Eurographics Workshop on Visual Computing for Biology and Medicine (2010)
Dirk Bartz, Charl Botha, Joachim Hornegger and Raghu Machiraju (Editors)

Importance-Driven Structure Categorization for 3D Surgery Planning

A. Baer[†1], K. Kellermann[1] and B. Preim[1]

[1]Department of Simulation and Graphics, University of Magdeburg, Germany

Abstract

We present an importance-driven categorization approach to automatically gather all currently required structures for the surgery planning process. Therefore, we analyzed common demands for tumor intervention planning and integrated domain knowledge to enable a determination of the relevant structures for various surgical questions. The categorization of structures in focus, focus-relevant and context is defined and initiated by the question. Our method uses the structure's specific meta data and geometric information to determine an importance value for each structure automatically. This importance value encodes the structure's priority for the current question and defines the structure's category. Furthermore, this value can be used to define a structure-specific visual style to generate expressive 3D surgery planning visualizations.

Categories and Subject Descriptors (according to ACM CCS): I.3.0 [Computer Graphics]: General- I.3.6 [Computer Graphics]: Methodology and Techniques - I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism.

1. Introduction

Computer aided surgery planning is especially useful for difficult cases, e.g. the removal of large or deep seated tumors. The computer assistance supports the exploration of the patient-specific volume dataset and the resectability assessment. A detailed surgery assessment including the intervention's type and extent in advance enables the minimization of the injury risk for critical structures and the surgery stress for the patient. Besides 2D visualizations, patient-specific 3D visualizations of segmented structures are used to virtually plan and simulate a potential intervention strategy. Anatomical structures and pathologies are segmented to provide additional quantitative information (e.g. distances and volumes) and to facilitate the spatial exploration. Special illustration techniques like silhouettes, hatching or textures enhance the structure's shape and support the generation of expressive 3D visualization [KHSI04]. Thus, computer assistance comprises segmentation, quantification, visualization, interactive exploration and simulation of the planned surgery. We focus on visualization and interactive exploration.

† alexandra.baer@ovgu.de

In clinical practice, surgery planning systems should provide a combination of CT or MRI slices, direct volume rendering (DVR) and 3D visualizations of the segmented structures. The slices provide the opportunity to validate the reliability of the segmentation results. DVR enables a visualization of all structures and, therefore, provides additional information and an overview of spatial relations. Interactive 3D visualizations are required to define an appropriate intervention strategy. Such visualizations are usually rather complex, since they show all segmented structures of the dataset. This results in several occlusions that hamper the exploration of the dataset. Moreover, the surgeon has to manually define, whether a structure is visible according to the current question. Since the surgeon has to consider various surgical questions, a well-defined set of 3D visualizations including the currently relevant structures for each structure is required.

An importance-driven visualization technique for automatic focusing on features within a volumetric data set was introduced by Viola et al. [VFSG06]. This pioneering work clearly showed that a distinction of the importance of anatomic structures is essential for creating expressive visualizations. We extend this work and use the importance-driven concept to categorize the segmented structures into focus and context according to the current question. Moreover, we generate question-specific 3D visualizations required for the tumor surgery planning process. However, it is difficult to define an expressive categorization. In principle, common approaches realize this with one of two strategies:

- Static focus: The structure categorization is realized by using predefined importance values for each structure.
- Dynamic focus: The focus structure can be manually selected by the user while the importance of the context structures are predefined and, therefore, static.

Both strategies guide the user's attention and enable a structure categorization (focus-context) by using appropriate visualization techniques that visually separate the structures. The first strategy is suitable if the importance of each structure is static. This approach is optimized for one specific predefined structure set and, therefore, for one 3D visualization. In contrast, a dynamic focus definition allows more individual 3D visualization of structures, since the user has the ability to select a preferred focus. Even though, the context structures have to be predefined for each selected focus separately. Since the structure's importance varies depending on the question and on the existing pathologies, this approach is not suitable for the tumor planning process of individual patient datasets. The bones for example are commonly defined as context structure for orientation purposes. However, if the question concerns the infiltration of the tumor respectively to the bone, this structure will be a focus-relevant structure.

We introduce a third strategy, where the structure's importance automatically adapts to a dynamic focus and a current question, e.g. "Is a muscle infiltrated by a tumor?" or "Is there a safe access to the tumor?". We dynamically determine the currently relevant structures depending on their semantic relation to the focus by integrating domain knowledge and analyzing the patient's individual data.

Outline

In Section 2, we discuss related work. Section 3 gives an insight into the medical background. Since we concentrate on the generation of 3D visualizations for tumor surgery planning, we analyzed surgical questions used in such a planning process. Based on that, we developed an adequate structure classification described in Section 5, which enables an importance-driven structure categorization corresponding to the question analysis results. Moreover, this analysis supports the determination of categorization parameters to define the structure's individual importance for the current question. Parameters, that enable a detailed structure characterization, are presented in Section 5 followed by Section 6 presenting the categorization process performed for each question to gain question-specific 3D visualizations. We conclude our paper with a brief discussion of our results and a presentation of future plans.

2. Related Work

3D visualizations of human datasets are integrated in computer aided systems for surgery planning, medical education, simulation, and training. Segmented structures of CT or MRI datasets are presented and the user is able to explore the data. These 3D models usually show all segmented structures and the user selects the structures of interest. In medical education systems, customized 3D visualizations are achieved using semantic relations between anatomic structures.

Höhne et al. [HPP*95] implemented functional and spatial ontologies to provide structure relations with their VOXEL-MAN system. Using the Visible Human Dataset, they create visualizations that support a question-specific data exploration. Questions are related to anatomy, e.g. blood supply or innervation of a region. A similar approach especially for teaching radiologists was introduced by Balabanian et al. [BYV*08]. They visualize a volume dataset and enable hierarchy-based interactions. Both approaches are designed for educational purposes. An identification or characterization of pathologic structures is not integrated. Tietjen et al. [TPHS06] introduced a system that supports the planning of neck surgeries (neck dissections). Besides the CT slices, they provided 3D models that show all segmented structures. They support two therapeutic questions, e.g. "Where is the tumor located?" and "Are there enlarged lymph nodes?" by emphasizing the tumor or pathologic lymph nodes. Their system does not include an automatic structure selection and the user has to manually select disturbing structures to hide them. Semantic concepts are primarily integrated in medical education systems. Since we aim for a structure categorization, we focus on visualization techniques that include semantic rules or importance-driven techniques, too. The following approaches initiate the structure categorization by defining the focus either manually or derived from the user's interaction with the visualization.

Viola et al. [VKG05] and [VFSG06] introduced importance-driven approaches to volume rendering. They estimate an appropriate viewpoint and incorporate importance-driven cutaway and ghosted-view techniques to facilitate expressive volume renderings. Their methods rely on static predefined importance values for each structure and manually selected focus structures or regions. Surrounding structures are weighted and visualized distance-dependent from the focus. Svakhine et al. [SES05] described the idea of illustrative motifs. Their visualizations are guided by a specific motif like the level of expertise of the viewer. The motif defines the settings template that serves as the input for a particular illustration style and defines the user interface that is required to individually manipulate the illustration. The semantic transfer functions introduced by Rezk Salama et al. [RSKK06] and Rautek at al. [RBG07] improved the focus and context specification. They use spatial focusing, which is defined as area-based focusing using different geometric shapes and, therefore, reflects the attentive focus. Rezk Salama et al. [RSKK06] presented a high-level user interface for the specification of a mapping from volume attributes to a visual style using transfer functions with semantics. Similar to Rezk Salama et al. [RSKK06], Rautek at al. [RBG07] introduced a semantic layers concept for illustrative volume rendering. This method bases on fuzzy logic arithmetics as well as their later on presented interaction-dependent semantics concept [RBG08]. The user's interaction, distance to the illustration, and the data semantics define the structure classification in focus and context regions.

We focus on the generation of question-specific 3D visualizations of segmented structures. Based on the focus and the current question, the importance of each structure is calculated automatically. The following sections introduce the required structure characterization and the automatic categorization derived from the surgeon's questions.

3. Medical Background

A tumor diagnosis is based on symptoms and various examinations. The individual therapeutic strategy is determined upon oncologic guidelines. As a prerequisite, the tumor's degree of severity that is a staging concerning the anatomic location and distribution of the tumors has to be defined. This is accomplished with the internationally established TNM classification system. The tumor (T), nodes (N), and metastases (M) are characterized in detail. Since the occurrence, extent, number and location of pathologic and suspicious structures have to be assessed, this classification supports the preoperative surgery planning.

Questions that influence the surgical strategy relate for example to the infiltration of muscles or vessels. If the major vessels are affected the patient may be inoperable or requires an additional vessel reconstruction. Potential surgical questions may be:

- Where are the pathologic structures located?
- Are there any lymph nodes larger than 1, 3 or 6 cm?
- Are there structures within a critical distance to the tumor?
- Are these structures even infiltrated?
- Which structures will be at risk or injured if this access path is chosen?

These questions have to be answered step by step to gather all required information. A surgery planning process including the surgical questions is specific for an anatomic region, the surgical intervention and depends on the individual medical expert. To provide a representative sample, we interviewed nine medical experts for liver, three for neck and two for spine surgery planning. Thus, we are able to generalize our approach to different pathologies and furthermore, to derive basic surgical questions. Based on these extensive surgeon interviews, the TNM classification and an analysis of liver, neck and thorax surgical planning, we derived two common components:

Pathologic and suspicious structures: The number, location, and extent of pathologic and suspicious (potentially pathologic) structures have to be assessed. The location is usually defined by an anatomic domain-specific coordinate system e.g. the liver segments for liver surgery and lung lobes and lung segments for thorax surgeries. This enables a consistent localization.

Risk structures: Structures that are potentially at risk have to be identified and located. The risk may relate to infiltrations by pathologic structures or close proximity. The planned surgery can affect the structures, too. Access paths or safety margins should be validated to prevent injuries of crucial anatomic structures.

4. Question-specific 3D Visualizations

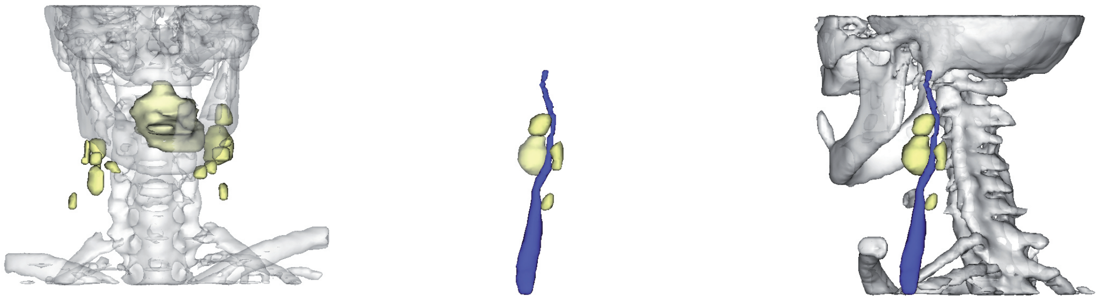
Since the surgeon has to consider various questions to define the type and extent of a surgery, a well-defined set of question-specific 3D visualizations is required to support the planning process. Question-specific 3D visualizations should be customized to a surgical question and, therefore, guide the user's attention to the region of interest. This might be structures (e.g. tumor or enlarged lymph nodes) or relations between structures (e.g. critical distances or existing infiltrations). A well-defined set of such visualizations represents the essential surgical questions to assess and plan the required intervention.

4.1. Data

Surgery planning is usually based on 2D slices of CT or MRI. Especially for difficult anatomic cases, additional quantitative information and an advanced spatial exploration is achieved by segmenting the relevant structures and generating 3D visualizations. Moreover, the segmentation provides and facilitates the separation of different soft tissue with overlapping image density values in the 2D slices. The planning process for the neck, abdominal or orthopedic regions is preferable performed with a combination of 2D slices and 3D visualizations. Our work focuses on the generation of appropriate 3D visualizations of segmented structures even though there are areas, where other techniques may be preferred. The segmentation is usually provided by some radiological workstations or external services that integrate advanced segmentation techniques.

4.2. Focus, Focus-Relevant and Context Structures

Primarily, we focus on the automatic selection of the currently relevant structures. Thus, a dynamic importance-driven structure categorization is performed. Important structures have to be visualized and emphasized to ensure



(a) Where are the pathologic structures located?

(b) Is there an infiltration risk for vena jugularis left?

(c) Is there an infiltration risk for vena jugularis?

Figure 1: *The 3D visualizations (a) and (b) represent two different surgical questions. In contrast to (b), the visualization (c) illustrates the bones as context structure for orientation purpose.*

their visibility and recognizability. Structures that are not important for this question do not have to be visible or at least have to be appropriately visualized. This is necessary to prevent obstructive occlusions and distraction of the user's attention. Moreover, to provide several question-specific 3D visualizations, the structure's importance dynamically adapts to the current question. The structure's priority respectively importance is derived by the surgeon's question and the focus structure. There are two possible cases:

Case 1: The surgeon considers a question
e.g. "Where are the pathologic structures located? "

Case 2: The surgeon selects a focus structure and considers a specific question concerning this structure
e.g. A vena jugularis is selected and the question is: "Is there an infiltration risk for this vein ?"

Besides the structures of interest (focus), the question defines all semantically related structures to this focus or at least describes the condition that identifies a structure as relevant. The focus is defined either implicitly (1) or explicitly (2). For case (1), the structure's individual importance derives from the question. In detail, the focus structures are all pathologic and all potential pathologic (suspicious) structures. For a neck surgery, the resulting structures are illustrated in Figure 1 (a) and Figure 4 (a). All lymph nodes larger than 1 cm are selected, since they might be metastases. The semantically relevant structure is the bone to enable a spatial localization by representing the median plane. In case (2), the focus is selected manually and the semantically relevant structures are defined by the question. Structures will be relevant if they are pathologic or at least suspicious and if their distance to the vein is below a critical distance. This question is illustrated in Figure 1 (b) for the neck. The suspicious lymph nodes within a distance of $5mm$, which is a critical distance for neck surgery, are selected. Thus, a question analysis contributes to the categorization that is described in Section 4.2.

Both cases define the structures that have the highest priority and, thus, have to be included in the 3D visualization. Therefore, our structure categorization represents the structure's individual importance for answering the question. We introduce a structure categorization that is based on the categories presented by Tietjen et al. [TIP05].

Focus structures are of highest interest for the current question.

Focus-relevant structures are related to the current focus and question. Focus-relevant structures are essential to answer the question. In contrast to Tietjen et al. [TIP05], the relation is characterized by a semantic importance.

Context structures are all other segmented structures with:

$$context \notin \{focus;\ focus - relevant\}$$

This category covers the structures that are not directly relevant, but support the anatomic orientation and classification especially used for patient and medical education as well as documentation of a surgery. The context structures are weighted according to their current importance, too. Figure 1 (c) represents a visualization used for documentation purpose. The bones, categorized as context, are illustrated, too. Thus, the spatial orientation is supported, especially suited for patient education.

The importance determination is the major prerequisite for a classification of structures corresponding to the mentioned categories. Our approach computes importance values that by analyzing the question, the individual structure's meta information and further parameters that describe the geometric relation between the structures and their pathologic risk. In the following Subsections 5 and 6, we introduce the importance-driven categorization process.

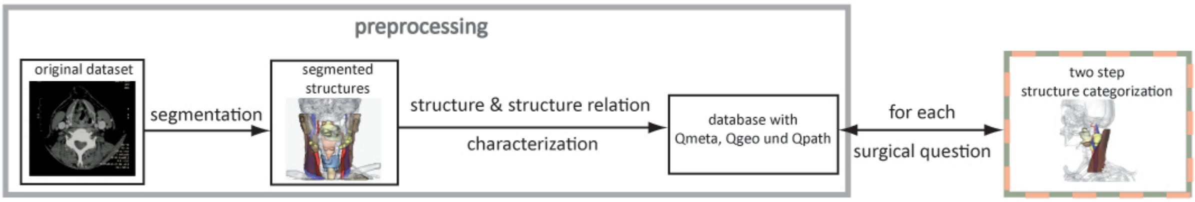


Figure 2: *The required process to gain question-specific 3D visualizations of an initial CT or MRI dataset. Our work is based on segmented structures. The structure characterization that results in the database is explained in Section 5. This is part of the preprocessing, which is done once per dataset. A structure importance is determined for each question with our two step categorization pipeline (see Section 6). Since the information required to define the structures' importance is the result of a database query, an question-adaptive importance determination is achieved.*

5. Structure Characterization

The structure's importance derives from the current question and, therefore, is not static. To realize an adaptive importance determination, we built a database that contains extensive information of the structures and their geometric relation to each other. This is accomplished once per dataset, in the preprocessing step. Figure 2 illustrates the single steps to gain a question-specific 3D visualization based on a CT or MRI dataset with our method. Our process starts with the structure and structure relation characterization during the preprocessing. We concentrate on the generation of 3D visualizations of segmented structures, since the segmentation process is usually provided by external services. The required structures for a question-specific 3D visualization are gathered by analyzing the datasets individual constructed database respectively to the current question (see Section 6). Hence, a generation of various visualizations that include only question-relevant structures are enabled.

We analyzed common surgical questions and determined two major question domains concerning the pathologic and suspicious and the risk structures, as explained in Section 3. Derived from that, we were able to identify three components that provide the information to enable a structure categorization, as mentioned in the previous section. These components are:

- meta information (Q_{meta})
- geometric properties (Q_{geo})
- pathologic risk (Q_{pat})

We call them question components, since a surgical question Q can be described as a set of those components and their specific parameters.

$$Q = \{Q_{meta}; Q_{geo}; Q_{pat}\} \tag{1}$$

Initially, the parameters of Q_{meta} and Q_{geo} are used to characterize the patient individual dataset, collect all information and construct the database. The input for the database construction are segmented structures from CT datasets including several structure information stored as a hierarchical XML file. The hierarchical file structure supports the automatic access of the required information. The individual parameters of each question component will be explained in the following Subsections 5.1 and 5.2. As explained in Section 5.3, Q_{pat} can be determined by using special parameter configurations of Q_{meta} and Q_{geo}. Nevertheless, we consider Q_{pat} as the third component, since the identification of pathologic structures is an independent task. Moreover, this component accelerates the pathologic risk determination.

5.1. Meta Information

The component Q_{meta} covers the meta information that is available for each structure. The type and amount of information is structure- and dataset-dependent. Thus, we initially collect all existing types of meta information and corresponding configurations. They represent the available meta information parameters and their possible values. Parameters are e.g. *structure group, type* and *side* and corresponding values may be *vessel, vein* and *left*.

Furthermore, we define a parameter called *character* that classifies each structure either as *anatomic, pathologic* or *suspicious*. Suspicious are structures that are not identified either as anatomic or pathologic. They will be treated in our categorization as anatomic and as pathologic. To support the classification, we define rules that are anatomic domain-specific based on the TNM classification. Structures will be pathologic or suspicious according to the TNM classification if their degree of severity is ≥ 1. We determine the degree by integrating domain-specific knowledge about structure types that are potential pathologic or suspicious. The structure's maximum extent enables a degree determination according to the TNM system. The appropriate character is semi-automatically assigned to structures.

This information represents the meta information component Q_{meta}. Already Q_{meta} enables a categorization of structures.

5.2. Geometric Properties

The component Q_{geo} consists of three parameters. Our method considers the minimal distance between the structures, the potential infiltration volume and structure occlusions. The parameters are used to gather information concerning these geometric relations between the structures.

5.2.1. Minimal Distance

This parameter is crucial to determine critical distances between structures e.g. to evaluate whether there is enough space to remove a structure safely or whether there is a potential infiltration risk for a structure. We determine the minimal distance between two structures with the approach of Preim et al. [PTSP02] and create a distance matrix that covers all calculated minimal distances. Since each structure is compared with all other structures, only values below the matrix diagonal are stored to prevent redundant storage.

5.2.2. Infiltration Volume

The infiltration volume of two structures is part of the assessment of risk structures (see Section 3). We determine the infiltration volume of two structures by calculating their overlapping volume using their segmentation masks. The results are stored as the infiltration parameter for the involved structures. We use the existence of an infiltration for the categorization process. The specific infiltration volume may be displayed as additional information e.g. required for the determination of remaining liver tissue for liver surgery planning.

5.2.3. Occlusion

The occlusion parameter allows an identification of container structures, which are defined by Viola et al. [VKG05]. Those structures enclose several relevant structures, e.g. the liver is a container structure and encloses relevant vessels. Container structures provide essential spatial information for the enclosed structures.

Hence, we calculate the averaged occlusion for a structure caused by other structures. Our approach is based on the imaged-based method from Mühler et al. [MNTP07]. They tried to find an optimal viewpoint for a compact anatomic 3D scene. They constructed a database including the occlusion information for each structure at each viewpoint. The viewpoints are positioned on a scene-surrounding sphere. We calculate the average occlusion for each structure. The viewpoint matrices are summed up and divided by the number of viewpoints. A container structure is identified depending on its average occlusion for all other structures.

This preprocessing step to gather all information for Q_{meta} and Q_{geo} enables a comprehensive data analysis, a structure characterization, and the determination of geometric properties.

5.3. Pathologic Risk

The third question component is the general pathologic risk Q_{pat}. This component is a combination of Q_{meta} and Q_{geo} to easily identify the potential risk caused by a structure for another and to select all structures at risk. The risk is characterized by the critical distance and the structure's character. Only structures with an opposed character (Q_{meta}) to each other are considered. The semantic rule states:

$$character_s \neq character_t \wedge critDist_{s,t} \rightarrow pathRisk_{s,t}$$

That means if the character of two structures is opposed, e.g. one of them is pathologic and one anatomic, and both structures are within a critical distance $critDist_{s,t}$, there will be a treatment risk. The critical distance is anatomic domain-specific. The distance of two structures will be critical if their minimal distance according to Q_{geo} is $\leq critDist_{s,t}$.

6. Structure Categorization

The dataset-specific database covers all information for calculating the structures' importance and performing an importance-driven categorization. A structure categorization is initiated per question. Hence, each question represents a database query. The focus is defined by the question or manually selected, as explained in Section 4.2.

6.1. Surgical Question

Our system represents a question as **parameter values** and **weights** applied to parameters of our question components.

A value may be *tumor* for the structure type parameter of Q_{meta} or a specific distance for the minimal distance parameter of Q_{geo}. Critical distances or safety margins are anatomic domain-specific. A potential question for a tumor resection is: "Which veins are affected by the tumor resection?". The structure categorization should result in the tumor as focus and veins within the safety margin (usually 1 *cm*) as focus-relevant. The question-specific values are structure type tumor and structure type vessel of Q_{meta} for focus and focus-relevant. The system represents the potential affection for the veins as request for Q_{geo}. Since only the risk for the veins is required, this is not a request for Q_{pat}. Hence, all veins within the safety margin (usually 1 cm) are focus-relevant.

The weights ($w_{parameter}$) represent the individual parameter's priority. Since the final categorization is performed by thresholding (see Figure 3), the individual $w_{parameter}$ have to be defined in proportion to the category threshold ($t_{category}$). In detail, a specific value for weights and thresholds is not crucial. When a structure has to fulfill more than one condition to be relevant, the single $w_{parameter}$ has to be lower than $t_{category}$ but the $\sum w_{parameter}$ of all required parameter weights has to be larger or equal than $t_{category}$. Thus, our system is robust concerning parameter variations. Table 1

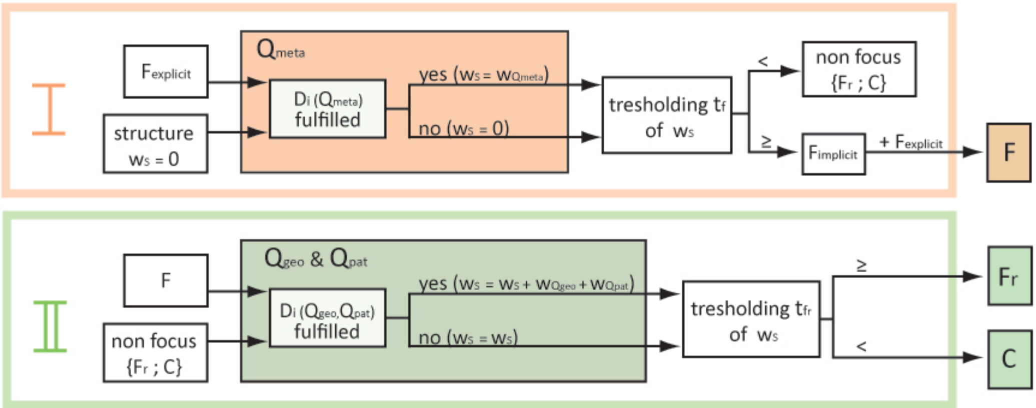


Figure 3: *The two step categorization pipeline. Step I identifies the focus structures F by using the meta information (Q_{meta}) of the current question. With conditions D_i (Q_{meta}) and weights $w_{Q_{meta}}$ the structure's weight w_s and, thus, importance is determined. The thresholding of w_s realizes the first categorization in focus F and non focus. All structures $\in \{F_r; C\}$ will be analyzed in step II with Q_{geo} and Q_{pat}. The conditions D_i (Q_{geo}, Q_{pat}) are evaluated and the individual structure's importance is adapted. A thresholding is performed similar to step I to classify focus relevant F_r and context C structures.*

demonstrates the weighting concept by the previously mentioned resection example. The corresponding parameter configurations and required weights are shown. Since the weight for structure type tumor (w_{tumor}) is defined as larger than the focus threshold (t_F), each tumor will be categorized as focus. Focus-relevant are all veins within the safety margin. Therefore, the individual w_{vein} and w_{margin} have to be lower than t_{F_r}. However, it is essential that $w_{vein} + w_{dist} \geq t_{F_r}$, due to the fact that the weights are summed up, to receive the final weight w_s that represents the structure's importance (see Figure 3). Structures that fulfill one condition may be context structures, e.g. veins or other structures within the safety margin. Resulting visualizations for this question are illustrated in Figure 4 (c) for the anatomic domains neck, thorax, and liver with $w_{tumor} = 1$, $w_{vein} = w_{margin} = 0.4$, and the thresholds $t_F = 1$ and $t_{F_r} = 0.8$.

	Parameter	Value	Weight
Q_{meta}	type	tumor	$w_{tumor} \geq t_F$
Q_{meta}	type	vein	$0 < w_{vein} < t_{F_r}$
Q_{geo}	min. distance	margin	$0 < w_{margin} < t_{F_r}$

Table 1: *The parameter values and weights for the question "Which veins are affected by the tumor resection?"*

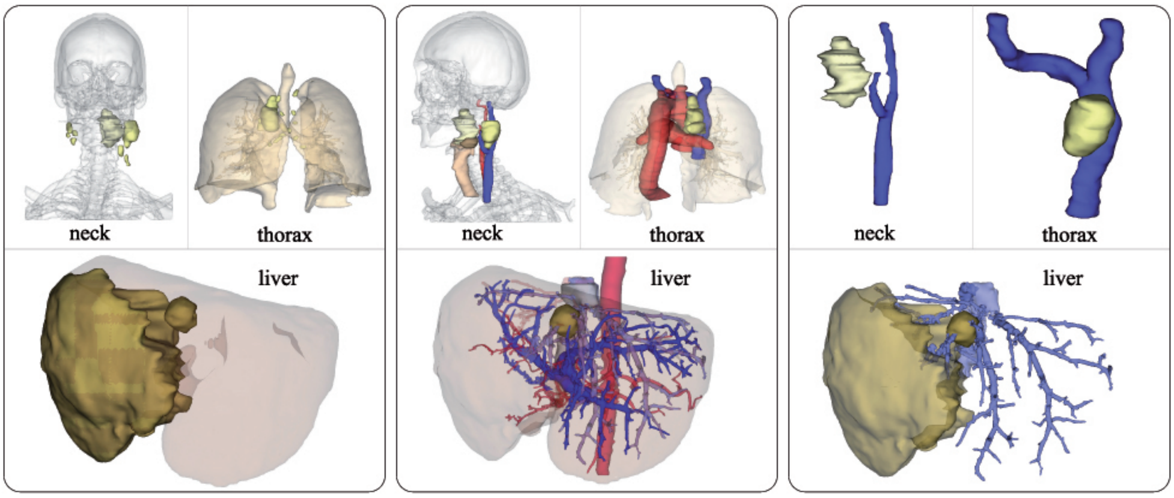
Since the required categorization parameters and weights are derived from the question, we offer the possibility to define parameter sets and weights as question templates. Thus, it is not necessary to manually configure the relevant parameters and weights for each question. However, we are able to provide a few templates for neck, liver, and thorax surgery, based on extensive surgeon interviews.

6.2. Categorization Pipeline

An automatic categorization of a structure is achieved with our two step pipeline illustrated in Figure 3. All segmented structures and a possibly selected focus ($F_{explicit}$) represent the input. At the beginning, the structures have an initial weight and, therefore, an importance of $w_s = 0$ and the selected focus a $w_{focus} \geq t_F$.

The first step identifies the focus structures (F). Each structure will be analyzed with respect to the question-specific parameters of Q_{meta}. Therefore, the structures will be compared to the parameter conditions (D_i (Q_{meta})), as explained in the example of Section 6.1. According to the structure's individual meta informations, the specific parameter weights are added to the structure's current importance (w_s). Thresholding enables the distinction of all focus structures (F). Structures with an importance $< t_F$ represent the input for the next step.

The second step categorizes focus-relevant (F_r) and context (C) structures. All non focus structures will be analyzed with respect to the question-specific parameters of Q_{geo} and Q_{pat}. Primarily, the assessment of risk structures is realized in this step. The set F is required to identify the relevant and context structures, since the parameter conditions D_i (Q_{geo}, Q_{pat}) refer to F. The structure's w_s of step one is the starting value for step two. Similar to the first step, the weight of each parameter will be added if the structure fulfills the corresponding condition. As shown in Figure 3, the sets F_r and C are categorized by thresholding t_{F_r} of the resulting w_s. The set C is arranged in order of importances. Therefore, when context structures are required for the visualization, the context structures can be illustrated by importance-driven techniques, too. This pipeline



(a) Where are the pathologic structures located?

(b) Which structures are within a critical distance to the tumor?

(c) Which veins are affected by the tumor resection?

Figure 4: *Question-specific 3D visualizations of neck, thorax, and liver for three surgical questions.(a) The pathologic structures are located. (b) Potential infiltrated structures (risk structures) are located and (c) veins required for the tumor resection are identified.*

enables an automatic structure categorization for each question. The structure's importance is determined according to the question-specific parameter configurations and weights. Thus, an adaptive structure selection is achieved.

6.3. Visualization

Since we concentrated on the appropriate selection of relevant structures, we basically used common surface rendering techniques to illustrate the results. Thus, the structures surface is colored and rendered opaque or semitransparent. However, our approach determines the individual structure's importance that is suitable for importance-driven visualization techniques e.g. the cutaway-views of Viola et al. [VKG05] or to define appropriate transfer functions for direct volume renderings.

7. Results and Discussion

Our method was applied to 10 neck-, four liver- and two thorax-datasets (containing up to 50 structures) which where categorized regarding 5 surgical questions. Three categorization results are illustrated in Figure 4. The time effort to generate the database, including all presented parameters (see Section 5), ranges from 2 to 25 minutes, depending on the complexity of the structures (system specifications: Intel Centrino2 processor - 3.2GHz, NVIDIA GeForce 9600, 1GB RAM). It takes $2-4$ minutes to generate the neck and thorax database. In contrast, the liver database generation takes around 20 minutes. The preprocessing time is directly related to the number of intersecting structures (e.g. vascular systems in the liver). Currently, the intersection and distance calculation is implemented in a basic manner. A more sophisticated approach (e.g. using spatial tree structures) can reduce the computation time. Due to its general characteristic, our conceptual approach can be easily extended to other fields of application and does not depend on a specific calculation of the necessary parameters. Since the database is build of matrices, additional parameters can be easily included as a new matrix. The preprocessing, including the segmentation process, takes $32-55$ minutes, supposed that the segmentation takes around 30 minutes. Question-specific 3D visualizations can be generated in real-time (< 3 seconds), since it is realized as a database query.

We presented a structure characterization and categorization to automatically generate question-specific 3D visualizations of patient individual datasets (see Figure 4). We explained the notion of surgical questions and its relevance for the surgical strategy. As a consequence, a set of 3D visualizations has to be created, which allows answering such questions step by step. However, our approach defines the currently important structures including the important parameter to create this 3D visualization. This result can be combined e.g. with the approach of Mühler and Preim [MP10], who developed a concept to create reusable anatomic 3D visualizations and animations. Furthermore, our approach is suitable for static geometric models. We do not consider deformable structures. 3D polygonal models of segmented structures are the major prerequisite for this approach to enable a categorization including the structure's geometric properties. Thus, the results depend on the segmentation. Each segmented structure can be categorized. If the segmentation results are a few huge connected structures e.g. the entire vein system of the liver as one structure, a more differentiated categorization of a single vein branch is not possible, as shown in Figure 4. Furthermore, structures that are not clearly identified either as anatomic or pathologic are classified as suspicious. Since those structures are treated as anatomic and as pathologic, we prevent a false structure categorization. The individual structures or structure types can be classified manually or in terms of individual defined classification rules. Thus, we offer the possibility to extent the database as well as the categorization algorithms by defining further rules or replacing the integrated algorithms by advanced techniques.

8. Conclusions

We presented an importance-driven structure categorization process for individual patient data. This categorization is the basic prerequisite for the generation of expressive 3D visualizations for tumor surgery planning. We analyzed common surgical questions to develop a categorization system that integrates domain knowledge, analyzes the patient-specific data and evaluates the current question. This enables an automatic selection of all currently relevant and required structures to answer the question. The individual structure's importance is dynamically calculated, and therefore, adapts to various questions, which enables a generation of question-specific 3D visualizations. Moreover, the determined importance values can be used to select an appropriate visual style for each structure. In clinical practice, the resulting 3D visualizations combined with the 2D CT or MRI slices and direct volume rendering represent a supportive computer assisted surgery planning system.

For future work, we aim at suitable visualization techniques that illustrate the individual structure's category to enhance the different importances. Furthermore, a well-defined set of question-specific 3D visualizations have to be defined and evaluated. Finally, workflows that bring the individual visualizations in a meaningful order would even better support the preoperative planning process.

Acknowledgment We thank Fraunhofer MEVIS for advanced MeVisLab features and Prof. Dr. Karl Oldhafer, Christoph Logge, Dr. Gero Strauß and Dr. Jörg Franke for providing datasets and fruitful discussions.

References

[BYV*08] BALABANIAN J.-P., YSTAD M., VIOLA I., LUNDERVOLD A., HAUSER H., GRÖLLER M. E.: Hierarchical volume visualization of brain anatomy. In *Proc. of VMV* (2008), pp. 313–322. 2

[HPP*95] HÖHNE K. H., PFLESSER B., POMMERT A., RIEMER M., SCHIEMANN T., SCHUBERT R., TIEDE U.: A new representation of knowledge concerning human anatomy and function. *Nature Medicine 1*, 6 (1995), 506–511. 2

[KHSI04] KIM S., HAGH-SHENAS H., INTERRANTE V.: Conveying shape with texture: experimental investigations of texture's effects on shape categorization judgments. *IEEE Transactions on Visualization and Computer Graphics 10*, 4 (2004), 471–483. 1

[MNTP07] MÜHLER K., NEUGEBAUER M., TIETJEN C., PREIM B.: Viewpoint selection for intervention planning. In *IEEE/Eurographics Symposium on Visualization* (2007), pp. 267–274. 6

[MP10] MÜHLER K., PREIM B.: Reusable visualizations and animations for surgery planning. In *Computer Graphics Forum (EuroVis)* (2010), p. to appear. 8

[PTSP02] PREIM B., TIETJEN C., SPINDLER W., PEITGEN H.-O.: Integration of measurement tools in medical visualizations. In *Proc. of VIS* (2002), pp. 21–28. 6

[RBG07] RAUTEK P., BRUCKNER S., GRÖLLER M. E.: Semantic layers for illustrative volume rendering. *IEEE Transactions on Visualization and Computer Graphics 13*, 6 (2007), 1336–1343. 2, 3

[RBG08] RAUTEK P., BRUCKNER S., GRÖLLER M. E.: Interaction-dependent semantics for illustrative volume rendering. *Computer Graphics Forum 27*, 3 (2008), 847–854. 3

[RSKK06] REZK SALAMA C., KELLER M., KOHLMANN P.: High-level user interfaces for transfer function design with semantics. *IEEE Transactions on Visualization and Computer Graphics 12*, 5 (2006), 1021–1028. 2, 3

[SES05] SVAKHINE N., EBERT D. S., STREDNEY D.: Illustration motifs for effective medical volume illustration. *IEEE Computer Graphics and Application 25*, 3 (2005), 31–39. 2

[TIP05] TIETJEN C., ISENBERG T., PREIM B.: Combining silhouettes, surface, and volume rendering for surgery education and planning. In *Eurographics / IEEE VGTC Symposium on Visualization* (2005), pp. 303–310. 4

[TPHS06] TIETJEN C., PREIM B., HERTEL I., STRAUSS G.: A software-assistant for pre-operative planning and visualization of neck dissections. In *Proc. of CURAC* (2006), pp. 176–177. 2

[VFSG06] VIOLA I., FEIXAS M., SBERT M., GRÖLLER M. E.: Importance-driven focus of attention. In *IEEE Transactions on Visualization and Computer Graphics* (2006), pp. 933–940. 1, 2

[VKG05] VIOLA I., KANITSAR A., GRÖLLER M. E.: Importance-driven feature enhancement in volume visualization. *IEEE Transactions on Visualization and Computer Graphics 11*, 4 (2005), 408–418. 2, 6, 8