Optimization of Vascular Surface Models for Computational Fluid Dynamics and Rapid Prototyping

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ABSTRACT

The generation of surface models for computational fluid dynamics and rapid prototyping implies several steps to remove artifacts caused by image acquisition, segmentation, and mesh extraction. Moreover, specific requirements, such as minimum diameters and distances to neighboring structures are essential for rapid prototyping. For the simulation of blood flow, model accuracy and mesh quality are important. Medical expert knowledge is often required to reliably differentiate artifacts and pathological malformations. Currently, a number of software tools needs to be employed to manually solve the different artifact removal and mesh editing tasks. Within this paper, we identify the related tasks and describe the procedure, which is used to receive artifact-free vascular surface models for these applications.

Categories and Subject Descriptors

I.3.5 [**Computer Graphics**]: Computational Geometry and Object Modeling—*Curve, surface, solid, and object representations*

Keywords

Model Generation, CFD, Simulation, Rapid Prototyping, Optimization, Reconstruction

1. INTRODUCTION

Vascular diseases, such as the coronary heart disease or cerebral and abdominal aneurysms are severe, often life-threatening diseases. Initiation and progress of these diseases are not fully understood. Many research projects clearly show, that diseases primarily occur at regions of complex and instable blood flow. This gives rise to blood flow simulations of specific patient data and eventually also including implants to predict treatment effects. Such simulations are based on many assumptions. Experimental validation based on a large variety of physical phantoms is essential to investigate the reliability of such simulations. Applications, such as rapid prototyping (RP) or computational fluid dynamics (CFD) for blood flow simulation require faithfully reconstructed surface models as input (see Fig. 1).

Vascular surface models are generated from tomographic medical image data (e.g., computed tomography (CT) or magnetic resonance imaging (MRI)). Depending on the employed segmentation and mesh generation methods, an initial vascular surface model may contain several artifacts. The causes of these artifacts are various: During image acquisition, low resolution, partial volume, and beam hardening effects as well as inhomogeneous or insufficient contrast agent distribution disturb the representation of the vessel lumen. As a consequence, vessels might occur locally narrowed or interrupted. Furthermore, beam hardening can cause small vessels to visually blend with closely located, bigger, high contrast vessels. These artifacts vary to a certain degree, e.g., such that adjacent or outgoing vessels are represented as high frequency noise on the surface of a bigger vessel. Other artifacts, like staircases, may occur during mesh generation. Thus, e.g., noise, staircases, blended vessels, or abruptly changing vessel diameters need to be removed faithfully.

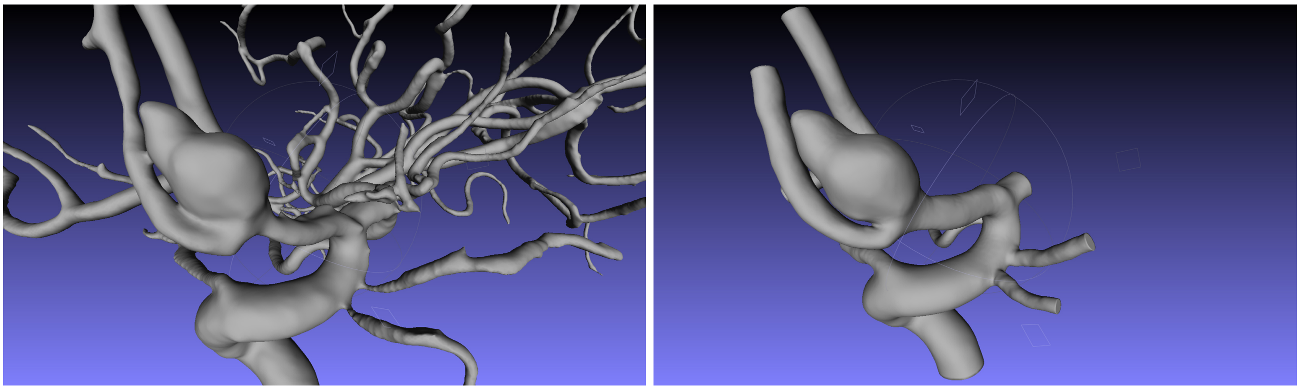
These tasks are, considered separately, not very complicated and can often be handled with specific tools and algorithms. However, the overall process to achieve appropriate models for CFD or RP requires a lot of manual effort in different software tools. This, however, may alter patient-specific properties of the target structure. Thus, medical experts need to be involved to validate the intermediate model adjustments as well as the final surface model. In this paper, we identify the problems and tasks occurring during generation of vascular surface models in the different steps of the model generation pipeline. Furthermore, we discuss current solutions, which involve multiple software tools to overcome the model generation difficulties.

2. PRIOR AND RELATED WORK

Surface models are usually derived from tomographic image data, acquired via MRI or CT. For vascular structures, special acquisition techniques (e.g., magnetic resonance angiography (MRA), computed tomography angiography (CTA), rotation angiography, time-of-flight MR angiography) are employed to receive a high contrast to the surrounding tissue. This eases a direct mesh extraction from the intensity data, but may still yield several artifacts in the resulting surface meshes.

2.1 Generation of Medical Surface Models

By employing manually, semi-automatic (e.g., thresholding, region-growing, ...), or fully automated segmentation methods (e.g., [7]), the target structures can be delineated and finally transformed into a surface mesh via, e.g., Marching Cubes (MC) algorithm [19], or level-set methods [31]. Specialized vessel surface reconstruction methods, such as MPU implicits [27, 28] or Convolution Surfaces [23], are available. Convolution Surfaces, however, are model-based



(a) (b)

Figure 1: (a) Example of an initial vascular surface model with an aneurysm and several artifacts at the branches. (b) Result of the complex model generation and artifact correction pipeline.

and require a vessel skeleton and diameter as input. Thus, they are not suitable to represent pathological vascular structure, such as aneurysms. In contrast, MPU implicits can be used to describe vessels with pathological deviations but use point clouds from binary segmentation masks as input. The intensity information of the original image data is ignored, which makes MPU implicits less accurate and partially sensitive to artifacts from image inhomogeneities. Similarly, Wu et al. [32] employ point clouds from binary masks for generating a 3d implicit indicator function, which is subsequently used as input for polygonization. Such specialized model generation methods for vascular structures may help to reduce some artifacts, as they guarantee a certain smoothness and vascular shape regarding the vessel profile, but also at branching points. Some issues, such as incomplete contrast agent dispersal or touching vessels, may also not be removed.
There are several specific methods available, e.g., that detect features and adjust sampling of the data [17], that apply an additional trilinear interpolation and subdivision to the surface elements (Precise MC [1]), or that relax an initial surface iteratively with additional position constraints (e.g., Dual MC [22], Constrained Elastic Surface Nets (CESN) [9, 14]). These methods are, however, only specific solutions, especially to the staircase problem, but can not remove all potential artifacts.

2.2 Artifact Reduction

The usage of segmentation masks for mesh generation yields strong staircase and terracing artifacts [6, 21], especially for image data with anisotropic voxel dimensions. By applying segmentation masks to the intensity data to remove irrelevant neighboring structures, local staircases may emerge. For the reduction of staircases, several methods are available, which, e.g., interpolate intermediate slices via shape-based interpolation [25] or apply smoothing filters on the mesh level (e.g., Laplace, Laplace+HC [30], LowPass [29], Mean Curvature Flow [13] filtering). Even local staircases can be removed systematically [20]. Especially vascular surface models may contain artifacts occurring, e.g., from incomplete contrast agent dispersal resulting in local narrowing or frayed parts. Moreover, beam hardening artifacts and closely located vessels may yield unwanted blending of separated structures (see Fig. 5) [20]. Such artifacts are usually not treated for pure visualization tasks. Thus, there are no specialized methods available to remove, e.g., blending artifacts or narrowed vessels faithfully.
The Vascular Modeling Toolkit (VMTK) [2, 3, 24] is a framework for the reconstruction and geometric analysis of vascular structures. However, methods for systematic removal of specific artifacts are not included. To receive an appropriate surface mesh for CFD or RP, several tools and expert feedback need to be employed (see Fig. 1) to manually remove artifacts.

2.3 Application in CFD and Rapid Prototyping

For the patient-specific simulation of blood flow, further requirements, such as mesh resolution and triangle quality play an important role [11, 12]. The shape of the mesh's triangles is required to be almost equilateral and homogeneous over the mesh, since the surface models are used as input for volume mesh generation. Thus, triangle quality and size influence convergence and accuracy of the simulation computations. An optimization can be achieved, e.g., by employing an advanced front remeshing algorithm [26]. The surface generation method by Wu et al. [32] does also take care of mesh quality during polygonization of their implicit function, which may reduce the number of steps to be taken within the model generation pipeline. Augsburger et al. [5] have shown, that the mesh extraction procedure may yield strongly varying simulation results depending on the involved segmentation and artifact reduction methods. Similarly, Cebral and Löhner [10] describe the strong dependence of blood flow characteristics on the vessel geometry.
RP is employed for different applications, such as treatment planning, simulation, measurement tasks, or even teaching of interventional techniques. Knox et al. [16] presented several examples of RP applied to pathological vascular structures for such purposes. Available literature, however, focuses more on the fabrication process [18, 4] than surface model generation. Thus, requirements for generating surface models are rarely specified.
The above mentioned artifacts and tasks are well-known. There are several methods available to account for individual

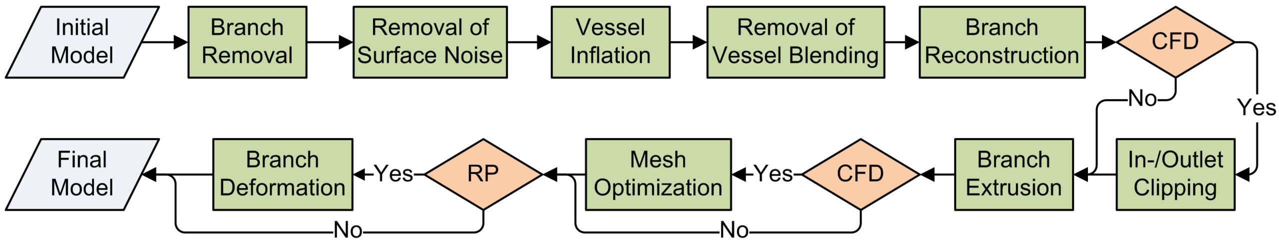


Figure 2: The employed surface optimization pipeline.

artifacts, but, in several cases, only medical experts can distinguish between an artifact and a pathology. There exists, however, no unified solution that allows users to generate an artifact-free surface model for the desired application.

3. SURFACE OPTIMIZATION PIPELINE

The reduction and removal of artifacts within the model generation procedure for CFD or RP raises several tasks. We will discuss the individual tasks for exemplary data of a cerebral aneurysm, acquired via CT angiography. The initial surface model has been extracted after thresholding of the contrast-enhanced image data via MC. Subsequently, after applying a connected component analysis, we receive the initial surface model of the target vessel with all connected vessel branches and several artifacts. In order to identify all artifacts reliably and distinguish them from real anatomical malformations, an expert-driven, iterative manual optimization process is necessary. Additional steps are required to make the vascular surface model suitable for application in CFD and RP.

3.1 Requirements

The generation of vascular surface models for visualization has extensively been studied, even under consideration of model assumptions. The requirements of pure visualization tasks, however, differ from those of CFD and RP. The simulation of blood flow in CFD primarily requires accuracy and quality of the surface (smoothness, triangle quality). To achieve reliable simulation results, even small surface artifacts need to be removed and size and shape of the mesh triangles usually need to be improved. Mesh generation for CFD has also been done extensively, in particular regarding mesh triangle quality and mesh size. However, no typical artifacts have been considered.

Physical vessel models created by RP can be used for various tasks, from teaching to treatment planning. A major application is to build phantoms. For instance, inverse transparent silicon models are used to experimentally simulate blood flow. Optical velocimetry methods are applied to gain information about the complex flow patterns within the different vessel configurations [8]. A surface reconstruction of the vessel serves as input for most of the RP techniques. However, some of the surface features cannot be physically reproduced due to procedural- and material-related constraints.

First, a mold needs to be constructed and subsequently be filled with a low melting material. The resulting cast is enclosed by silicon and finally the cast is removed from the resulting silicon block by melting it. Depending on the specific material, the final inverse silicon model and all intermediates of this process can represent surface details only to a certain degree. Additionally, it must be ensured that the mold can be opened without destroying the cast. In turn, it must be possible to remove the cast, without melted parts remaining in the silicon block. Thus, in order to reconstruct a physical model from the reconstructed surface, it must satisfy certain constraints, e.g., adequate distances between adjacent surface parts, no strong bending angles of vessels and the possibility to define a more or less planar cutting plane through the whole vessel reconstruction. Therefore, in some cases, it is necessary to deviate from the patient-specific vessel representation and to perform local adaptions. These adaptions, however, need to be performed carefully to ensure that the results are plausible from a medical point of view. Otherwise, the results of phantom tests and measurements might be useless. This delicate task needs to be performed with the help of an expert, in an iterative process balancing between anatomical correctness and producibility of the physical model.

These requirements lead to the following pipeline (see Fig. 2): starting with a mesh of the vascular tree and the aneurysm, unnecessary distant vessel branches or branches that are - in terms of flow direction - located behind the aneurysm, are removed. Subsequently, vessel blending artifacts, underestimated vessel diameters and surface noise are corrected. If necessary, insufficiently represented branches that are necessary for CFD or RP are reconstructed. After faithfully reconstructing the vessel surface, optimization for CFD and RP has to be performed. In-/outlets need to be cut perpendicular to the vessel centerline. In some cases, the in-/outlets have to be elongated artificially. The mesh quality has to be improved by employing a remeshing algorithm. After this procedure, the model is suitable for CFD.

For usage as RP input, the model may need to be altered, e.g., if surfaces are too close, if the vessel bending is too strong, or if it is not possible to apply a more or less planar cut through the complete model. These alterations are done by locally changing vessel diameters or bending vessels.

Details of each step are presented in the following sections, where we focus on artifact reduction purely on the mesh level. Alternatively, artifacts could be reduced by modifying the segmentation mask and the image data, which, however, may be more complicated and might introduce further artifacts [20].

3.2 Removing Branches

In CFD, each additional branch with in-/outlets increases computational effort. Thus, branches that do not directly affect the blood flow behavior in the target area (e.g., the aneurysm), need to be removed. Currently, branch removal is achieved by a combination of different software tools. At first, the vessel is clipped with 3d modeling software (e.g.,

BLENDER[1] or 3D STUDIO MAX[2]). Such 3d modeling software usually provides a large set of tools to modify 3d models. However, to remove the branch, a clipping geometry (e.g., a cube, a plane, ...) needs to be specified. After adjusting position and orientation of the clipping geometry, Boolean operations are applied to remove the negligible branches, resulting in a slight, flat bump on the main vessel and a closed surface.
Afterwards, this bump can be reduced by using SCULPTRIS[3] to iteratively and locally smooth the surface (see Sec. 3.3). Alternatively, branch removal can be performed in a more offensive way by cutting the thin vessel directly at the branching point on the larger main vessel. Cutting out this branching area leaves a hole in the main vessel which needs to be closed afterwards. This is again achieved via BLENDER. Depending on the size and profile of the cutting area, the closed hole may be subject to manual local deformation via SCULPTRIS.

3.3 Noise and Bump Removal

After initial mesh extraction and branch removal, the surface may contain vessel rudiments (see Fig. 3(a)) due to incomplete contrast agent dispersal or beam hardening. A possible solution are smoothing filters. However, typical uniform smoothing will cause strong volume shrinkage of the whole model and removes relevant details. Especially for vascular structures, locally adaptive filters are necessary, to focus smoothing to the artifact areas only. Since the artifacts being target for smoothing operations may vary in their shape and size, an automated approach detecting the artifacts reliably is very complicated. Thus, the most useful solution is an interactive approach where the user brushes over the artifact area. During brushing, all vertices in a defined neighborhood (topological or Euclidean distance) are smoothed appropriately. To achieve this, we employed SCULPTRIS, which provides several mesh brushing tools for dilation, extrusion and smoothing of surface meshes. For removal of bumps, the local smoothing operator can be used, which is parametrized by the operator size and strength.

3.4 Vessel Inflation

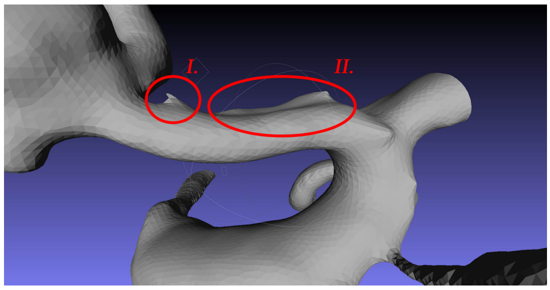
Locally narrowed vessels (see Fig. 4(a)) need to be adjusted for two reasons:

1. The geometry of the structure is incorrect and may thus yield wrong conclusions during visual inspection or during exploration of resulting RP models.

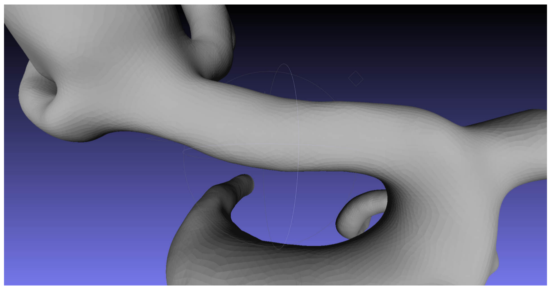
2. For usage in CFD, non-converging simulations or wrong simulation results have to be expected for, e.g., wall-shear-stress and flow velocity, but also vortices may occur which, altogether, may influence the flow behavior within the whole model.

To resolve this, the vessel needs to be inflated locally (see Fig. 4(b)). The artifact areas can basically be detected automatically by generating the vessel centerlines and comparing the behavior of vessel diameters along the centerlines. This implies a circular vessel shape, which must not be true in all cases. Vessels can be slightly flattened due to pressure

[1]http://www.blender.org/
[2]http://usa.autodesk.com/3ds-max/
[3]http://www.sculptris.com/

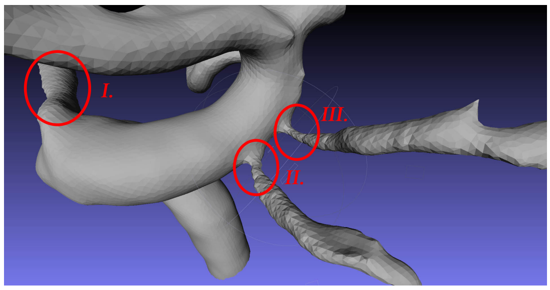


(a)

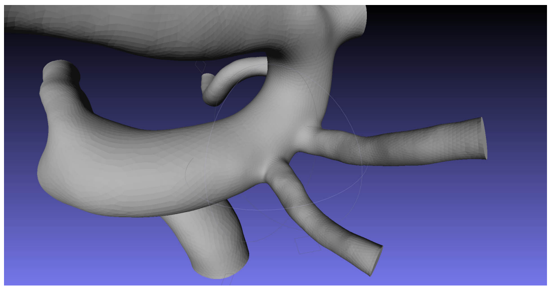


(b)

Figure 3: Example of rudimentary vessel branches and slight vessel blending (see Labels I. and II.) (a) before and (b) after local smoothing. Screenshots of MeshLab.



(a)



(b)

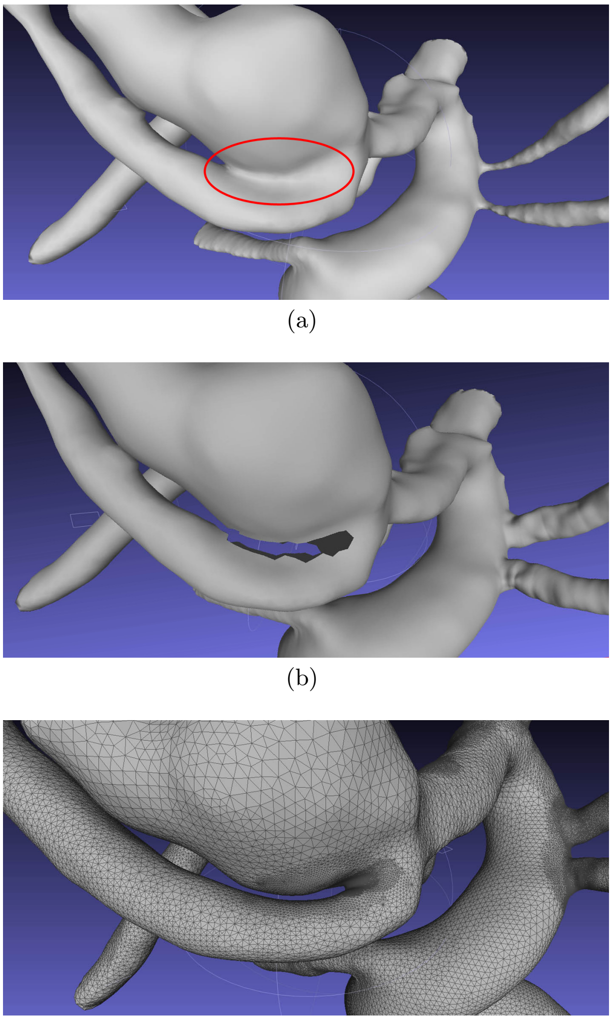
Figure 4: (a) Thin, anatomically incorrect vessel branches (see Labels I., II., and III.). (b) The vessels after local inflation and branch clipping. Screenshots of MeshLab.

from surrounding structures or they may contain pathological variations. Thus, an automated procedure may be error-prone, but could be used to support the user to identify these areas faster. After identification of possibly narrowed vessels, it is essential to refer to the image data again to validate the narrowing before further correction.
The narrowing artifact can again be corrected by using SCULPTRIS with a combination of the provided "Inflate" and "Smooth" tools. For both tools, operator size and strength need to be adjusted to fit to the size and diameter of the target vessel.

3.5 Removal of Vessel Blending

Vessel blending artifacts (see Fig. 5(a)) may arise locally restricted at touching vessels, but also very expanded, if a vessel passes another vessel over a long range. In particular, the latter is a critical situation, since the involved vessels are visually hard to distinguish and thus hard to divide faithfully.
The separation of blended structures is a complex problem whose specific solution depends on the data and the extent and shape of the artifact. Once more, 3d modeling software is employed to perform the mesh editing tasks. Via BLENDER, the mesh can be cut along the desired path to split the blended vessels. This process may be tedious, since the cutting path can be complex and needs to be drawn precisely on all sides of the artifact (see Fig. 5(b)). Especially finding an appropriate alignment of the cuts on the front and back side may be very complicated. Since the resulting hole needs to be closed, we added support triangles manually. The support triangles are added at critical points, where the "shape" of the hole changes significantly. By adding those triangles, the hole may be divided into several less complex parts, which eases final hole filling. Hole filling is done via MESHLAB[4], which detects and closes the holes automatically. For complex artifact shapes, this cutting and hole filling procedure may not be efficient anymore. As an alternative, we perform a stamping-like procedure in BLENDER, where we generate a stamping geometry (e.g., a cylinder or cuboid), which is then aligned with the artifact. This gives, however, a good preview of the resulting holes in the target model. After correct placement and slight adjustment of the stamping geometry, the artifact is cut using constructive solid geometry (CSG). CSG employs Boolean operations and yields correctly closed surface meshes. Depending on the artifact shape, this needs to be repeated several times but does still save a lot of effort, since the manual specification/drawing of support triangles and subsequent hole filling can be neglected.
After applying one of the above described artifact removal operations, local adjustments via SCULPTRIS may still be necessary. As a prerequisite for usage in SCULPTRIS, local remeshing and subdivision may be necessary (e.g., via BLENDER). Applying local, interactive smoothing or inflation, the artificial vessel surface is modified to achieve a plausible vessel shape and profile. Furthermore, for usage in RP, the distance between the separated vessels needs to be considered to prevent an anew blending during physical model building (see Sec. 3.10).

[4]http://meshlab.sourceforge.net/



(a) (b) (c)

Figure 5: Example of vessel blending and removal of the artifact. (a) Initial model with blending artifacts, (b) after manual cutting, and (c) after hole filling and smoothing. Screenshot of MeshLab.

3.6 Branch Reconstruction

Incomplete contrast agent dispersal and segmentation may also yield detached vessels. If such detached parts are essential for further evaluation of, e.g., the flow behavior, they need to be reconstructed to allow for a faithful virtual representation of the specific patient anatomy. The reconstruction of single branches requires a lot of manual effort, since two vessel rudiments need to be reconnected and thus be modified manually. For each vessel rudiment, cutting operations (and possibly local deformations) are necessary in order to reconstruct a valid vessel profile. These open vessel profiles may then be connected in different ways:

1. They may be extruded until they match each other, whereas it is unlikely that both endings will perfectly match after a linear extrusion and extremely stretched triangles may occur (see also Sec. 3.8). Thus, a plausible deformation (see Sec. 3.10) and local remeshing are also required to approximate a vessel geometry.

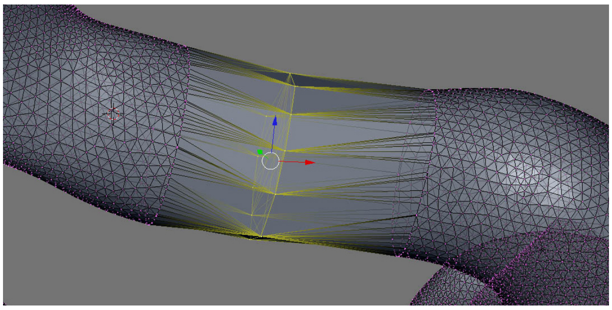


Figure 6: Screenshot of Blender during reconstruction of a formerly disconnected vessel branch.

2. Both open vessel rudiments may be connected via an artificial vessel geometry, e.g., a tube. The endings of the tube have to be fitted to the open vessel profiles and their vertices require correct merging. Again, the tube needs to be deformed to fit the centerline of the real vessel geometry.

We employ BLENDER to perform these operations (see Fig. 6). The procedure involves a lot of interaction to select the correct vertices and to drag them towards their new position. Along the newly reconstructed vessel geometry, the centerline needs to be adjusted to plausibly fit into the centerlines of the former vessel rudiments. At this point, an automated procedure could support the user by interpolating the new vessel centerline. This would allow to extrude the vessel rudiments without necessity of subsequent deformation. For the tube geometry approach, the centerline of the tube could be fitted along the interpolated vessel centerline automatically. Besides a deformation along the vessel centerline, slight deformations of the vessel profile may also be necessary, e.g., if the connected real vessel geometry does not exhibit a perfect circular shape. For that, again, SCULPTRIS can easily be used by using the provided brushing tools for inflation, deflation, and smoothing.
As a last step, the vertices at the "touching" open vessel profiles need to be merged for a correct triangulation. Currently, this is also done manually in BLENDER.

3.7 In-/Outlet Clipping

For application in CFD, in-/outlets need to be specified (see Fig. 4(b) and 8(c)) to define inflow and outflow behavior. Similar to branch removal in Section 3.2, we use the 3d modeling software BLENDER for generating in-/outlets. We create a clipping geometry and adjust its location and orientation iteratively according to the vessel centerline (see Fig. 8(b)). This process has to be repeated several times for all contained vessel branches. Finally, Boolean operations are performed to clip the vessel perpendicular to the centerline (see Fig.8(c)). It has to be ensured that clipping yields a closed surface mesh.
User interaction could be supported by an automated alignment of clipping volumes perpendicular to the centerline, where the user only needs to drag each clipping volume along the centerline. Such functionality is, however, typically not contained in the available 3d modeling software.

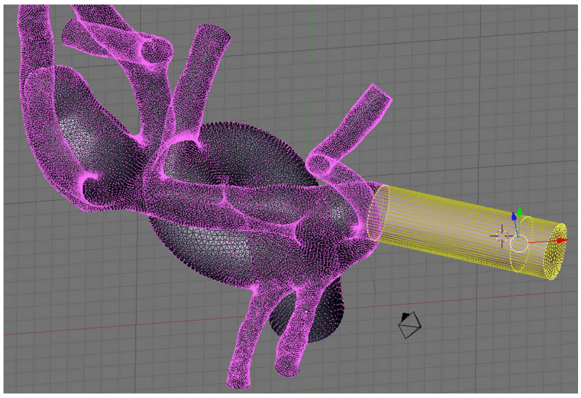


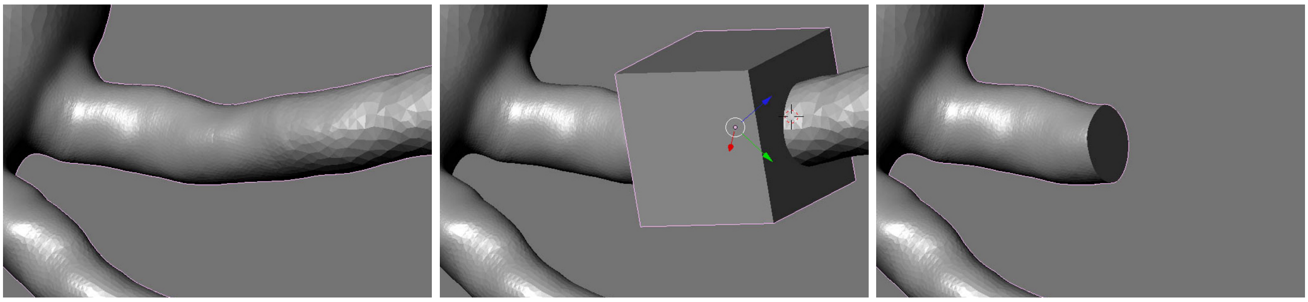
Figure 7: The in-/outlet area is selected and extruded to fit the requirements of CFD for a minimum vessel length at the in-/outflow areas. Screenshot of Blender.

3.8 Branch Extrusion

For CFD, the in-/outlets require a minimum length of the adjacent vessel. The inflow and outflow areas may not be directly adjacent to bent vessel parts to achieve more stability during simulation. This task is currently solved via BLENDER. The surface mesh needs to be edited manually by selecting the in-/outlet area of the vessel and subsequently extruding it (see Fig. 7). This procedure involves a lot of manual effort but could be supported algorithmically, if centerline information is involved. Thus, the user might only drag the in-/outlet along the (automatically extrapolated) centerline or its own average surface normal. During this elongation operation, it is, however, not sufficient to simply move the vertices of the in-/outlet areas, since this will result in extremely stretched triangles along the vessel surface. For the resulting tubular structure, local remeshing is required to guarantee similar mesh properties compared to the initial surface model.
Besides CFD, RP may also require branch extrusion. This requirement arises from the phantom building procedure, where a mold is created and needs to be filled. Thus, the vessel extrusion is used as casting channel. In such a case, the extrusion may not match further anatomical requirements.

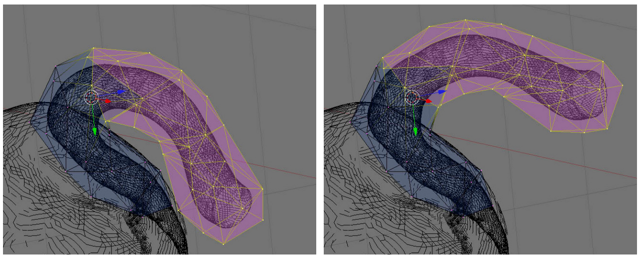
3.9 Mesh Optimization

For application in CFD, high mesh quality in terms of a good triangle edge ratio and homogeneous triangle size need to be ensured for stability and convergence of the simulation computations. To remesh the modified surface model, we employ NETGEN [26]. First of all, feature edges, which have to be preserved during remeshing, need to be detected and highlighted. This is essential for the feature edges at the earlier specified in-/outlets. Feature detection is performed semi-automatically by adjusting two parameters until the visual result (edge highlighting) fits the user's requirements. After user interaction and specification of the desired mesh granularity, NETGEN automatically proceeds with an advancing front algorithm. As a result, the complete surface model has been remeshed, whereas the feature edges at the in-/outlets are have been maintained.



(a) (b) (c)

Figure 8: Generation of an in-/outlet: (a) Initial branch; (b) Vessel with clipping box; (c) Result after clipping and removal of the separated part. Screenshot of Blender.



(a) (b)

Figure 9: Example of vessel branch deformation via hull volumes. (a) Before deformation and (b) after deformation. Screenshots of Blender.

After performing the tasks described in the previous sections, the surface model is ready for subsequent generation of a volume mesh required for CFD.

3.10 Branch Deformation

Usually, the most important requirement during surface model generation is *accuracy*. Especially for usage in surgical planning, radiation treatment or CFD simulation it is prohibited to alter the shape of the target structure. In contrast, RP may require bending of closely located vessel branches to prevent blending during phantom building.
For deformation of vessel branches, we employed the software BLENDER, which provides deformation via hull volumes and harmonic coordinates [15]. Thus, a hull volume is generated which is then used to control the deformation of the inner target structure. In our case, we generate the hull volume for all vessel branches that are located too close to other parts of the model. The structure can then be deformed via mouse interaction until it fits the specific local demands. The underlying algorithm guarantees that volume and local properties of the vessel are preserved while the global shape is modified (see Fig. 9).

4. CONCLUSION

The reconstruction of vascular surface models for applications, such as CFD or RP, involves a number of different and complex steps. For CFD, accuracy and mesh quality play an important role. In contrast, RP may even require local deformations to account for requirements from the physical model building process. Within this paper, we discussed these requirements and the tasks arising for solving the specific problems. For generating vascular surface models, no automated procedure can be used, since the occurring artifacts require an extensive, often interactive treatment and expert knowledge to distinguish an artifact and a pathology. Thus, we described current solutions to remove the specific artifacts and to prepare the surface model for usage in CFD and RP.
The above described steps may alter the shape of a target structure locally. For several artifacts, the original shape of the model (e.g., the vessel radius) is obvious, even to non-medical employees, and can thus be adjusted appropriately. Finally, the plausibility of these changes as well as the general shape of model still need to be validated by medical experts.
It is obvious, that the described model generation process is complex and may get tedious. The target model needs to be exchanged between different separated software tools. Thus, a unified solution offering the described tools for remeshing, local smoothing, local inflation, and cutting is desirable and could help to guide the user through this process faster and to achieve a better basis for discussion and collaboration with medical experts.

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