Towards a Proposal for a Vessel Knowledge Representation Model

I. Macía[1,2], M. Graña[2], and C. Paloc[1]

[1] Vicomtech, Visual Communications Technologies Centre
`http://www.vicomtech.org`
[2] Grupo de Inteligencia Computacional, UPV/EHU
`http://www.ehu.es/ccwtinco`

Abstract. We propose the development of a knowledge representation model in the area of Blood Vessel analysis, whose need we feel for the future development of the field and for our own research efforts. It will allow easy reuse of software pieces through appropriate abstractions, facilitating the development of innovative methods, procedures and applications. In this paper we present some key ideas that will be fully developed elsewhere.

1 Introduction

The vessel structure of the blood circulatory system is one of the most complex structures of the body. Blood vessel anatomy has been studied from castings and in-vivo examinations in order to build models that provide valuable insight into the normal and variant circulatory anatomy, helping to understand the causes, evolution and outcome of several vascular-related diseases. However, many answers to simple questions about vascular morphology and angiogenesis remain open [9]. Recent advances on medical imaging provide high resolution images of the vessel structures, so that the generation of accurate patient-specific geometric *in-vivo* vessel models [1] and related quantitative measurements has become feasible. This has resulted in a wide range of new applications for computer-assisted diagnostic, intervention and follow-up of vascular-related diseases.

The diversity of medical and biological applications and the availability of huge amounts of high-quality information for vessel analysis has raised the problem of vascular knowledge representation in its full multi-faceted complexity . The purpose of this paper is to present some key ideas for the development of appropriate knowledge representation and manipulation tools for vessel structures which could serve as a common ground for the development of compatible and reusable systems. We motivate this study in the diversity of applications found in the literature, and in our actual research experience [7,5,8]. We aim towards a *Vessel Knowledge Representation* (VKR) model that, due to its efficiency and versatility, may be used for a wide variety of image-based vessel extraction schemes and vessel analysis applications.

The structure of the paper is as follows. In Section 1 we provide a review of the topics of interest related to the definition of the VKR model: knowledge

R. Setchi et al. (Eds.): KES 2010, Part IV, LNAI 6279, pp. 80–87, 2010.

on vascular morphology, vessel-related diseases, angiographic diagnosis, vessel extraction and analysis techniques from these images and corresponding applications. As a corolary, in Section 2 we describe the requirements for a Vessel Knowledge Representation model, whose description is sketched in Section 3. Finally we provide final conclusions (Section 4).

2 Requirements of the Vessel Knowledge Representation (VKR) Model

The VKR model is being defined through a process of identification and abstraction of structural, geometrical and morphological properties of vessels in the literature and in our own research experience. This leads to the identification of data structures, operations and components used in the most common models and schemes for vessel extraction. This model can then be converted into an appropriate data representation, such as a mesh surface model, a refined segmentation or a symbolic visual representation. When rendered, these representations can be used for localization and for interactive exploration of the VKR model and underlying properties in some of the applications described above. Alternatively, these derived data representations can also be used, for example, for numerical studies, such as simulations of haemodynamics, structural analysis or other medical and research applications out of the scope of this paper. The VKR model must include the geometry and topology of vessel trees with constituting branches, bifurcations and sections, as well as vascular accidents such as stenoses, aneurysms and abnormal regions, such as those feeding neighboring tumors. Models of these physical entities and related concepts used in vessel analysis applications must be devised and structured by using object-oriented design techniques.

We can make more precise some desired properties of our VKR model design:

- *Versatility*:
  - Modelling of low level entities, such as vessel centerlines or sections, without compromising higher level elements, such as the global graph-based model of the vessel tree and its traversal mechanisms.
  - Allowing several coexisting representations of the same vascular system, providing easy transformation among representations.
  - Decoupling algorithms from underlying data structures. Abstract mechanisms must be provided for accessing, traversing and manipulating the data.
- *Efficiency*: as data amounts are huge in this kind of applications, and time requirements are increasingly tight, efficiency in terms of computational time and use of resources is highly desired.
- *Utility*: to be useful the VKR must take into account actual design practices and constraints from:
  - The vessel extraction algorithms used for generating the vessel data structure from the angiographic image data.

  - A broad range of clinical and research applications that will be increasing in complexity and response time requirements.
- *Complexity Hierarchy*: the framework should be able to provide different levels of complexity and abstraction in order to represent the vessel structures at different levels. The structures need to be represented at least at the tree, branch and section level and at each level geometric, topological and semantic information layers need to be managed.
- *Integrability and Specificity*: the framework needs to be designed so it can be easily integrated into pre-existing frameworks which deal with certain specific models, processes and data structures efficiently, such as the *Insight Toolkit* [13], for medical image segmentation, registration and analysis and the *Visualization Toolkit* [10], for visualization of resulting vascular structures together with image data.

3 Model Description

The VKR model is the core of the diverse operations and functions related with vessel analysis techniques, as shown in the workflow diagram depicted in Figure 1. The boxes in this diagram correspond to data types of some kind, while the labeled arrows correspond to transformations or manipulations of the data. We have omitted the closed operations, such as branch pruning or image filtering. The VKR vessel representation can be obtained directly from the angiographic image or volume or indirectly from the results of an intermediate image segmentation process. In the latter case, the segmentation detects the image/volume regions corresponding to the vessels, from which the vessel representation can be obtained by skeletonization, to obtain the centerlines, followed by section or boundary estimation. Alternatively, a set of disconnected volume vessel regions can be obtained by a global detection process of vessel features, followed by pruning and/or reconnection of centerline patches. We include in the diagram obvious storage and retrieval operation of the VKR to/from a file or database. The VKR model is the natural domain to perform measurements which can be added to it as an enrichment.

By assigning symbolic graphical representations or *glyphs* (such as lines, spheres, cones or more complicated shapes...) to the underlying components of the VKR model, a symbolic visual representation of the vessel tree can be obtained. This may be used as a roadmap, for agile exploration and interaction, or may be directly overlaid or projected onto the angiographic images, slices, or volumes in order to provide visual cues.

The VKR model could be the basis to build up a surface mesh of the vessel boundaries by several techniques such as contour sweeping of the cross-sections or by an explicit or implicit surface model. The VKR model could also be used to generate a mask or ROI on the CTA/MRA volume for further processes. The VKR data could then be converted into a mesh surface by iso-surface reconstruction [6]. Generated surface meshes could then be used for direct visualization and navigation, possibly mixed with other symbolic, surface, volume or slice renderings, in a kind of Augmented Reality computational environment. In the same spirit, the identified and labeled branches can be mapped into the CTA/MRA volume or mesh surface, allowing increased interaction via direct structure picking. The mapping can go both ways, allowing the access to the VKR model from the visualization of the CTA/MRA volume, and visualization of CTA/MRA data corresponding to VKR selections.

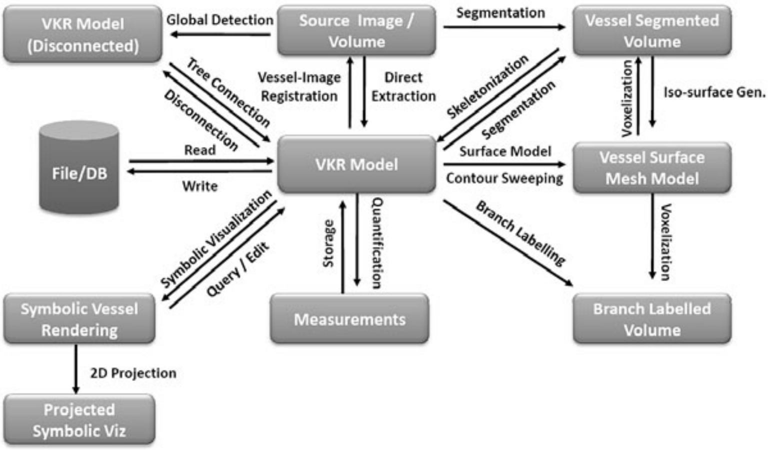

Fig. 1. VKR Workflow Diagram

3.1 Data Structures

Vessel Graph. In general, we can consider the vessel network as a binary tree structure since in most cases bifurcations split a branch into two [4], with some exceptions like the Circle of Willis in the brain [11]. Therefore, a graph representation is the natural choice for the structural representation in the VKR. A graph typically consists of nodes, representing the modelled concepts, and edges, that connect the nodes and represent their relationships, which is in terms of parent/child for tree structured graphs. In our case, a *Vessel Node* represents an abstraction of an element used for vessel representation and analysis at graph level. Such an element may be a vessel branch, bifurcation or vessel accident, among others. Anatomical vessel branches are modelled as nodes (*Branch Node*) and if we need to assign properties to the bifurcations, we can also explicitly model them (*Bifurcation Node*). In order to provide more modelling flexibility, we define also *Composite* nodes, which make use of the *Composite Pattern* [3] in order to group nodes. This way the group of nodes acts as a single entity, hiding their internal relationships and offering the possibility of building a hierarchy of several levels of abstraction complexity in the graph.

Vessel Branch. A virtual vessel branch is represented in VKR by a *BranchNode,* and it corresponds to the vessel segment that extends between consecutive bifurcations. A physical vessel branch may also be represented by several concatenated *BranchNode* instances. This would be useful when the user wants to make a difference between different parts along the length of a physical branch, for example by indicating that part of a branch is stenosed. This is performed by associating corresponding accident node representations, such as the *Stenosis Model*, to the *Branch Node*. The core of a vessel branch in our model is the *Centerline Model*.

Centerline Model. The vessel centerline or medial loci [2] is an important part of our model, since it is a good descriptor of elongated objects. Compared to other descriptors, such as boundary descriptors, the centerline captures better the vessel shape and provides a straightforward way of obtaining the relationships between the different branches of the vessel tree [12], since the centerline can be easily converted into a graph structure. Furthermore, it serves as a reference for calculating and storing local properties, both inside and on the boundaries of vessels. For example, the vessel length is measured along the centerlines and diameters are measured over sections whose center is the centerline. Therefore, we aim to provide an explicit, yet flexible and agile, representation of the centerline.

Section Model. *Vessel Sections* are localized at centerline points and they are assumed to vary along the vessel length. This variability is reflected in the parameters that define the section, for example, the diameter. Vessel sections, like centerlines, can also be defined at increasing levels of complexity. The simplest level is to define the section as a circle, giving its center and radius/diameter. Since our sections are defined at explicit centerline points, the center is already given. The next level of complexity is an elliptical shape. More advanced mathematical models include radial functions and B-spline contours.

3D Surface and Voxel Models of Vessels. So far we have dealt with explicit modelling of cross-sections. Another possibility, when dealing with 3D image data, is to directly generate a 3D surface mesh from the centerline. If the 3D mesh is generated for the complete vessel tree, it can be referred to branches or even to centerline points (and thus to sections) of the VKR model by proximity to the corresponding centerline. This reference can be direct, by splitting the model into surface patches and keeping references to them, or indirect, simply by associating a scalar value, acting as identifier, to the mesh points that corresponds to referred branches. This way a forth-and-back relationship may be kept between the VKR and surface models. Explicit sections may also be obtained by intersection with corresponding section planes.

If a segmentation is available, obtained either *a priori* or from the VKR model, it can be referred to corresponding branches by just labelling the mask pixels/voxels with corresponding branch identifiers. In this case, keeping references to separate volume "patches" seems to be more difficult to handle but it is a possibility that could be useful in cases where the source angiographic volumes are huge. The reason is that, in most software frameworks, only arrays corresponding to rectilinear volumes can be stored, and for sparse structures such as the vessels, sometimes many of these voxels are empty. Another possibility is to store these labelled voxels as sparse images, which is currently not implemented.

Vessel Bifurcations. Bifurcations may be represented explicitly in the VKR model by means of the *BifurcationNode* object that defined at graph level. The use of this node type would be optional, and may be required when we want to model special features of the bifurcation, when (quantification) operations need to be assigned to the bifurcation, such as estimation of branch angles, and when there may exist more than one parent branch.

Vessel Features. In the VKR model, vessel "features" (*Feature Node*) represent special characteristics of the vessels that need to be highlighted. Their definition may include models for vessel accidents or simply comments used for diagnostic. A feature may affect or may be associated to a part of a branch, a whole branch or a set of branches, entirely or partially. In order to make explicit these relationships, two mechanisms are devised:

1. *FeaturesNodes* are assigned as children (or alternatively as parents) of affected *Branch Nodes.*
2. *FeatureNodes* keep a *Vessel Region* structure that indicates which vessel branches are affected and to which extent. This is achieved by keeping a set of *Vessel Branch* node identifiers, and for each identifier, the starting and end indexes of the points in corresponding centerlines that comprise the area affected by the feature.

Since a feature may affect more than one branch, *Feature Nodes* are treated in a special manner and are not even visited when performing many operations that require traversal of the graph. In this sense, FeatureNodes can be treated as "hypernodes" and their relationship with *Vessel Branch* nodes (or possibly other nodes) is not that of a parent-child relationship but merely a reference.

An example of use of a *Feature Node* is to perform an annotation, such as a diagnostic remark in a application for computer aided vascular diagnosis. The clinician would choose the branches affected by a given feature, for example, those feeding a tumor or included on it, and assign them the corresponding nodes comment.

Models of Vessel Accidents or Disease. The VKR model offers the possibility of providing representation models for vessel accident or disease. Examples of these models are the *Stenosis Model* and *Aneurysm Model.* These models contain the quantitative morphological measurements and other properties that are typical of a given vessel accident or related disease. We aim to provide flexibility for defining application-specific models of this kind.

3.2 Supported Operations

Operations that can be performed on the VKR model data structures can be classified by their nature or by the type of object they operate on. For example, quantification operations can be performed at graph, branch, centerline or section level, among others. Based on their nature we distinguish the following types:

- *Access Operations*: these are abstract access mechanisms that allows to perform other types of operations. For example, graph traversal is an operation that allows to access nodes on the vessel graph and perform other operations on them.
- *Edition Operations*: allows to change the internal structure and properties of the model.
- *Quantification Operations*: evaluation of quantitative measurements over different elements of the model.
- *Input/Output Operations*: used to load and save the model data.
- *Data Transformation Operations*: include generation of the VKR model and transformation into another representation that can be useful for intended applications.
- *Model-specific Operations*: these are internal operations that are specific to certain elements of the model, such as the centerlines or sections.

4 Conclusions

The applications and techniques of Blood Vessel Analysis have produced a complex landscape of algorithms and data representations that hinders the composition of procedures, the reuse of software and the comparative analysis in terms of computational efficiency and quality of final results (visualization, measurement, edition, and others). We have detected the need of proposing a foundational Vessel Knowledge Representation (VKR) model that may allow the exchange of data among applications and users. One of the goals of VKR is the reuse of software pieces, providing a ground functional layer that may serve as the basis for new developments, thus alleviating development efforts. The model is intended to be used as an intermediate representation between image-based extraction schemes and clinical and research applications, to perform quantitative measurements on extracted vessel structures and to provide the necessary vessel representation and handling tools for the target applications. In this paper we have identified, from the literature and our own research work, some key knowledge representation items, as well as the key operations that are the building blocks for nowadays and future vessel analysis processes and applications. We are already applying the VKR model in vessel-related applications related to our current research areas.

References

1. Antiga, L., Ene-Iordache, B., Remuzzi, A.: Computational geometry for patient-specific reconstruction and meshing of blood vessels from mr and ct angiography. IEEE Transactions on Medical Imaging 22(5), 674–684 (2003)
2. Blum, H.: A transformation for extracting new descriptors of shape. In: Wathen-Dunn, W. (ed.) Models for the Perception of Speech and Visual Form, pp. 362–380. MIT Press, Cambridge (1967)
3. Gamma, E., Helm, R., Johnson, R., Vlissides, J.: Design Patterns: Elements of Reusable Object-Oriented Software. Addison-Wesley, Reading (2000)
4. Huang, W., Yen, R.T., McLaurine, M., Bledsoe, G.: Morphometry of the human pulmonary vasculature. Journal of Applied Physiology 81, 2123–2133 (1996)
5. Legarreta, J.H., Boto, F., Macía, I., Maiora, J., García, G., Paloc, C., Graña, M., de Blas, M.: Hybrid decision support system for endovascular aortic aneurism repair follow-up. In: Graña Romay, M., Corchado, E., Garcia Sebastian, M.T. (eds.) Hybrid Artificial Intelligence Systems. LNCS, vol. 6076, pp. 500–507. Springer, Heidelberg (2010)
6. Lorensen, W.E., Cline, H.E.: Marching cubes: A high resolution 3d surface construction algorithm. Computer Graphics 21(4), 163–169 (1987)
7. Macía, I., Graña, M., Paloc, C., Boto, F.: Neural network-based detection of type ii endoleaks in cta images after endovascular repair. Int. J. of Neural Systems (submited 2010)
8. Maiora, J., García, G., Macía, I., Legarreta, J.H., Paloc, C., de Blas, M., Graña, M.: Thrombus change detection after endovascular abdominal aortic aneurysm repair. In: Proc. of Computer Assisted Radiology and Surgery, CARS 2010 (2010) (in Press)
9. Santamore, W.P., Bove, A.A.: Why arteries are the size they are. Journal of Applied Physiology 104, 1259 (2008)
10. Schroeder, W., Martin, K., Lorensen, B.: The Visualization Toolkit: An Object-Oriented Approach to 3D Graphics, 4th edn., Kitware (2006)
11. Schwarz, M., Nguyen, M.P., Kiencke, U., Heilmann, C., Klemm, R., Benk, C., Beyersdorf, F., Busch, H.J.: Integration of the circle of willis into avolio's model of the arterial hemodynamics. In: 6th IASTED Int. Conf. on Biomedical Engineering (2008)
12. Siddiqi, K., Pizer, S.: Medial Representations: Mathematics, Algorithms and Applications. Springer, Heidelberg (2008), ISBN 978-1402086571
13. Yoo, T.S., Ackerman, M.J., Lorensen, W.E., Schroeder, W., Chalana, V., Aylward, S., Metaxas, D., Whitaker, R.: Engineering and algorithm design for an image processing api: a technical report on itk - the insight toolkit. Stud. Health. Technol. Inform. 85, 586–592 (2002)