High-quality Surface Generation for Flow Simulation in Cerebral Aneurysms

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Abstract:
High-quality surface extraction is a crucial prerequisite for high-quality flow simulation and analysis in cerebral aneurysms. In this paper we present a two-step approach that first efficiently extracts a smooth surface from segmented aneurysms by means of MPU Implicits and then further improves the mesh quality to generate high-quality surfaces as input for the numerical simulation of blood flow in cerebral aneurysms. The presented work is an important step towards methods to assess growth, rupture risk, and therapeutic alternatives in the treatment of cerebral aneurysms.

Keywords: surface extraction, flow simulation, aneurysms, visualization

1. Motivation

The determination of functional properties in cerebral aneurysms like speed of vascular blood flow, pressure, and wall shear stress may support the diagnostic assessment of growth and rupture risk of cerebral aneurysms. In vivo blood flow measurement in cerebral aneurysms is technically demanding due to the high velocity of blood flow and skull ultra sound deaden. Estimating blood flow properties by means of computational fluid dynamics (CFD) simulation represents a feasible and promising approach, since we are able to determine morphology and necessary simulation parameters from 3D angiography data and dynamic angiographic X-ray measurements [2].

A crucial requirement for CFD simulation in aneurysms is the generation of appropriate surface mesh representations of the patient-specific anatomy. Generated surfaces for CFD simulation should not contain block and staircase artifacts, which commonly arise from the limited resolution of segmented radiological data. Furthermore, CFD simulation requires input meshes which must have a good triangle quality. Thin elongated triangles as well as block and staircase artifacts may otherwise yield numerical problems in CFD that may make simulation impossible. Common approaches to smooth these artifacts in the segmentation mask or in extracted surface meshes, especially of filigree vascular structures, mostly remove relevant detail and yield reduced accuracy [1].

In this paper we present a method based on MPU Implicits that generates accurate surfaces from binary segmentation masks and efficiently eliminates block and staircase artifacts. In a second step the triangle quality of the generated surface meshes is improved sufficiently to enable an accurate flow simulation and the determination of blood flow properties in cerebral aneurysms of diagnostic importance.

2. Method

Present work is based on a complex multi-staged pipeline [3]. In contrast, our approach is based on two efficient subsequent steps. First, smooth and accurate surface representations of the segmented patient data are generated by means of MPU Implicits. Subsequently, the triangle quality of the generated surface is improved to meet the CFD simulation requirements.

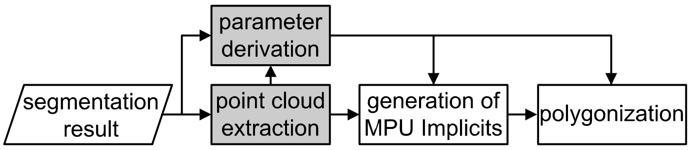


Fig. 1: Surface generation pipeline for vascular structures with MPU implicits.

2.1. Surface Extraction by Means of MPU Implicits

With Multi-level Partition of Unity Implicits (MPU Implicits) a bounding surface for a given point cloud with associated normal vectors is approximated.

We extract surfaces of the cerebral aneurysms with MPU Implicits according to [4] by processing the following four sub-steps (see Fig. 1):

- extraction of a point cloud with normal vectors that represents the segmented structures,
- automatic derivation of appropriate parameters to gain optimal accuracy and smoothness,
- generation of the MPU Implicits, and
- surface mesh generation (polygonization).

2.1.1. Point Cloud Extraction

We generate points for each outer boundary voxel and place the points at the voxel center or the center of one or more faces of the voxel according to the constellation of adjacent object voxels (Fig. 2a). For a sufficient representation of thin vascular branches with one voxel in diameter these are detected by a top-hat-transformation (3x3x3) and oversampled (Fig. 2b). To avoid staircase artifacts due to the oversampling some sub-voxels are treated as object voxels according to their 3D-18-neighbourhood (Fig. 2c). The normal vector for each point is derived from the image gradient or the normal of the boundary face of the voxel. This process is described in more details in [5].

2.1.2. Automatic Parameter Derivation for the Generation and Polygonization of MPU Implicits

The generation and polygonization of MPU Implicits is managed by a multiplicity of parameters. The manual selection of appropriate values is a tedious task and would not be feasible in clinical routine. Hence, we are using some standard parameters for the extraction of vascular structures and methods to automatically adopt parameter values to the current voxel size and point cloud extent. A description of the automatic determination of appropriate values can be found in [4].

As the last step, the vascular branches of the aneurysm have to be cut to define inlet and outlet regions for the simulation. Actually this clipping has to be done manually.

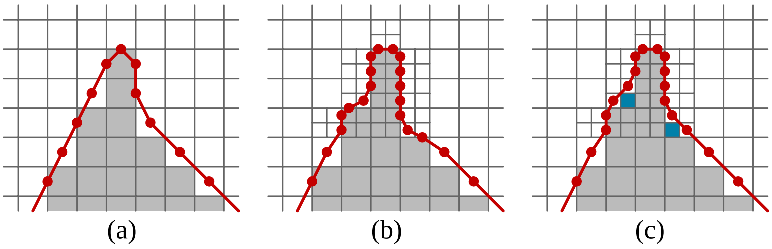
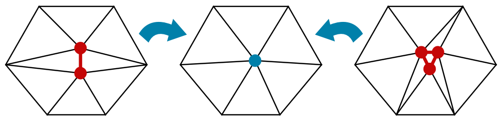
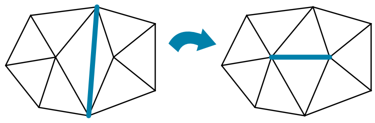


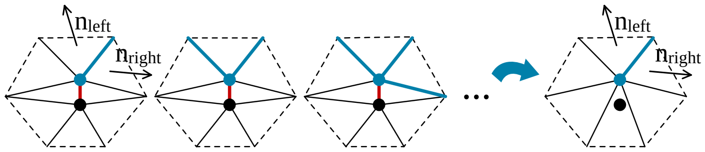
Fig. 2: Placement of points in outer boundary voxels according to the 3d-6-neighbourhood (a). Due to sub-sampling, the constellation of points adheres very strictly to the original voxel grid (b). Additional sub-voxels are labeled as object-sub-voxels to prevent staircase artifacts (c).



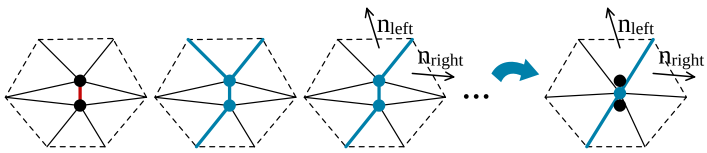
(a) collapsing of very small edges and triangles



(b) edge flipping



(c) collapse edge to the *feature vertex* of the edge, if it has only one



(d) collapse edge to the edge center, if both ends of the edge are *feature vertices*

Fig. 3: Edge collapse and edge flipping to improve the triangle quality. Sharp edges in the mesh (defined by the angle between the normals of the adjacent faces) are treated as *feature edges* and their ends as *feature vertices.*

2.2. Optimization of the Surface Mesh Quality

To meet CFD simulation requirements, the triangle quality of the extracted surfaces has to be improved. By flipping and collapsing edges of very small or thin elongated triangles (see Fig. 3) the mesh quality can be improved sufficiently. This is done iteratively until a desired quality (e.g., equi-angle skewness < 0.7) is reached.

3. Results

Surfaces generated by the presented approach excel in smoothness (no block and staircase artifacts) and accuracy. In Figure 4 (a-d) extracted surfaces are compared with surfaces generated by means of standard surface extraction. Due to smoothness, accuracy, and further triangle quality improvement, extracted surfaces are an optimal input for the generation of tetrahedral (volume) grids and the subsequent CFD simulation of blood flow. Figure 5 shows simulation results for an extracted cerebral aneurysm.

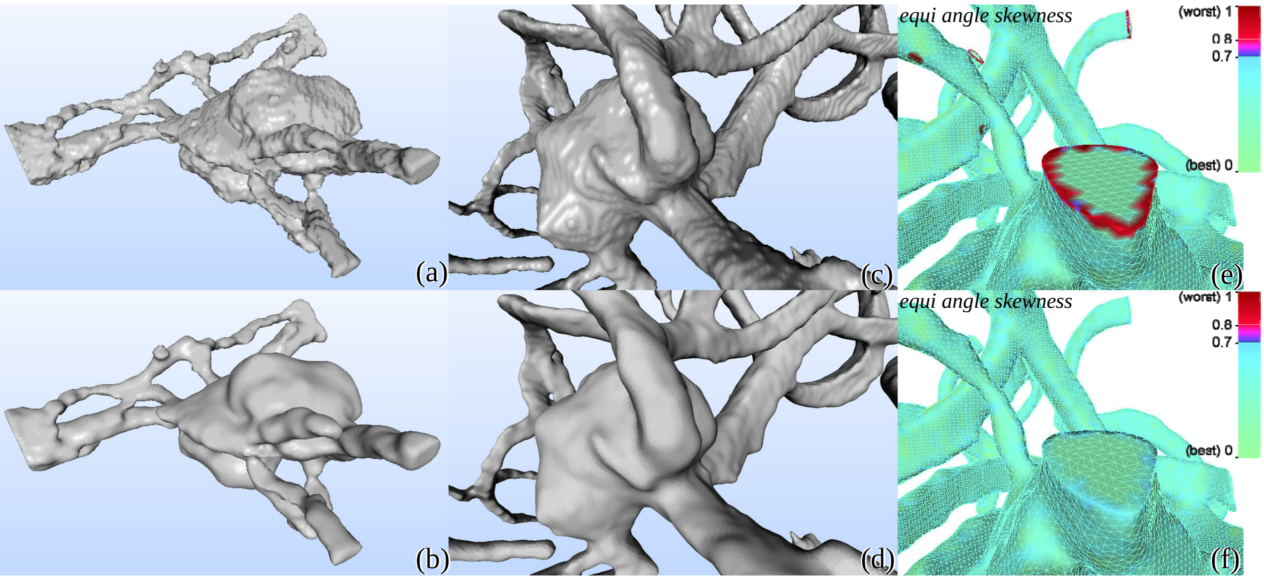


Fig. 4: Comparison of extracted surfaces by standard surface extraction (a) and (c) and our approach (b) and (d). The mean and maximum error as fraction of the voxel diagonal is in range 0.19 to 0.21 and 1.46 to 1.48, respectively. Optimization of the mesh quality with bad shaped triangles at clipped inlet and outlet regions (e) and improved mesh (f) with a mean *equi-angle skewness* of 0.30 and a maximum below 0.7.

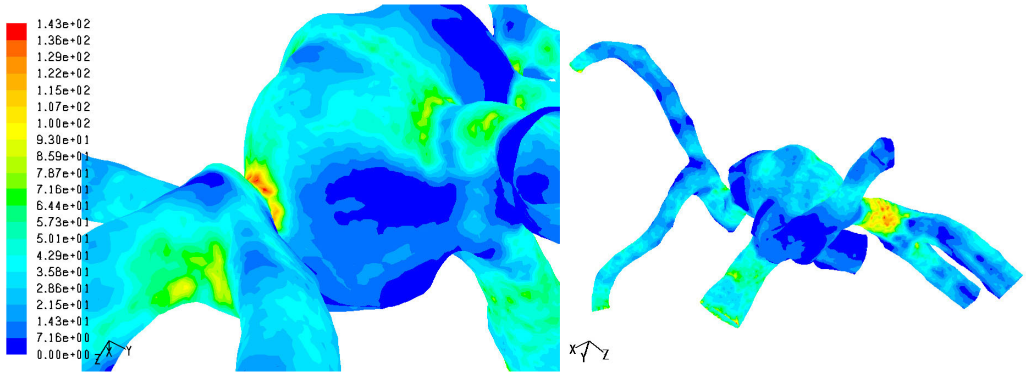


Fig. 5: Simulation results: wall shear stress in an extracted cerebral aneurysm. (CFD simulation with FLUENT 6.3)

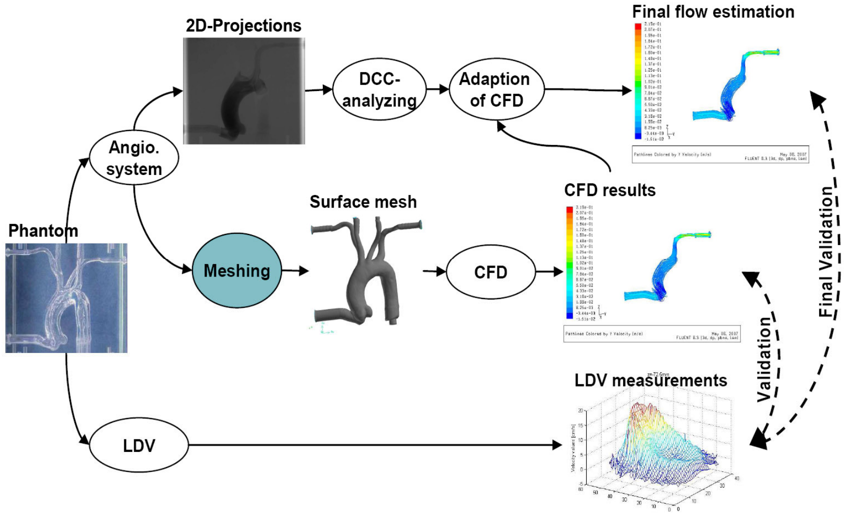


Fig. 6: Overview of the complex flow estimation procedure in [2] that benefits from the proposed surface mesh extraction method.

4. Conclusion

We presented an MPU Implicit based approach for the high-quality generation of vascular surface models from patient-specific data. Due to the largely automated procedure and quality of generated surfaces, this method is of high relevance for CFD simulation. Currently, the presented method is applied in an interdisciplinary project for blood flow analysis by means of dynamic angiography, CFD simulation and Laser-Doppler-Velocimetry (see Fig. 6) [2]. Future work will deal with adaptive polygonization of the MPU Implicits representation to further improve the mesh quality.

Literature

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