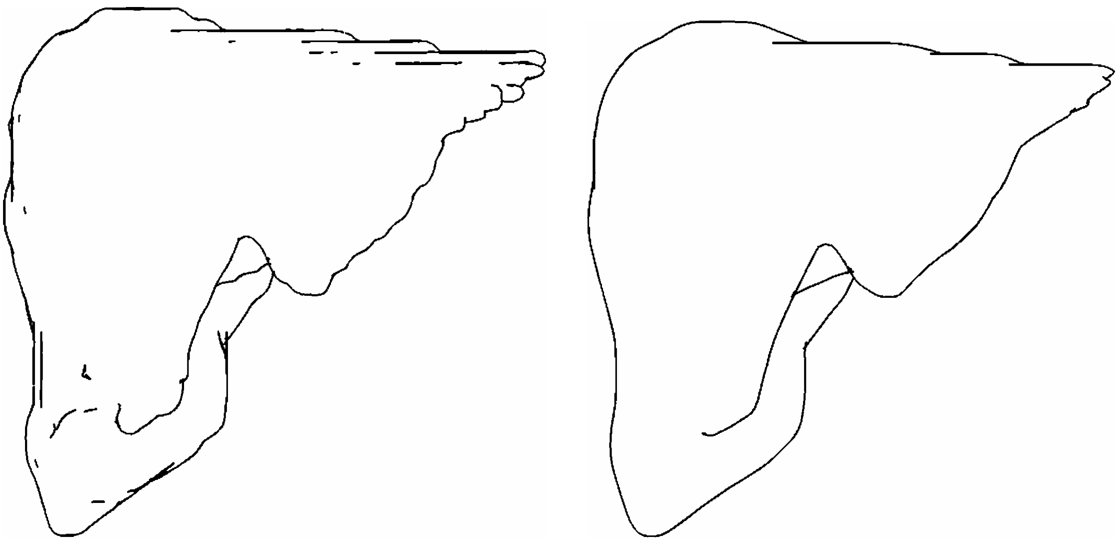

Fig. 3: Left: Silhouette generation based on a typical segmentation result of the liver in abdominal CT data. Right: The polygonal model was strongly smoothed (relaxation filter with 7 iterations and relaxation factor 1.0) prior to silhouette generation. Images are courtesy of Christian Tietjen, University of Magdeburg.

Illustrative techniques enrich the expressiveness of medical 3d visualizations by emphasizing silhouettes or characteristic features, such as ridges and valleys. This development is not finished yet; new hatching and stippling techniques are devised which convey geometric properties such as curvature. These new techniques exhibit considerably more parameters than silhouette rendering. The analysis of anatomic structures and the evaluation of sample image should lead to recommenddations how to apply such techniques for certain anatomic structures.

4. EXPLORATION OF NODULES AND LYMPH NODES WITH CUTAWAYS AND GHOSTINGS

As another example of model-based visualization we consider the exploration of nodules and lymph nodes. The occurrence and localization of enlarged and potentially malignant lymph nodes is an essential information for planning surgical interventions, for example, in the neck region [15]. By contrast to vascular structures, lymph nodes, tumors and lung nodules do not exhibit a complex topology. Instead they are rather small and compact. They are explored together with adjacent structures in order to evaluate whether these structures are infiltrated. Without other structures displayed, small nodules cannot be localized. Often, it is a severe problem to display all these structures simultaneously with sufficient opacity such that they can be recognized.

As an illustration technique, originating from technical illustrations, cut-aways might be applied. Cut-away views are generated by removing a geometric shape to expose hidden objects. Instead, cut-aways are applicable to show compact small objects. Compactness and relative size can be geometrically analyzed.

As a variation of cut-away views the cut region can be displayed transparently instead of a complete removal. This technique is referred to as *ghostview* (Feiner and Seligman [7]). An essential decision in the use of cut-away views and ghostings is the selection of a cut geometry. It should be regular to be recognizable as an illustration technique (anatomical shapes are not regular). The shape should “fit” to the objects which should become visible. Since lymph nodes, nodules, and metastasis have roughly circular shapes (model assumption), cylinders are appropriate cut-regions. Fig. 4 shows cylindrical ghostviews used for neck dissection planning. Intervention planning, however, requires a systematic exploration of all enlarged lymphnodes. Based on this task knowledge, an exploration technique is needed which supports a sequential emphasis of all relevant lymphnodes. In [15] we suggested to use the Tab-key in order to emphasize all lymphnodes based on a sequence which considers size and local coherency. The issue of validation and correctness, which we carefully discussed for the visualization of vascular structures, however, is not relevant here.

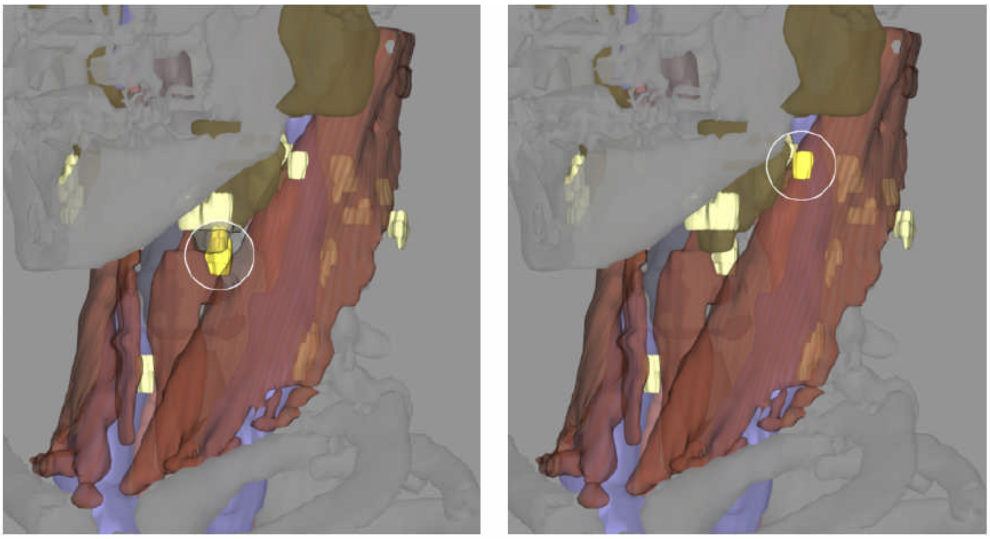

Fig. 4: Lymphnodes in the neck region are emphasized by means of cylindrical ghostviews. A sequential exploration of all lymph nodes is supported taking into account the lymph node’s size and position. Image is courtesy of Arno Krüger, University of Magdeburg.

5. DISCUSSION

The previous sections presented a variety of examples where visualization and illustration techniques have been fine-tuned to particular target structures such as nodules and vascular structures. “Model-based” techniques are also needed for a variety of other applications, such as the visualization of diffusion tensor data, where á priori knowledge on white matter tracts and their branchings is incorporated in the visualization and clustering of fiber tracts [9] [30].

Similar to segmentation problems, the suitability of visualization and illustration techniques depends on the object shape, size and on the occurrence of other objects in the neighborhood. In many intervention planning applications, image analysis is regarded as a challenge and visualization as a simple matter of using some wide-spread commercial rendering system. This is an over-simplified view of the difficult problem of conveying the essential information to the user. Visualization, on the other hand, can benefit from the substantial work on representing à priori knowledge for image segmentation. Smoothness constraints as they are used for Active Contours are relevant for silhouette rendering: If segmentation results fail to meet smoothness constraints, they cannot be directly employed for silhouette generation.

Model-based image segmentation recently started to represent not only one "target" structure, but also spatial relations of adjacent structures, see e.g., the Active Structural Shape Models developed by Al-Zubi [1]. Similarly, the effectiveness of visualization techniques applied to one anatomic structure depends on the visualization techniques applied to other anatomic structures which are displayed simultaneously. Therefore, it is essential that intervention planning tasks are carefully studied in order to determine which collections of objects are explored simultaneously. These collections should be provided as predefined selections and the default visualization techniques should be chosen in such a way that the whole collection is comprehensibly displayed. As a simple example, colors and transparencies of such objects should be selected such that contrasts are easily perceived and all relevant objects are sufficiently visible.

Comparison of Model-based Segmentation and Visualization

In Table 1, we compare information used for model-based segmentation and visualization.

Table 1: Model-based segmentation and visualization

Information	**Model-based segmentation**	**Model-based visualization**
Grey value distribution	×	-
Gradient magnitude/ curvature metrics	×	×
Geometric shape	×	×
Topology	×	×
Structural relation between objects	×	×
Visual perception	-	×
Task knowledge	-	×

While the distribution of grey values of the target structures in CT and MRI data is valuable information for model-based segmentation, this information is not relevant for model-based visualization. Derived information such as gradient magnitude or curvature metrics is essential for edge-based segmentation, such as Live Wire. For visualization, these metrics can be regarded as indicators for the certainty of the visualization. Primary tumors for example, often have weak borders and their precise extent is uncertain. This information can be employed to select a visualization technique which conveys this uncertainty (for example a semitransparent volume rendering instead of a “perfect” shiny isosurface). We regard as geometric shape any shape descriptor; such as compactness or anisotropy. Assumptions related to shape descriptors are useful to identify the target structure and to visualize it appropriately. Similar, topology information, such as connectedness and the number of holes is essential for segmentation and visualization. The use of structural information for image analysis was clearly demonstrated. For visualization, it can be used for the design of color mapping schemes which employ information on adjacency of structures. Finally, visualization strongly benefits from research in visual perception. Whether something can be perceived at all, whether color differences can be discriminated, whether objects can be discriminated at a glance (“preattentive” vision) is dependent on the selection of visualization parameters. Many user studies have been carried out and provide a valuable source for á priori knowledge (recall Colin Ware’s book [29]). Finally, task knowledge can be exploited to derive which objects are essential for certain tasks and to guide the selection of visualization parameters.

Despite the similarities between model-based segmentation and visualization there are also fundamental differences. Model-based segmentation is employed to automatically segment one target structure (with rather fixed topology). Model-based visualization is more general and refers to classes of anatomic structures, such as vascular systems or lymph nodes.

While there is one correct segmentation, there are potentially many appropriate visualization settings for a particular set of anatomic structures. The “right” visualization cannot be determined in a fully automatic manner. The suitability of visualization parameters depends on user preferences, previous experiences and on the visual capabilities of a particular user. The exploration of 3d models with appropriate interaction facilities is desirable and may lead to additional insights. In particular, rotation and zooming provide insight into spatial relations. However, the unrestricted exploration involves too many parameters. Therefore, a model-based approach is desired to start the exploration with a meaningful combination of visualization techniques.

6. CONCLUDING REMARKS

We introduced model-based visualization as a concept where the appropriateness and parameterization of visualization techniques is carefully adapted to shape and size of the object, and to the context of its visualization in intervention planning. To realize model-based visualizations, the shape of the target structure has to be analyzed, for example, with respect to the branching pattern. The wide literature on shape description may be employed to select appropriate shape descriptors (see e.g. [6] for a recent book on shape classification).

We argue that model-based visualization is an essential goal in order to effectively exploit the huge space of visualization options. The fully interactive specification of all visualization parameters is not feasible since it is time-consuming and leads to visualization results which are not reproducible.

Outlook

There is an urgent need for further research in the adaptation of visualization techniques to particular intervention planning tasks. In particular, the appropriateness of visualization techniques must be assessed by the target users: medical doctors who prepare for complex interventions. Prospective user studies are required which compare visualization techniques with respect to their consequences for the surgical strategies. Such user studies require that visualization techniques are integrated in dedicated software-assistants. The search for automatic “suggestions” for visualization techniques does not replace the design of graphical user interfaces to change or fine-tune parameters. We restricted the discussion in this paper to static visualizations. The model-based generation of animation sequences for intervention planning is an interesting challenge for future research.

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