Semiautomatic neck curve reconstruction for intracranial aneurysm rupture risk assessment based on morphological parameters

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Abstract
Purpose Morphological parameters of intracranial aneurysms (IAs) are well established for rupture risk assessment. However, a manual measurement is error-prone, not reproducible and cumbersome. For an automatic extraction of morphological parameters, a 3D neck curve reconstruction approach to delineate the aneurysm from the parent vessel is required.

Methods We present a 3D semiautomatic aneurysm neck curve reconstruction for the automatic extraction of morphological parameters which was developed and evaluated with an experienced neuroradiologist. We calculate common parameters from the literature and include two novel angle-based parameters: the characteristic dome point angle and the angle difference of base points.

Results We applied our method to 100 IAs acquired with rotational angiography in clinical routine. For validation, we compared our approach to manual segmentations yielding highly significant correlations. We analyzed 95 of these datasets regarding rupture state. Statistically significant differences were found in ruptured and unruptured groups for maximum diameter, maximum height, aspect ratio and the characteristic dome point angle. These parameters were also found to statistically significantly correlate with each other.

Conclusions The new 3D neck curve reconstruction provides robust results for all datasets. The reproducibility depends on the vessel tree centerline and the user input for the initial dome point and parameters characterizing the aneurysm neck region. The characteristic dome point angle as a new metric regarding rupture risk assessment can be extracted. It requires less computational effort than the complete neck curve reconstruction.

Keywords Intracranial aneurysm · Neck curve · Morphological parameters · Rupture risk assessment

Introduction
Rupture risk assessment for intracranial aneurysms (IAs) remains challenging, since vascular malformations are highly individual with respect to their shape and underlie varying hemodynamic conditions [1]. 2D measurements (e.g., ostium size, dome-to-neck ratio and aspect ratio) are carried out and are used as rupture risk indicators in clinical routine [2, 3]. However, these measurements are highly user—as well as image-dependent, and the viewing angle for the 2D projections influences the resulting parameter values [4].

To overcome this problem, several studies considering 3D shape parameters of IAs were carried out during the last years [5–10]. Raghavan et al. [9] compared five size and eight shape indices with respect to the rupture status. They showed that none of the size parameters were significantly different between the ruptured and unruptured group, while five shape indices reached significance. A total of 119 aneurysm models were analyzed by Xiang et al. [11]. They identified the size ratio as the only independently significant factor in their morphology model. However, shape complexity parameters such as undulation index, ellipticity index and non-sphericity index were also significantly different between ruptured and unruptured aneurysms. Lv et al. [7] focused on morphological discriminants for the rupture
status of posterior communicating artery aneurysms. They evaluated 129 cases, and their univariate analysis revealed that the size of aneurysm dome, the aspect ratio, the size ratio as well as the dome-to-neck ratio were significantly associated with rupture. Recently, Varble et al. [10] used a database of 311 aneurysms to quantify morphological characteristics of patient-specific IAs. They could demonstrate that only the size ratio was different between internal carotid artery (ICA) aneurysms, middle cerebral artery aneurysms and anterior/posterior communication artery aneurysms. Furthermore, they concluded that ICA aneurysms are subject to less rupture-prone morphological characteristics in comparison with other locations within the Circle of Willis.

Overall, it can be noticed that several drawbacks occur. First, some studies considered only a low number of aneurysms (e.g., 27 IAs in [9] and 45 IAs in [5]). Additionally, the separation of the aneurysm from the healthy parent vessel is often realized using a (planar) cut-plane [6, 9, 11] instead of an anatomical neck curve (NC) that also accounts for the highly variational aneurysm shapes including possible bulges. Furthermore, the influence of imaging parameters like reconstruction kernels also influences the morphology [12].

As a consequence, relevant parameters such as diameters, surfaces, volumes as well as derived ratios can be clearly over- or underestimated compared to the actual situation leading to wrong conclusions with respect to the rupture risk assessment.

The recent study addresses those issues and provides an analysis, which is based on high-quality data. Specifically, 3D segmentations of 100 IAs were carried out based on extensive technical experience [13–16]. We present a semiautomatic NC reconstruction that allows for automatic extraction of the morphological parameters. An evaluation is carried out based on 100 manually drawn NCs. Finally, a statistical analysis identifies relevant shape parameters to differentiate between ruptured and unruptured aneurysms.

Materials and methods

In this section, we describe the acquired datasets and the semiautomatic NC reconstruction. Afterward, the extraction of morphological parameters is described.

Data acquisition and segmentation

The datasets included in this study comprise 100 IA datasets from 70 patients (age: 33–93 years, 14 male and 56 female). The maximum height of the aneurysms ranged from 1.63 to 11.72 mm, with a mean value of 5.12 mm and a median value of 4.69 mm. The maximum diameter of the aneurysms ranged from 2.29 to 15.60 mm with a mean value of 6.58 mm and a median value of 5.86 mm. Fifty-three of these aneurysms were ruptured, whereas 42 aneurysms were not ruptured. The status of the remaining five aneurysms was unclear since they were acquired during clinical routine. All patients included in this study underwent digital subtraction angiography (DSA) at the University Hospital Magdeburg, Germany, because of ruptured or incidentally discovered aneurysms. The examinations were part of the necessary clinical work-up and were performed on an Artis Q (Siemens Healthineers, Forchheim, Germany). The imaging protocol included a 3D rotational angiography (3D RA) in each patient, which is considered the gold standard in diagnostics and post-processing due to its high resolution. The 3D vascular trees were reconstructed from the data of the 3D RA using a threshold-based segmentation as proposed in [17], and then converted into a 3D triangulated surface mesh. Based on the surface mesh, the vessel’s centerline was semi-automatically extracted with the vascular modeling toolkit (VMTK, vmtk.org) [18]. Hence, the user manually selects the seed points by selecting the inlet and all outlets. The use of the data and its analysis comply with the guidelines of the local ethics committee.

For the evaluation of our approach, a manual NC segmentation for each of the 100 IAs was acquired by an experienced neuroradiologist. Each IA surface model was loaded into Blender 2.74 (Blender Foundation, https://www.blender.org/), and the NC was manually placed using the “knife” tool. The user can arbitrarily place lines onto the surface mesh which were manually corrected to obtain a closed NC. The obtained NCs were interpreted as gold standard for the evaluation of our approach.

Semiautomatic neck curve reconstruction

Our framework is implemented in MATLAB (MathWorks, Natick, USA). Thus, the implementation is speed up by using vectorized data structures as well as MATLAB’s Parallel Computing Toolbox, which supports image processing operations on the GPU.

For the automatic NC extraction, we discussed basic requirements for the resulting curves based on manually drawn NC from clinical experts. Inspired by the approach of Neugebauer et al. [19] and our discussions, we aim at an ostium plane that is roughly bent around the centerline of the parent vessel. Hence, we decide to employ the two nearest vessel branches to the aneurysm itself. Compliant to this approach, we also extract two points on the parent vessel surface that are located before ($P_1$) and after ($P_2$) the bulging of the aneurysm (between centerline and dome), since these points were always crossed by the manual NCs.

To describe the bending of the NC, we require two additional points $P_3$ and $P_4$. The bending of the NC depends on the vessel radius and the aneurysm shape. The connected points yield the NC. Since the neck is the smallest part at...
Fig. 1 Pipeline for the semiautomatic NC reconstruction. First, the user clicks in the scene on the aneurysm to define $D_{\text{Start}}$ (a). $D_{\text{Start}}$ is used to extract $S_{B_{\text{Start}}}$ on the centerline $C$ and the dome $D$. Next, the base points $B_1$ and $B_2$ are extracted (b). Afterward, $P_1$ and $P_2$ are determined (c). $C$ is replaced with a spline-based corrected centerline $C_{\text{Spline}}$. $P_3$ and $P_4$ are reconstructed (d), which are connected to the NC (see inlay).

the transition from parent vessel to aneurysm, the connection of these points is restricted to shortest paths on the aneurysm surface. Although the work by Neugebauer et al. [19] used these four characteristic points as well, we use different extraction methods as well as a modified connection approach for them.

The workflow is illustrated in Fig. 1 and comprises four steps:

- **Step 1** One-click selection of the aneurysm (see Fig. 1a).
- **Step 2** Extraction of the dome point $D$ and base points $B_1$ and $B_2$ (see Fig. 1b).
- **Step 3** Extraction of $P_1$ and $P_2$ at the aneurysm surface (see Fig. 1c).
- **Step 4** Extraction of $P_3$ and $P_4$ to reconstruct the NC (see Fig. 1d).

**Step 1: One-click selection of the aneurysm**

In Step 1, the user selects the aneurysm with a single click which also initializes our method. We refer with $D_{\text{Start}}$ to the selected position (recall Fig. 1a). $D_{\text{Start}}$ should be near the actual dome point $D$. The dome point $D$ refers to the aneurysm point with largest distance to the parent vessel. To speed up the subsequent steps, only parts of the surface mesh and centerline within 15 mm distance to $D_{\text{Start}}$ are used. The user can increase or decrease this value.

**Step 2: Extraction of the dome point $D$ and the base points $B_1$ and $B_2$**

In Step 2, the base points $B_1$ and $B_2$ and the dome point $D$ are extracted (see Fig. 1b). First, the set of points $S_{B_{\text{Start}}}$ is determined, where $S_{B_{\text{Start}}}$ comprises all points $B_i$ of the centerline such that the vector $\vec{B_iD_{\text{Start}}}$ does not intersect the triangle mesh (recall Fig. 1b). We set $D$ to $D_{\text{Start}}$. If any neighbored vertex $N_i$ of $D$ exhibits a larger average distance to $S_{B_{\text{Start}}}$, we set $D = N_i$ and iteratively repeat this process until $D$ is the most distant point to $S_{B_{\text{Start}}}$. Two vertices are neighbored if they share an edge on the triangle mesh. We extract $S_B$ comprising all points $B_i$ of the centerline, where $B_iD$ does not intersect the triangle mesh.

Next, $B_1$ and $B_2$ are extracted from $S_B$, see Fig. 2. To account for bifurcation aneurysms including branching centerlines, three points $T_1$, $T_2$ and $T_3$ are extracted. $T_1$ and $T_2$ form the pair of points from $S_B$ with the maximum possible distance to each other. $T_3$ is the point with maximum distance to $T_1$ and $T_2$. If $T_1$, $T_2$ and $T_3$ form a non-degenerated triangle, $B_1$ and $B_2$ are selected as the two points from $T_1$ to $T_3$ with shortest distance to $D$ (recall Fig. 2). Otherwise, $B_1$ and $B_2$ are set to the points with largest distance to each other. We empirically define $T_1$, $T_2$ and $T_3$ to form a degenerated triangle if the longest triangle edge $e_1$ and the remaining edges $e_2$ and $e_3$ fulfill $0.8 \times e_1 < e_2 + e_3 < 1.2 \times e_1$. 

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Extraction of $B_1$ and $B_2$ from $T_1$, $T_2$ and $T_3$ for two aneurysms. For bifurcation aneurysms, $T_1$, $T_2$ and $T_3$ form a triangle and $B_1$ and $B_2$ exhibit smallest distances to $D$ (left). For sidewall aneurysms, $T_1$, $T_2$ and $T_3$ form a thin and degenerated triangle (right).

Fig. 2

Extraction of $P_1$ and $P_2$. The distances to the surface mesh starting at segment $B_1D$ in direction $B_2B_1$ are extracted as intersection points (a). They are plotted in the distance plots as $d_1$, $d_1^*$ and $f_1$ are extracted (b). The maximum of $f_1$ defines the position of $P_1$. $P_2$ is extracted accordingly. As a result, $P_1$ and $P_2$ are located at the aneurysm neck along the parent vessel. They are characterized by minimum distances to the segments $B_1D$ and $B_2D$ near the aneurysm neck region.

Extraction of $P_1$ and $P_2$ at the aneurysm surface

In Step 3, points $P_1$ and $P_2$ are extracted (see Fig. 1c). $P_1$ and $P_2$ are located at the aneurysm neck along the parent vessel. They are characterized by minimum distances to the segments $B_1D$ and $B_2D$ near the aneurysm neck region.

For the calculation of $P_1$, we cast rays in direction $B_2B_1$ by sampling the segment $B_1D$ and determine the distances $d_1$ to the intersections with the surface, see Fig. 3. Possible neck points are characterized by a local minimum of $d_1$ near the aneurysm neck region. To determine this region, only points originating between $r_1 \times r_1$ and $s_1 \times r_1$ on the segment $B_1D$ are considered, where $r_1$ is the vessel radius at $B_1$. For the vessel radii extraction, rays are cast perpendicular to the centerline at $B_1$ and the median distance to the surface is assigned to $r_1$. We empirically set $t_1 = 0.5$ and $s_1 = 2.0$. These parameters can be adapted by the user since it may occur that the vessel radii cannot be correctly determined due to the large variations considering the aneurysm shapes.

As a result, $d_1$ is restricted to the aneurysm neck region. We plot $d_1$ in a distance plot (see Fig. 3b). We fit a line through $d_1$ yielding $g_1$. Since we are only interested in minima, we set all values $d_1(x) < g_1(x)$ to $g_1(x)$ and obtain $d_1^*$. The position of $P_1$ is defined at the maximum position of $f_1(x)$, where $f_1(x)$ provides the shortest distance for each point ($x$; $d_1^*$) to the line defined by $g_1$. Once we obtained $x$, we extract the corresponding intersection point with the surface mesh and obtain $P_1$ (see Fig. 3c).

This method works well for large variations of aneurysm shapes. For example, the specific aneurysm shape yields various minimum distances to $B_1D$ in Fig. 3d. In particular, a location near the dome would result in a false candidate for $P_1$ (see arrowhead, Fig. 3d). Due to the restriction to the aneurysm neck region based on parameters $t_1$ and $s_1$, this candidate is not considered for $P_1$.

Analogously, we repeat this procedure for $B_2$ to obtain $d_2$ and finally $P_2$.

Extraction of $P_3$ and $P_4$ of the neck curve

In Step 4, we extract $P_3$ and $P_4$ as the last two sample points for the NC. The centerline is distorted caused by the aneurysm sac. To compensate for this distortion, we gather points of the centerline of $B_1$ and $B_2$ from the outside, i.e.,
Fig. 4 Illustration of the extraction of $P_3$: $P_{3\text{initial}}$ is determined inside the aneurysm (see dashed circle), and $P_3$ is identified as nearest surface point to $P_{3\text{initial}}$ which are not in between them. We employ these sample points to fit a cubic spline curve and replace centerline points between $B_1$ and $B_2$ with the corresponding spline points (see Fig. 1d). Thus, we interpolate the points in between assuming continuity in the curve and its gradient direction.

Next, the initial position of $P_3$ is extracted. Therefore, we determine the point $M$ which is equidistant to $B_1$ and $B_2$ and lies on the centerline, see Fig. 4. The initial position of $P_3$ is denoted as $P_{3\text{initial}}$ and interpolated by $P_{3\text{initial}} = M + \frac{1}{2}(r_1 + r_2) \times \vec{v}$, where $\vec{v}$ is the normalized vector of $MP_1 + MP_2$. Then, $P_3$ is identified as nearest surface point to $P_{3\text{initial}}$.

To obtain the shortest NC, we iteratively move $P_3$ along the surface mesh, in case one of its neighbors yields a shorter NC than the initial position. That means, we extract for each neighbor $N_i$ of $P_3$ the shortest paths from $P_1$ to $N_i$ and from $N_i$ to $P_2$. If we obtain a shorter path, we set $P_3 = N_i$ and repeat the procedure. For finding the shortest connections, we interpret the surface mesh as graph structure and use MATLAB’s `shortestpath()` function based on [20].

$P_4$ is extracted by rotating the vector $MP_3$ around the axis $B_2B_1$ with an angle in between 180° and 270°. We empirically set this angle to 220°. In accordance to $P_3$, $P_4$ is moved as long as a neighbor exists that yields a shorter path from $P_1$ to $P_2$ containing this point. However, the large variations of aneurysm anatomies lead to cases where the NC is defined under the parent vessel, see Fig. 5. To overcome this problem, we automatically extract exclusion points. We determine $P_3’_1$ and $P_3’_2$ opposite $P_1$ and $P_2$. $P_3’_1 = C_{P_1} - \overrightarrow{CP_1}P_1$ and $P_3’_2 = C_{P_2} - \overrightarrow{CP_2}P_2$, where $C_{P_1}$ and $C_{P_2}$ are nearest points on the centerline to $P_1$ and $P_2$. We then exclude all surface mesh points within 1 mm distance to $P_3’_1$ and $P_3’_2$ for the shortest path search. We furthermore extract the closest pair of points $Q_1$ and $Q_2$ (where $Q_1$ is within 1 mm distance to $P_3’_1$ and $Q_2$ is within distance to $P_3’_2$), extract the shortest path between these points and add the path vertices to the exclusion points. Thus, the NC cannot intersect with these paths. The final NC is provided by the shortest paths from $P_1$ to $P_3$, $P_3$ to $P_2$, $P_2$ to $P_4$ and $P_4$ to $P_1$ (recall Fig. 1d).

Although our approach works for a wide variety of saccular and bifurcation IAs, it requires a pronounced neck curve. Very small aneurysms may not exhibit a visible distinguish-
Fig. 6 Extraction of the ostium plane for a basilar artery aneurysm (a). From the NC points, the mean \( C_{NC} \) and the principal components \( pc_1 \), \( pc_2 \) and \( pc_3 \) are extracted (b). The ostium plane is defined by \( C_{NC}, pc_1 \) and \( pc_2 \) (c). The NC can be projected on this plane (d). Triangulation of the NC and the projected NC yields two surfaces (e).

Fig. 7 Illustration of the morphological parameters \( H_{max}, W_{max}, H_{ortho}, W_{ortho} \) and \( D_{max} \) (a), as well as the angles \( \alpha, \beta \) and \( \gamma \) between the base points \( B_1 \) and \( B_2 \) and the dome \( D \) (b). The NC separates the aneurysm vertices from the parent mesh to approximate \( A \) and \( V \) (c). The surface area of the ostium is extracted for the reconstructed NC (\( OA_1 \)) as well as for the projected NC (\( OA_2 \)) (d). The angle-related parameters account for the tilting of the aneurysm (e). Here, the aspect ratio is identical, but \( \gamma \) and \( \Delta_{}\alpha\beta\) differ.

Morphological analysis

With the extracted NC, we can automatically and robustly determine common morphological parameters [5, 9]. Since many parameters from the literature require a planar ostium plane, we provide this plane as well. We denote the center of the neck curve, i.e., the mean of all neck curve points using \( C_{NC} \). Next, we employ a principal component analysis (PCA) to all neck curve points yielding principal component vectors \( \vec{pc}_1, \vec{pc}_2, \) and \( \vec{pc}_3 \), see Fig. 6. First, we define the ostium plane as plane through \( C_{NC} \) with the plane vectors \( \vec{pc}_1 \) and \( \vec{pc}_2 \). Second, we project each NC point onto this plane by determining the intersection point in direction of \( \vec{pc}_3 \), which equals the plane’s normal (recall Fig. 6).

We extract the following 20 parameters, which are illustrated in Fig. 7.
Evaluation

Our semiautomatic NC reconstruction was applied to all 100 datasets, and we could automatically extract the morphological parameters for each aneurysm. First, the comparison of the semiautomatic NC to the manually drawn curves is carried out. Afterward, the results of the morphologic parameter extraction w.r.t. rupture state are presented.

Comparison of semiautomatic and manual NC approach

We compared the semi-automatically determined NC (NC\textsubscript{new}) to the manually segmented one (NC\textsubscript{manual}) for each aneurysm. Therefore, we employ the average distance and standard deviation between two NCs presented by Cárdenes et al. [21]. The resulting average distances are provided in the box plot (Fig. 8), with a median value of 1.35 mm. In Fig. 9, the average distances w.r.t. the maximum aneurysm diameter are depicted separately. We use the result of this metric to identify the three cases with lowest and highest average differences, recall Fig. 8. Comparison of the average distances of the manual and semiautomatic NC to the individual aneurysm’s maximum diameter yields the following results: 25% of the cases exhibit errors smaller than 14%, 50% smaller than 25% and 75% smaller than 36% of the maximum diameter.

The clinician requested similar results concerning the morphological parameters based on NC\textsubscript{manual} and NC\textsubscript{new}. We conducted a correlation analysis based on the Pearson correlation coefficient (PCC) for the parameters $A$, $V$, $O A_1$, $O A_2$, $D_{\max}$, $H_{\max}$, $W_{\max}$, $H_{\text{ortho}}$, $W_{\text{ortho}}$, $N_{\max}$ and $N_{\text{avg}}$ since these are most often used in clinical practice.

Our analysis yields significant correlations with $p < 0.001$ for all parameters: PCC($A$) = 0.974 (i.e., the PCC($A$) denotes the PCC for parameter $A$ based on NC\textsubscript{manual} and $A$ based on NC\textsubscript{new}), PCC($V$) = 0.940, PCC($O A_1$) = 0.971, PCC($O A_2$) = 0.961 ($p < 0.000$), PCC($D_{\max}$) = 0.934, PCC($H_{\max}$) = 0.960, PCC($W_{\max}$) = 0.962, PCC($H_{\text{ortho}}$) = 0.951, PCC($W_{\text{ortho}}$) = 0.947, PCC($N_{\max}$) = 0.938 and PCC($N_{\text{avg}}$) = 0.963. As a result, we can conclude that NC\textsubscript{manual} and NC\textsubscript{new} yield significantly correlating parameter values for the morphologic parameters and the usage of our semiautomatic NC approach is justified.

Results of morphological parameter analysis

For the statistical evaluation, we only used 95 aneurysms with clear rupture state. Unclear rupture states arise if a patient suffered from multiple aneurysms and the ruptured one could not be clearly identified. First, an analysis for normal distribution was carried out; the Kolmogorov–Smirnov test did

- $A$ the area of the aneurysm (without the ostium), i.e., the surface area of all triangles separated by the neck curve.
- $V$ the volume of the aneurysm (the NC is triangulated by connecting all neck curve points with $C_{\text{NC}}$).
- $O A_1$ area of the ostium (the NC is triangulated by connecting all neck curve points with $C_{\text{NC}}$).
- $O A_2$ area of the ostium with the NC projected onto a plane.
- $D_{\max}$ maximum diameter of the aneurysm, i.e., the distance of the two most distant points of the aneurysm.
- $H_{\max}$ maximum height, i.e., maximum distance of an aneurysm point to $C_{\text{NC}}$.
- $W_{\max}$ maximum width of the aneurysm perpendicular to $H_{\max}$. This distance is obtained by connecting $C_{\text{NC}}$ with the point corresponding to $H_{\max}$ and sampling rays perpendicular to this connection.
- $H_{\text{ortho}}$ height of the aneurysm approximated as length of the ray perpendicular to the ostium plane starting from $C_{\text{NC}}$.
- $W_{\text{ortho}}$ maximum width parallel to the projected ostium plane.
- $N_{\max}$ maximum NC diameter, i.e., the maximum possible distance of two NC points.
- $N_{\text{avg}}$ average NC diameter, i.e., the mean distance of $C_{\text{NC}}$ to the NC points.
- $A_{\text{CH}}$ area of the convex hull of the aneurysm vertices.
- $A_{\text{CH}}$ area of the convex hull of the aneurysm vertices.
- $E I$ the ellipticity index: $E I = 1 - \frac{\pi}{3} \frac{V^{2/3}}{A_{\text{CH}}}$.
- $N S I$ the non-sphericity index: $N S I = 1 - \frac{\pi}{3} \frac{V^{2/3}}{A}$.
- $U I$ the undulation index: $U I = 1 - \left( \frac{V}{V_{\text{CH}}} \right)$.
- $\gamma$ absolute value of difference between the angles $\alpha$ (i.e., the angle between $B_1 \overrightarrow{D}$ and $B_1 \overrightarrow{B_2}$) and $\beta$ (i.e., the angle between $B_1 \overrightarrow{B_2}$ and $D \overrightarrow{B_2}$).
- $\gamma$ angle at $D$, i.e., between $\overrightarrow{D B_1}$ and $\overrightarrow{D B_2}$.

It must be noted that all of these parameters can be automatically extracted based on a given NC and no manual user interaction is necessary. Furthermore, parameters except $\Delta_{\alpha \beta}$ and $\gamma$ were already introduced in the literature. During the NC detection development, the parameters $\Delta_{\alpha \beta}$ and $\gamma$ were identified as well suited to characterize tilted aneurysms with respect to their parent arteries. In contrast to $A R_1$ and $A R_2$, $\gamma$ describes the height and width ratio of aneurysms and their tilting at the same time (recall Fig. 7e). Furthermore, $\Delta_{\alpha \beta}$ provides information about the tilting itself. We carried out statistical evaluation to assess whether ruptured and unruptured aneurysms differ w.r.t. their morphological parameters. All tests were carried out with SPSS 22.0 (IBM, New York, USA).
Boxplot of the extracted averaged distances (in mm) between manual and semiautomatic NCs for the 100 tested datasets (median = 1.53 mm, 25th percentile = 0.74 mm, 75th percentile = 1.94 mm, left). Depiction of the semiautomatic NC results for the three best (right, top row) and three worst (right, bottom row) datasets with respect to average differences between semiautomatic NC (green) and manual NC (blue). The average differences are provided for each of the cases in the figure.

Bar plot of the average distance between manual and semiautomatic NC for all 100 datasets in relation to the maximum aneurysm diameter: the markers +, * and x refer to 10%, 50% and 100% of the maximum aneurysm diameter, respectively. Not show normal distributed data for each of the provided parameters.

Therefore, the nonparametric Mann–Whitney-U test was applied for each parameter, see Table 1. The ruptured and unruptured aneurysms significantly differ regarding the parameters $D_{\text{max}}$, $H_{\text{max}}$, $AR_1$, $AR_2$ and $\gamma$. Mean value and standard deviation are provided in Table 2, and box plots are depicted in Fig. 10. The box plots for the unruptured and ruptured IAs present the parameter distribution based on NC$_{\text{manual}}$ and NC$_{\text{new}}$. Subsequently, we calculated the correlation between these parameters based on the Pearson correlation coefficient (PCC). Interestingly, all of these five parameters significantly correlate with each other: $\text{PCC}(D_{\text{max}}; H_{\text{max}}) = 0.972$, $\text{PCC}(D_{\text{max}}; AR_1) = 0.473$, $\text{PCC}(D_{\text{max}}; AR_2) = 0.498$, $\text{PCC}(D_{\text{max}}; \gamma) = -0.343$, $\text{PCC}(H_{\text{max}}; AR_1) = 0.646$, $\text{PCC}(H_{\text{max}}; AR_2) = 0.662$, $\text{PCC}(H_{\text{max}}; \gamma) = -0.500$, $\text{PCC}(AR_1; AR_2) = 0.980$, $\text{PCC}(AR_1; \gamma) = -0.822$, and $\text{PCC}(AR_2; \gamma) = -0.812$, with $p < 0.01$ for all tests.

Discussion

This study introduces a new approach to semi-automatically reconstruct the neck curve of patient-specific IAs. It was adapted to 100 IAs with varying sizes, locations and type.
Table 1 Result of the nonparametric Mann–Whitney-U (MWU) test for the morphological parameters

<table>
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<th>Parameter</th>
<th>MWU</th>
<th>Z</th>
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<td>0.071</td>
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<tr>
<td>V</td>
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<td>-1.533</td>
<td>0.125</td>
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</tr>
<tr>
<td>AR2</td>
<td>771</td>
<td>-2.525</td>
<td>0.012*</td>
</tr>
<tr>
<td>V_{Ch}</td>
<td>895</td>
<td>-1.593</td>
<td>0.111</td>
</tr>
<tr>
<td>A_{Ch}</td>
<td>890</td>
<td>-1.631</td>
<td>0.103</td>
</tr>
<tr>
<td>E1</td>
<td>930</td>
<td>-1.330</td>
<td>0.184</td>
</tr>
<tr>
<td>NSI</td>
<td>918</td>
<td>-1.420</td>
<td>0.156</td>
</tr>
<tr>
<td>UI</td>
<td>1061</td>
<td>-0.346</td>
<td>0.730</td>
</tr>
<tr>
<td>Δ_{af}</td>
<td>869</td>
<td>-1.788</td>
<td>0.074</td>
</tr>
<tr>
<td>γ</td>
<td>734</td>
<td>-2.803</td>
<td>0.005**</td>
</tr>
</tbody>
</table>

*Strongly significant correlation, double-sided, p < 0.01; **significant correlation, double-sided, with p < 0.05

Table 2 Mean values (\(\bar{x}\)) and standard deviation (\(s\)) of the parameters \(D_{max}, H_{max}, AR1, AR2\) and \(γ\) extracted with the semiautomatic neck curve approach

<table>
<thead>
<tr>
<th></th>
<th>(D_{max}) (mm)</th>
<th>(H_{max}) (mm)</th>
<th>AR1</th>
<th>AR2</th>
<th>(γ) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruptured</td>
<td>7.22</td>
<td>5.81</td>
<td>1.35</td>
<td>1.55</td>
<td>31.91</td>
</tr>
<tr>
<td></td>
<td>3.04</td>
<td>2.68</td>
<td>0.56</td>
<td>0.66</td>
<td>14.03</td>
</tr>
<tr>
<td>Unrupted</td>
<td>6.13</td>
<td>4.64</td>
<td>1.08</td>
<td>1.22</td>
<td>44.25</td>
</tr>
<tr>
<td></td>
<td>2.74</td>
<td>2.37</td>
<td>0.47</td>
<td>0.53</td>
<td>19.14</td>
</tr>
</tbody>
</table>

(sidewall and bifurcation aneurysms). The presented method could extract \(P1\) and \(P2\) characterizing the transition from parent vessel to aneurysm between centerline and dome as well as \(P3\) and \(P4\) describing the bending of the NC. As illustrated in Fig. 10, the parameters extracted from the semiautomatic approach correlate well with those from the manually drawn curves. Largest differences are present for \(AR1\) which depends on \(N_{max}\). This might be caused due to different bendings of the neck curves at the parent vessel.

A 3D NC determination and subsequent parameter extraction is superior to 2D measurements [4, 22], where inadequate viewing directions for the 2D projections could hamper the result, see the example in Fig. 11a. The 2D projections in clinical practice have to account for possible occlusions of surrounding vessels, and often a clear view on the parent vessel for subsequent endovascular treatment is required.

Extraction of ostium neck curves is challenging due to the wide variety of shape and size. Karmonik et al. [23] presented a 2D NC extraction which requires an analysis of vessel radius change opposite the aneurysm and could not produce the desired results for bifurcation aneurysms (see Fig. 11b). The estimation of Jerman et al. [24] is similar to our approach since ray tracing is also enabled to get the NC points. The approach by Cárdenes et al. [25] uses Voronoi diagrams for the NC extraction. Hence, a centerline inside the aneurysm is necessary.

Comparisons of the semiautomatic and manual NCs reveal a median error of 1.53 mm for the average displacements based on the metric introduced in [21]. Thus, our median average distance is definitely lower than the values reported in an additional study by Cárdenes et al. [21] comparing different neck curve extractions. They reported average median distances lower than 0.5 mm for automatic neck curve extraction methods based on deformable model extensions or geodesic curves with topological restrictions. For manual cutting plane placement, the average median distances are even lower than 0.37 mm. In consequence, these methods will yield better results w.r.t. average distance of neck curves than our approach. On the contrary, we strongly reject planar neck curves (see the example in Fig. 11d) and their dataset only comprised 26 cases.

Our approach was inspired by Neugebauer et al. [19], but we experienced several drawbacks of their method. First, the vessel radii of the parent vessel are often not identical (recall example in Fig. 11c), which caused problems for extraction of \(P1\) and \(P2\). This step also suffers from thin and bulged aneurysm shapes, where a minimum distance between the centerline and a projected centerline has to be determined. We solved this problem by restricting the possible occurrences of \(P1\) and \(P2\) to the aneurysm neck region, recall Fig. 3d. In addition, the extraction of \(P3\) and \(P4\) might stuck at local minima, i.e., bulges of the aneurysm next to the centerline can be missed, see Fig. 11c. With our method, the extraction and adaption of \(P3\) and \(P4\) prevents this problem, see the result in Fig. 12. Nevertheless, their approach was tested on seven cases, while our method could only be developed based on the large variations in the 100 datasets. On the other hand, our approach requires a pronounced neck. Although a manual selection of \(P3\) and \(P4\) can be carried out to cope with very small aneurysms without a visible neck, this is a shortcoming of our approach. An approximation of the aneurysm neck with a 2D cutting plane (as suggested in [5, 6, 9]) introduces errors when evaluating morphological parameters, since the perfect position of this plane remains unclear in case of bulging aneurysms, recall Fig. 11d.
Fig. 10 Box plots of the parameters $D_{\text{max}}$, $H_{\text{max}}$, $\text{AR}_1$, $\text{AR}_2$ and $\gamma$ extracted based on the semi-automatic neck curve approach NC\textsubscript{new} and the manually drawn neck curves NC\textsubscript{manual}. Hence, $\gamma$ is only available for NC\textsubscript{new}. For each set of aneurysms (unruptured and ruptured), an individual box plot is provided.

Fig. 11 drawbacks of various approaches and specific aneurysm cases. When extracting $D_{\text{max}}$ in 2D, the view direction influences the result (a). Example of a bifurcation aneurysm (b). Example of an aneurysm with bulges (c). A shortest path starting from $P_1$ may miss aneurysm bulges marked with an arrowhead. The plane-based approximation of the ostium is error-prone for inclined aneurysms (d). It is not clear if the red or the black dashed cutting plane yields the better ostium plane.

Fig. 12 Result of our NC reconstruction algorithm for the case presented in Fig. 11c (left) including the manually drawn curve (right).

The statistical evaluation of morphological parameters reveals that $D_{\text{max}}$, $H_{\text{max}}$, $\text{AR}_1$, $\text{AR}_2$ and $\gamma$ statistically significantly correlate with the aneurysm rupture status. This is especially remarkable, since we introduce $\gamma$ as characteristic angle at the dome $D$. Although Dhar et al. [5] introduced angle-based parameters (aneurysm inclination angle and vessel angle), we do not rely on these parameters since they are only defined for sidewall IAs and depend on the direction from which the geometry is viewed. Furthermore, the viewing direction and thus the parameter extraction had to be manually carried out in their approach. We extracted $\gamma$ for all 100 aneurysms (including sidewall and bifurcation IAs) independent on the viewing direction.

Comparing them with values reported in the literature yields the following results. Lauric et al. [6] pointed out the variations for $\text{AR}$ in the literature, arising from different definitions of aneurysm height (orthogonal height, maximum height and “depth” height which is only defined inside the aneurysm sac) and aneurysm neck diameter (maximum, average or minimum). We obtain similar values for $\text{AR}_1$: $1.35 \pm 0.56$ or 53 ruptured IAs and $1.08 \pm 0.47$ for 42 unruptured IAs compared to their values: $1.41 \pm 0.55$ for 60 ruptured and $1.14 \pm 0.45$ for 74 unruptured IAs. Similar results are obtained for $\text{AR}_2$: we obtain $1.55 \pm 0.66$ for ruptured and $1.22 \pm 0.53$ for unruptured IAs. Lauric et al. report $1.62 \pm 0.74$ and $1.27 \pm 0.51$, respectively. The definition of
the aspect ratio by Dhar et al. [5] matches AR2. They reported a mean value of $1.5 \pm 0.45$ for 25 ruptured and $1.2 \pm 0.55$ for 20 unruptured aneurysms, which agrees very well with our results.

Lauric et al. [6] report $D_{\text{max}}$ mean values of $9.05 \pm 4.00$ mm and $H_{\text{max}}$ mean values of $7.41 \pm 3.55$ mm for 60 ruptured and $D_{\text{max}}$ mean values of $6.9 \pm 2.78$ mm and $H_{\text{max}}$ mean values of $5.36 \pm 2.37$ mm for 74 unruptured IAs. These trends are reflected by our results, where ruptured IAs exhibit larger mean values than unruptured ones, but we obtain slightly different values ($D_{\text{max\ ruptured}} = 7.22 \pm 3.04$ mm, $D_{\text{max\ unruptured}} = 6.13 \pm 2.74$ mm, $H_{\text{max\ ruptured}} = 5.81 \pm 2.68$ mm, $H_{\text{max\ unruptured}} = 4.64 \pm 2.37$ mm). In addition, mean values of $6.76 \pm 2.03$ mm for 30 ruptured and $4.6 \pm 2.85$ mm for 37 unruptured IAs were reported for a slightly different $D_{\text{max}}$ extraction in [26]. When comparing morphological measures, it must be noted that their predictive values regarding rupture risk also depend on the aneurysm location [10] and considerably variations exist regarding their definition [6]. We account for this problem by extracting different variations of the aspect ratio yielding $A R_1$ and $A R_2$ instead of a single parameter. Hence, future studies and clinical trials should provide information and standardized guidelines which method is preferable.

Due to the high correlations between the morphological parameters $D_{\text{max}}, H_{\text{max}}, A R_1, A R_2$ and $\gamma$, it may be not necessary to extract all of them. Future work should evaluate different classifiers based on different parameter sets w.r.t. their discriminative power. Since extraction of $\gamma$ does not require the complete NC but only $D, B_1$ and $B_2$ (i.e., only Step 2 of our pipeline, depicted in Fig. 1b), a future classification approach could be speed up. Initial experiments identified $\gamma$ and the $EI$ as most important parameters based on our training dataset for a gradient-boosted tree classifier. Hence, a combination of parameters is superior to the usage of a single one. Future work can reveal which combination of the presented parameters yields best prediction results. Dhar et al. [5] also carried out multivariate logistic regression analysis stating that only two of their five parameters were identified as independently significant; the size ratio and the undulation index UI. Regarding the effect size of our approach, we achieved only a small effect [27] due to the large sample size.

We do not evaluate interaction effects yet. Although all significant parameters correlate with each other maybe interaction effects between nonsignificant parameters can be examined. This will be part of a subsequent analysis. In addition, a prospective study comprising untreated longitudinal IAs is of great interest, but these datasets are rare in clinical practice.

For the assessment of artifacts due to noise, we added artificial random noise to the triangle meshes inspired by [28]. An example for case 53 is provided in Fig. 13. Therefore, each vertex of the surface mesh was randomly displaced in direction of its surface normal. The maximum amount of the displacement for each step was determined by the percentaged average edge length of the triangle mesh. With a noise level that randomly alters vertices up to 300% of the average edge length, the NC could still be successfully extracted. Only with a noise level of 350%, the identification of $V_1$ and $V_2$ was not possible anymore, see Fig. 13.

For the 100 aneurysms, no manual correction was required. The reproducibility of our method depends on the centerline, $D_{\text{Start}}$ and parameters $t$ and $s$. For centerline extraction, we employ an already well-established method [18]. $D_{\text{Start}}$ does not influence $D$ in a mesh where $D$ has the largest distance to the centerline. If there is noise present, $D$ may be found at the local maximum. A post-processing step could further reduce this variability, by first separating the aneurysm from the parent vessel and then repeat the procedure but using the separated aneurysm for possible locations of $D$ instead the neighbored surface vertices of $D_{\text{Start}}$. Parameters $t$ and $s$ do influence the result, but we provide default values such that the same NC is extracted.

A ground truth for neck curves is not available yet. Future work could include more manual drawn neck curves from more clinical experts; however, manual definition is a very time-consuming task. Furthermore, errors during manual drawing may occur as well especially for complex and irregularly shaped aneurysms.

Beside the precise morphological evaluation of the 3D aneurysm shape, an automatized ostium detection is highly beneficial for the quantification of hemodynamic flow simulations [29]. Particularly, since relevant blood flow parameters that are associated with rupture (e.g., normalized wall shear stress, shear concentration index, oscillatory shear

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**Fig. 13** Extraction of the NC (green) for triangular meshes with random noise that displaces each vertex in direction of its normal. The manual NC (blue) is provided for comparison. The percentage describes the amount of maximum displacement w.r.t. the average edge length.
index [30]) need to be calculated with high accuracy, wrong aneurysm-vessel-separation or high user-dependency can lead to clear variations regarding the analysis.

Conclusions

We presented a semiautomatic 3D NC reconstruction algorithm which yields reproducible results and was successfully applied to 100 IAs. The employed IA triangle surface meshes are based on segmented rotational angiography images. However, the approach is suitable for segmented CTA and MRA datasets as well. The NC reconstruction yields an anatomical shaped curve, i.e., the NC does not lie in a plane. It allows for automatic extraction of common morphological parameters as well as a newly introduced characteristic angle $\gamma$ at the aneurysm’s dome. Statistical evaluation yields statistical significant correlation of the morphological parameters $D_{\text{max}}$, $H_{\text{max}}$, $A_{\text{R}1}$ and $A_{\text{R}2}$ with rupture status which is in good agreement with the literature. Thus, the 3D NC reconstruction is well suited for further applications including the quantification of hemodynamic flow simulations. The newly introduced characteristic angle $\gamma$ at the dome yields statistical significance as well and correlates with the other morphological parameters indicative for rupture status. Considering that $\gamma$ can be extracted at a very early stage of our method relying on $B_1$ and $B_2$ but not on the complete NC, a benefit for future classifiers is expected.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. For this type of study, formal consent is not required.

Informed consent Informed consent was obtained from all individual participants included in the study.

References


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