Morphological Parameters Associated with Ruptured Posterior Communicating Aneurysms

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Introduction

The rupture risk of unruptured intracranial aneurysms is known to be dependent on the size of the aneurysm. However, the association of morphological characteristics with ruptured aneurysms has not been established in a systematic and location specific manner for the most common aneurysm locations. We evaluated posterior communicating artery (PCoA) aneurysms for morphological parameters associated with aneurysm rupture in that location. CT angiograms were evaluated to generate 3-D models of the aneurysms and surrounding vasculature. Univariate and multivariate analyses were performed to evaluate morphological parameters including aneurysm volume, aspect ratio, size ratio, distance to ICA bifurcation, aneurysm angle, vessel angles, flow angles, and vessel-to-vessel angles. From 2005–2012, 148 PCoA aneurysms were treated in a single institution. Preoperative CTAs from 63 patients (40 ruptured, 23 unruptured) were available and analyzed. Multivariate logistic regression revealed that smaller volume (p = 0.011), larger aneurysm neck diameter (0.048), and shorter ICA bifurcation to aneurysm distance (p = 0.005) were the most strongly associated with aneurysm rupture after adjusting for all other clinical and morphological variables. Multivariate subgroup analysis for patients with visualized PCoA demonstrated that larger neck diameter (p = 0.018) and shorter ICA bifurcation to aneurysm distance (p = 0.011) were significantly associated with rupture. Intracerebral hemorrhage was associated with smaller volume, larger maximum height, and smaller aneurysm angle, in addition to lateral projection, male sex, and lack of hypertension. We found that shorter ICA bifurcation to aneurysm distance is significantly associated with PCoA aneurysm rupture. This is a new physically intuitive parameter that can be measured easily and therefore be readily applied in clinical practice to aid in the evaluation of patients with PCoA aneurysms.

Abstract

The rupture risk of unruptured intracranial aneurysms is known to be dependent on the size of the aneurysm. However, the association of morphological characteristics with ruptured aneurysms has not been established in a systematic and location specific manner for the most common aneurysm locations. We evaluated posterior communicating artery (PCoA) aneurysms for morphological parameters associated with aneurysm rupture in that location. CT angiograms were evaluated to generate 3-D models of the aneurysms and surrounding vasculature. Univariate and multivariate analyses were performed to evaluate morphological parameters including aneurysm volume, aspect ratio, size ratio, distance to ICA bifurcation, aneurysm angle, vessel angles, flow angles, and vessel-to-vessel angles. From 2005–2012, 148 PCoA aneurysms were treated in a single institution. Preoperative CTAs from 63 patients (40 ruptured, 23 unruptured) were available and analyzed. Multivariate logistic regression revealed that smaller volume (p = 0.011), larger aneurysm neck diameter (0.048), and shorter ICA bifurcation to aneurysm distance (p = 0.005) were the most strongly associated with aneurysm rupture after adjusting for all other clinical and morphological variables. Multivariate subgroup analysis for patients with visualized PCoA demonstrated that larger neck diameter (p = 0.018) and shorter ICA bifurcation to aneurysm distance (p = 0.011) were significantly associated with rupture. Intracerebral hemorrhage was associated with smaller volume, larger maximum height, and smaller aneurysm angle, in addition to lateral projection, male sex, and lack of hypertension. We found that shorter ICA bifurcation to aneurysm distance is significantly associated with PCoA aneurysm rupture. This is a new physically intuitive parameter that can be measured easily and therefore be readily applied in clinical practice to aid in the evaluation of patients with PCoA aneurysms.
Methods

Ethics Statement
The study was approved by the Brigham and Women’s Hospital Institutional Review Board. Written consent from the patients was waived by the Institutional Review Board.

Patient selection
The study population consisted of all patients with a diagnosis of posterior communicating artery (PCoA) aneurysm treated at the Brigham and Women’s Hospital during a 7-year period between 2005 and 2012. Aneurysms that underwent reoperation, those that were associated with arteriovenous malformations, or those that lacked preoperative CT angiography (CTA) were excluded. Demographic and clinical information were collected from medical records. In particular, patient data on risk factors commonly associated with aneurysm development or aneurysm rupture were collected, including smoking status, family history, presence of multiple aneurysms, history of hypertension, and prior history of aneurysm rupture/SAH. The study was approved by the Institutional Review Board.

Reconstruction of 3D models
As described in our prior study [10], we utilized 3D Slicer (referred as “Slicer” in the following text), an open source, multi-platform visualization and image analysis software [15,16]. Preoperative CT angiography (CTA) images were utilized to generate composite three-dimensional (3D) models of the aneurysm and surrounding vasculature. All CTAs were performed on a Siemens® SOMATOM Definition scanner with slice thickness of 0.75 mm and increment of 0.5 mm. We were able to separate the vascular compartment by thresholding. Aneurysm contours were then reconstructed using a triangle reduction and smoothing algorithm. This 3D surface model of the aneurysm and surrounding vessels could be manipulated freely in the Slicer environment. (Figures 1 and 2) Fiducial-based tractography was then utilized to manually measure volumes, lengths and angles in 3D space.

Definition of morphological parameters
Morphological parameters examined in 3D aneurysm models included several variables already defined in the studies investigating other types of aneurysm (aneurysm size, aneurysm volume, aspect ratio, aneurysm angle, vessel angles, and size ratio, flow angles, and vessel-to-vessel angles) [7,8,10,17] as well as several novel parameters that applied to the specific anatomy of the PCoA and surrounding vasculature. All CTAs were performed on a Siemens® SOMATOM Definition scanner with slice thickness of 0.75 mm and increment of 0.5 mm. We were able to separate the vascular compartment by thresholding. Aneurysm contours were then reconstructed using a triangle reduction and smoothing algorithm. This 3D surface model of the aneurysm and surrounding vessels could be manipulated freely in the Slicer environment. (Figures 1 and 2) Fiducial-based tractography was then utilized to manually measure volumes, lengths and angles in 3D space.

Statistical Analysis
Differences in demographic and clinical characteristics by rupture status were examined using chi-square and two-tailed t-tests for binary and continuous variables, respectively. Univariate analysis was performed to compare the value of each morphological parameter between the ruptured and unruptured groups. Multivariate logistic regression was used to calculate the odds ratios (ORs) and 95% confidence intervals (95% CI) for the likelihood of aneurysm rupture after adjusting for age, sex, smoking status, family history, presence of multiple aneurysms, hypertension, and prior history of SAH. Morphological variables pertaining to the PCoA were excluded from this analysis since the PCoA was poorly visualized in a majority of patients. Subgroup analysis was subsequently conducted in patients with visualized PCoAs. Again, multivariate logistic regression was conducted with clinical and morphological variables, this time including the PCoA parameters. Statistical significance was defined as a type I error less than 0.05. Multivariate logistic regression was also conducted to create a model for predicting presence of intracerebral hemorrhage. This analysis included morphological variables between the maximum aneurysm height and mean vessel diameters of all branches associated with the aneurysm. Specifically, the diameters of a particular vessel are determined by averaging the diameter of the cross-section at the neck of the aneurysm (D1) with the diameter of the cross-section at 1.5xD1 from the neck of the aneurysm. This average diameter was calculated for all vessels involved with the aneurysm to generate the composite mean vessel diameter utilized to calculate the size ratio. The vessel angle is angle between the respective vessel and the plane of the aneurysm neck. Centerlines for each vessel were determined by linking the two center points of the cross-sections utilized to measure the vessel diameter in size ratio. The ICA1/PCoA flow angle is the angle between the vector of maximum height of the aneurysm and the vector of centerline through the ICA1/PCoA that represents the vector of flow. This angle represents the angle at which the aneurysm is tilted with respect to the vector of flow through parent vessels. The new parameters devised specifically for PCoA aneurysms are described below. (Figures 1 and 2)

Angles. All previously described vascular angles including aneurysm, vessel, and vessel-to-vessel angles were measured with respect to the ICA1, ICA2, and PCoA. With respect to PCoA aneurysms, flow generally enters via the proximal ICA and divergences from the aneurysm into the PCoA and distal ICA. There were two vessel-to-vessel angles measured. (Figure 2) The ICA1 to ICA2 angle refers to the angle between the distal ICA (ICA2) and the proximal ICA (ICA1). This parameters measure the degree to which the blood flow through the proximal ICA (ICA1) must deviate in order to emerge into the distal ICA (ICA2). The ICA1 to PCoA angle refers to the angle formed between the proximal ICA (ICA1) and PCoA. This angle serves to measure the degree of blood flow deviation from the proximal ICA (ICA1) into the PCoA. The PCoA is not always well visualized, thus vascular angles for the PCoA are missing for many patients. Of note, the vessel-to-vessel angles are independent of the aneurysm itself and capture the context of the surrounding vasculature within which the aneurysm arises.

Distance to ICA Bifurcation. This parameter is specific to the anatomy of the PCoA and has not previously been investigated. The distance to the ICA bifurcation is defined by the distance from the proximal neck of the aneurysm and the bifurcation of the ICA into the middle cerebral and anterior cerebral arteries.
pertaining to the aneurysm itself, and its relation to the internal carotid artery. All statistical analyses were performed using JMP Pro 10, SAS version 9.2 (SAS Institute Inc, Cary, North Carolina) and Excel 2007 (Microsoft Corp., Redmond, WA).

**Results**

**Univariate Analysis**

From 2005–2012, 148 PCoA aneurysms were treated in a single institution, and preoperative CTAs from 63 patients were analyzed. There were a total of 40 ruptured and 23 unruptured aneurysms. Demographic and clinical data is provided in Table 1. The mean age was 55.86±14.2 years. Patients with unruptured aneurysms were slightly older (means of 58.09 years unruptured vs 54.58 years ruptured), though this difference was not statistically significant. Fifty-four (86%) patients were women, and the gender compositions of the two arms of our study were similar (86% unruptured, 85% ruptured). Patients with unruptured aneurysms were significantly more likely to have multiple aneurysms or a history of prior aneurysm rupture (p = 0.034). Ruptured aneurysms were associated shorter distance to ICA bifurcation in a relationship that approached significance (11.3 mm unruptured versus 10.4 mm ruptured, p = 0.076). (Table 2) Rupture was also associated with larger ICA1 to ICA2 angle, and ICA1 to PCoA angle but these trends were not statistically significant. Larger ICA1 to ICA2 angle was significantly associated with lateral projection of the aneurysm (lateral projection 85.8 degrees vs not lateral projection 73.5 degrees, p = 0.013), linking the orientation of the surrounding vasculature with the direction and development of the aneurysm dome. Finally, PCoA aneurysms with lateral projection were more associated with rupture, and this relationship also approached significance (50% of unruptured vs 55% of ruptured, p = 0.052). Aneurysm sizes, as measured by maximal aneurysm height were similar between unruptured and ruptured aneurysms (5.85 mm unruptured vs 5.97 mm ruptured, p = 0.441).

**Multivariate Analysis**

Multivariate logistic regression was conducted with the inclusion of known clinical risk factors for aneurysm rupture including age, gender, smoking, hypertension, family history, and presence of multiple aneurysms. A model was generated with these risk factors and the relevant morphological variables pertaining to the aneurysm and its relation to the ICA (Table 3). PCoA variables were not included in multivariate analysis because the PCoA was poorly visualized in the majority of patients. Our model revealed that a smaller volume, larger aneurysm neck diameter, and shorter ICA bifurcation to aneurysm distance were the most strongly associated with aneurysm rupture after adjusting for all other clinical and morphological variables (volume OR 0.98, 95% CI 0.95–0.99, p = 0.011; aneurysm neck diameter OR 3.52, 95% CI 1.01–11.79, p = 0.048; ICA bifurcation distance OR 0.44, 95% CI 0.19–0.80 p = 0.005).

Multivariate subgroup analysis was subsequently conducted in patients with visualized PCoA and included both clinical risk factors and morphological variables specific to the aneurysm and
its relation to the PCoA (Table 4). Several parameters were significantly associated with rupture, including younger age (OR 0.71, 95% CI 0.63–0.8, p = 0.031), increased neck diameter (OR 79.5, 95% CI 1.74–1.5 × 10^11, p = 0.018), and shorter ICA bifurcation to aneurysm distance (OR 0.04, 95% CI 5.78 × 10^{-5}–0.59, p = 0.011).

Of the 40 ruptured PCoA aneurysm included in our study, 9/40 presented with intracerebral hemorrhage on imaging. On univariate analysis, larger proximal ICA (ICA1) diameter (p = 0.023), shorter ICA bifurcation to aneurysm distance (p = 0.026), larger ICA1 to PCoA angle (p = 0.024), and lateral projection of ruptured PCoA aneurysms (p = 0.014) were significant independent predictors of intracerebral hemorrhage. (Table 5) Multivariate logistic regression demonstrated that the presence of intracerebral hemorrhage was significantly associated with male sex (female OR 7.5 × 10^{-6}, 95% CI 6.8 × 10^{-20}–0.5, p = 0.032), patients with lack of hypertension (hypertension OR 3.4 × 10^{-4}, 95% CI 2.7 × 10^{-4}–0.2, p = 0.009), aneurysms with lateral projection (OR 644, 95% CI 2.1–2.6 × 10^4, p = 0.020), smaller volume (OR 0.9, 95% CI 0.6–0.98, p = 0.010), larger maximum height (OR 16.4, 95% CI 1.7–4.2 × 10^2, p = 0.007), and smaller aneurysm angle (OR 0.9, 95% CI 0.6–0.99, p = 0.029). (Table 6)

**Discussion**

Posterior communicating artery aneurysms are among the most likely intracerebral aneurysms to rupture, and even smaller PCoA aneurysms that have not approached traditional size thresholds for intervention tend to rupture at a high rate [6,14,18–22]. Thus, further clinical and morphological parameters beyond size need to be delineated to assist in accurately predicting rupture risk when considering management options.

Because of the results from ISUIA, the size of the aneurysm has traditionally been the main determining factor for predicting rupture risk and treatment decisions for unruptured intracerebral aneurysms. However, follow-up studies have found that the majority of PCoA aneurysms rupture at smaller sizes than would be expected based on ISUIA [6,14,23]. This may represent the fact that flow induced hemodynamic stress involved at aneurysm site is important for rupture, independent of the size of the aneurysm itself [24–28]. In our study, aneurysm size as determined by maximal height was similar between ruptured and unruptured PCoA aneurysms. This is likely a result of treatment bias as larger unruptured PCoA aneurysms are more likely to undergo intervention. Given the matched aneurysm sizes between the two groups, the results of this study largely reflect the impact of morphological parameters unrelated to size.

In our prior study of morphologic characteristics of MCA aneurysms, we had divided morphologic enteries into 3 categories: morphology of the aneurysm itself, interaction between the aneurysm and associated vessels, and the relationship among the surrounding vasculature [10]. In our analysis of PCoA aneurysms, the most significant factors are the relationships of the surrounding vasculature.

Smaller ICA bifurcation to aneurysm distance was associated with ruptured aneurysms in both univariate and multivariate analyses. The mean difference between the two groups was almost one millimeter and represented a more than 10% decrease in distance. The scenario of the ICA bifurcation being far away from the PCoA origin is akin to a middle cerebral artery (MCA) bifurcation aneurysm while the scenario of the ICA bifurcation being immediately after the aneurysm is somewhat geometrically similar to an anterior communicating artery (ACoA) aneurysm. This is consistent with the results of the UCAS study where anterior communicating artery aneurysms have a higher rupture rate than middle cerebral artery aneurysms [6]. Hemodynamic modeling of aneurysms may be helpful in explaining this phenomenon [29–32]. Fluid dynamics evaluation of the two geometries have demonstrated high wall shear stress at the branch point in the scenario of long ICA versus low wall shear stress between two branch points in the case of short ICA [29,30]. In addition, low wall shear stress has been shown to be associated with aneurysm rupture [31]. Thus, while the difference in fluid dynamics between the two scenarios that contributes to rupture risk remains to be elucidated, the results are consistent with prior fluid dynamics results.
Ruptured aneurysms were also associated with larger ICA1 to ICA2 angles and ICA1 to PCoA angles but these trends were not statistically significant. A larger ICA1 to ICA2 angle means a sharper turn in the ICA. Aside from the ICA, the main daughter vessel influence on hemodynamics at the point of the aneurysm is conferred by the PCoA. The effect of a larger proximal ICA1 to PCoA angle is consistent with our prior study of MCA aneurysms where a sharper parent-daughter angle was significantly associated with ruptured aneurysms [10]. The greater the angle between the ICA1 and PCoA, the smaller the deviation of flow from the ICA1 parent vessel to the PCoA daughter vessel. This relationship can have a profound impact on the hemodynamics of flow and wall shear stress at the vascular branchpoint and aneurysm dome, and be linked to an increased risk of rupture [24,30,31,33–35].

The anatomical relationship of the ICA and PCoA vessels and aneurysms within the supraclinoid segment of intracranial vasculature is both varied and complex, and their orientation

### Table 2. Univariate analysis for rupture.

|                       | Unruptured (n = 23) | Ruptured (n = 40) | p value |
|-----------------------|---------------------|-------------------|---------|
| Age                   | 54.6 (15.4)         | 58.1 (11.7)       | 0.156   |
| Female sex            | 87%                 | 85%               | 0.830   |
| Smoking               | 52.2%               | 66.7%             | 0.259   |
| Hypertension          | 39.1%               | 45.7%             | 0.612   |
| Family history        | 63.0%               | 13.6%             | 0.363   |
| Multiple aneurysms    | 65.2%               | 37.5%             | 0.033   |
| Volume (mm³)          | 115.2 (133.2)       | 98.8 (79.3)       | 0.313   |
| Neck diameter (mm)    | 4.4 (1.5)           | 4.3 (1.3)         | 0.429   |
| Aneurysm max height (mm) | 5.9 (2.9)         | 6.0 (2.3)         | 0.441   |
| Aneurysm angle        | 94.6 (22.9)         | 93.7 (26.4)       | 0.444   |
| Aspect ratio          | 1.1 (0.6)           | 1.2 (0.5)         | 0.364   |
| Lateral projection    | 30%                 | 55%               | 0.052   |
| Size ratio            | 1.8 (1.1)           | 1.9 (0.9)         | 0.360   |
| Distance to ICA bifurcation (mm) | 11.3 (2.3)    | 10.4 (1.9)        | 0.076   |
| ICA1 vessel angle     | 52.8 (36.5)         | 50.1 (22.5)       | 0.385   |
| PCoA vessel angle     | 54.2 (26.6)         | 50.7 (22.1)       | 0.373   |
| ICA1 flow angle       | 106.4 (22.8)        | 102.4 (34.1)      | 0.306   |
| PCoA flow angle       | 88.1 (31.5)         | 93.7 (47.9)       | 0.368   |
| ICA1 to ICA2 angle    | 77 (19.2)           | 81.5 (20.9)       | 0.220   |
| ICA1 to PCoA angle    | 98.8 (19.4)         | 113.3 (29.3)      | 0.080   |

### Table 3. Multivariate analysis for rupture.

|                       | Odds Ratio (95% CI) | p value |
|-----------------------|---------------------|---------|
| Age                   | 0.95 (0.84–1.05)    | 0.347   |
| Female sex            | 2.9 (0.2–64.36)     | 0.441   |
| Smoking               | 0.33 (0.29–2.47)    | 0.287   |
| Hypertension          | 3.51 (0.35–57.23)   | 0.295   |
| Family history        | 1.85 (0.04–93.54)   | 0.743   |
| Multiple aneurysms    | 0.20 (0.01–1.66)    | 0.145   |
| Volume (mm³)          | 0.98 (0.95–0.99)    | 0.011   |
| Neck diameter (mm)    | 3.52 (1.01–17.9)    | 0.048   |
| Aneurysm max height (mm) | 2.13 (0.37–15.73)  | 0.404   |
| Aneurysm angle        | 1 (0.96–1.03)       | 0.812   |
| Aspect ratio          | 0.92 (0.03–22.77)   | 0.960   |
| Size ratio            | 0.65 (0.01–44.63)   | 0.838   |
| Distance to ICA bifurcation (mm) | 0.44 (0.19–0.80) | 0.005   |
| ICA1 vessel angle     | 1 (0.97–1.03)       | 0.865   |
| ICA1 flow angle       | 0.99 (0.95–1.02)    | 0.501   |
| ICA1 to ICA2 angle    | 1.02 (0.97–1.06)    | 0.490   |

### Table 4. Multivariate analysis for rupture in the subgroup of aneurysms with visible PCoA.

|                       | Odds Ratio (95% CI) | p value |
|-----------------------|---------------------|---------|
| Age                   | 0.71 (0.03–0.98)    | 0.031   |
| Smoking               | 7.04 (0.002–7.16 × 10^{-9}) | 0.652 |
| Hypertension          | 2.79 (4.9 × 10^{-4}–4.07 × 10^{-2}) | 0.730 |
| Family history        | 7.34 × 10^{-19} (7.47–) | 0.060 |
| Neck diameter (mm)    | 79.5 (1.74–1.5 × 10^{-10}) | 0.018 |
| Aneurysm max height (mm) | 0.49 (0.045–130)   | 0.565   |
| Distance to ICA bifurcation (mm) | 0.04 (5.78 × 10^{-5}–0.59) | 0.011 |
| ICA1 vessel angle     | 1.05 (0.88–1.36)    | 0.528   |
| PCoA vessel angle     | 2.54 (6.96 × 10^{-2}–2.65 × 10^{-2}) | 0.920 |
| ICA1 flow angle       | 1.7 × 10^{-4} (1.15 × 10^{-16}–64.9) | 0.206 |
| PCoA flow angle       | 0.99 (0.87–1.95)    | 0.948   |
has specific implications for the vascular and morphological parameters we considered. Yasargil described five categories of ICA-PCoA aneurysms according to the orientation of the aneurysm fundus: anterolateral, superolateral, superior posterolateral (supratentorial), inferior posterolateral (infratentorial), and inferior posteromedial [36]. The most important configurations in modern practice relate to the lateral versus inferior projection of the aneurysm dome since inferiorly projecting aneurysms commonly compress the oculomotor nerve while laterally projecting aneurysms can be tightly adherent to the temporal lobe and are monly compress the oculomotor nerve while laterally projecting aneurysms would therefore be important in evaluating not only the risk of rupture but also the possible sequelae of a rupture. Lateral projection of the aneurysm dome is a well-known risk factor for intracerebral hemorrhage, and this was confirmed in our analysis [38]. The projections of these aneurysms into the temporal lobe make them much more likely to cause intracerebral hemorrhage upon rupture. Interestingly, smaller volume, larger maximum height, and smaller aneurysm angle were also significantly associated with intracerebral hemorrhage. Smaller volume and larger aneurysm maximum height implies a more elongated aneurysm which would be more likely to project into the temporal lobe and result in an intracerebral hemorrhage. The association of lack of hypertension with intracerebral hemorrhage may be because hypertension increases rupture risk at a smaller size [39], that is, prior to the aneurysm being large enough to project into the temporal lobe. Finally, the association with male sex does not have a clear morphological explanation and warrants further study.

**Limitations**

There are a number of limitations to this study. This is a retrospective study of patients with PCoA aneurysms who were treated. There is therefore an inherent bias selection of the unruptured aneurysms. Also, all inferences made about the parameters examined can be associated with ruptured aneurysms only, and are not necessarily predictors of rupture risk. Furthermore, certain features of the aneurysm may be altered by the ruptured state. Nevertheless, the significant parameters in this study are largely that of the surrounding vasculature, which would not be altered by the rupture of an aneurysm. Finally, our model is a simplified one where material properties of the arterial wall, boundary conditions and other parameters that would affect the fluid dynamics were not taken into account. Measurements were performed manually taking advantage of the 3D slicer software fiducial tractography capabilities. Though significant steps have been made towards automated methods of assessing morphology to achieve greater consistency in measurement [40], we believe that measures made this way best recreate the applicability of our methodology in a clinical setting. This affords a clinician the ability to make measurements utilizing patient CTAs and open source software in an efficient manner.

**Conclusion**

We performed a study dedicated to the morphological characteristics of posterior communicating artery aneurysms and

### Table 5. Univariate analysis for intracerebral hemorrhage.

|                   | ICH (n = 9) | None (n = 31) | p value |
|-------------------|-------------|---------------|---------|
| Age               | 60.2        | 52.9          | 0.146   |
| Female sex        | 77.8%       | 87.1%         | 0.607   |
| Hypertension      | 37.5%       | 48.2%         | 0.594   |
| Multiple aneurysms| 55.6%       | 32.3%         | 0.210   |
| Lateral projection| 88.9% (8/9) | 45.2% (14/31) | 0.014   |
| Volume (mm³)      | 77.2        | 106.0         | 0.135   |
| Neck diameter (mm)| 4.1         | 4.4           | 0.208   |
| Aneurysm max height (mm)| 6.1 | 5.9 | 0.388 |
| Aneurysm angle    | 88.4        | 95.5          | 0.232   |
| Aspect ratio      | 1.3         | 1.2           | 0.241   |
| ICA1 diameter (mm)| 3.6         | 2.9           | 0.0231  |
| ICA1 vessel angle | 41.6        | 53.0          | 0.106   |
| ICA1 flow angle   | 107.6       | 100.6         | 0.223   |
| Size ratio        | 2.0         | 1.9           | 0.385   |
| Distance to ICA bifurcation (mm) | 9.2 | 10.9 | 0.026 |
| PCoA vessel angle | 48.8        | 51.5          | 0.439   |
| PCoA flow angle   | 81.8        | 98.0          | 0.309   |
| ICA1 to ICA2 angle| 82.9        | 81.0          | 0.382   |
| ICA1 to PCoA angle| 131.5       | 106.6         | 0.024   |

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### Table 6. Multivariate analysis for intracerebral hemorrhage.

|                   | Odds Ratio (95% CI) | p value |
|-------------------|---------------------|---------|
| Age               | 1.1 (0.9–2.2)       | 0.437   |
| Female sex        | 7.5·10⁻⁶ (6.8·10⁻²⁰–0.5) | 0.032   |
| Hypertension      | 3.4·10⁻⁶ (2.7·10⁻⁴–0.2) | 0.009   |
| Multiple aneurysms| 1.9 (0.3–289)       | 0.748   |
| Lateral projection| 644 (2.1–2.6·10¹¹)  | 0.020   |
| Volume (mm³)      | 0.9 (0.6–0.98)      | 0.010   |
| Neck diameter (mm)| 18.3 (0.2–1.0·10⁶) | 0.305   |
| Aneurysm max height (mm)| 16.4 (1.7–4.2·10³) | 0.007   |

|                   | Odds Ratio (95% CI) | p value |
|-------------------|---------------------|---------|
| Aneurysm angle    | 0.9 (0.6–0.99)      | 0.029   |
| Aspect ratio      | 970 (9.006–2.0·10⁶) | 0.339   |
| ICA1 diameter (mm)| 0.06 (3.3·10⁻⁶–2.2) | 0.129   |
| ICA1 vessel angle | 0.92 (0.76–1.02)    | 0.144   |
| ICA1 flow angle   | 1.1 (0.96–1.7)      | 0.204   |

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found that ruptured aneurysms were significantly associated with shorter distance from the aneurysm to the internal carotid artery bifurcation. Furthermore, presentation with an intracerebral hemorrhage is associated with smaller aneurysm volume, larger aneurysm maximum height and smaller aneurysm angle, in addition to lateral projection, male sex, and lack of hypertension. Although they do not replace well-established clinical determinants of PCoA aneurysm rupture risk such as aneurysm size, these features do add an additional dimension of analysis that can be rapidly applied by clinicians when examining 3D reconstructions of ruptured aneurysms. These morphological associations are unique to the PCoA aneurysms and highlight the importance of location specific features when determining the natural history of aneurysms.

Author Contributions
Conceived and designed the experiments: RD AH NL KF AD. Performed the experiments: AH NL NC MS. Analyzed the data: AH RD NL NC MS. Wrote the paper: AH RD NL AD KF.

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