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Integrating aneurysm morphology and clinical factors into an exploratory rupture risk score

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Abstract: Accurate discrimination between intracranial aneurysms at high risk of rupture and those with low rupture potential remains a major clinical challenge. While aneurysm morphology and clinical factors have both been implicated in rupture risk, their integration into simple, clinically applicable prediction tools is limited. We conducted a retrospective observational study including a heterogeneous cohort of intracranial aneurysms evaluated at a single tertiary center. In patients with multiple aneurysms, each aneurysm was analyzed as an independent observation. Morphological parameters were obtained from three-dimensional vascular imaging, including dome width, neck width, bottleneck factor, and the presence of a daughter dome. Clinical variables included age, sex, arterial hypertension, and type 2 diabetes mellitus. Multiple predefined bottleneck factor thresholds were tested for association with rupture. Based on univariate analysis and clinical relevance, an exploratory rupture risk score was constructed and internally validated using bootstrap resampling, permutation testing, and calibration assessment of the proposed score and multivariable models. The study cohort comprised 259 aneurysms, of which 113 were ruptured and 146 unruptured at presentation. Bottleneck factor thresholds ranging from >1.2 to >2.0 were significantly associated with rupture, with the strongest association observed at a threshold >1.4 (OR 5.54, 95% CI 3.19–9.61; $p < 0.001$). In multivariable analysis, bottleneck factor >1.4 (adjusted OR 4.47, 95% CI 2.39–8.35; $p < 0.001$) and daughter dome presence (adjusted OR 41.06, 95% CI 9.37–179.81; $p < 0.001$) remained independently associated with rupture. The additive score demonstrated moderate discrimination (AUC 0.78), with improved performance observed in multivariable models (AUC 0.826–0.884). A partially reconstructed PHASES score yielded an AUC of 0.73. A simple morphology-driven rupture risk score integrating bottleneck factor, daughter dome presence, and arterial hypertension demonstrated consistent internal associations and moderate discriminatory performance in a heterogeneous intracranial aneurysm cohort. These findings are exploratory and hypothesis-generating, and external validation in independent prospective populations is required before clinical implementation.

Keywords: intracranial aneurysm; rupture; bottleneck factor; daughter dome; rupture risk score.

1. Introduction

Saccular intracranial aneurysms, defined as focal outpouchings of the arterial wall, are considered acquired vascular lesions affecting approximately 3% of the general population, with increasing detection rates driven by the widespread use of modern neurovascular imaging techniques [1-3]. Although relatively uncommon, with an estimated annual incidence of aneurysmal subarachnoid hemorrhage (aSAH) of approximately 9 per 100,000 individuals, aneurysm rupture remains a devastating event, associated with high early mortality and substantial long-term morbidity among survivors [4-6].

Given the potentially catastrophic consequences of rupture, preventive treatment of unruptured intracranial aneurysms has been widely adopted. However, both surgical and endovascular interventions are associated with non-negligible risks, including neurological morbidity and mortality, particularly in low-risk aneurysms [7-10]. As a result, accurate identification of aneurysms at high risk of rupture, while avoiding overtreatment of lesions with low rupture potential, remains a central challenge in contemporary cerebrovascular practice.

Several clinical and anatomical factors have been associated with aneurysm rupture risk, including patient demographics, vascular risk factors, and aneurysm location [5], [9], [11]. In parallel, a growing body of evidence has highlighted the importance of aneurysm morphology in rupture risk stratification. Geometric indices reflecting aneurysm shape, such as aspect ratio and related dome-to-neck measurements, have been shown to influence intra-aneurysmal hemodynamics and wall stress, thereby contributing to rupture susceptibility [12-15]. In particular, irregular aneurysm morphology, including the presence of daughter domes, has consistently been associated with rupture across multiple studies [12], [13], [16].

Despite these advances, most existing rupture prediction models either rely heavily on population-level clinical factors or incorporate complex morphological parameters that may limit routine clinical applicability. While established tools such as the PHASES (Population, Hypertension, Age, Size, Earlier subarachnoid hemorrhage, Site) score provide valuable guidance, their performance varies across patient subgroups and aneurysm locations, and they may not fully capture morphology-driven rupture risk [11]. Although numerous studies have evaluated individual morphological markers of rupture, fewer investigations have examined whether a limited number of routinely measurable geometric parameters can be combined with clinical variables into a simplified additive framework applicable in daily practice. Most published models rely either on large multicenter datasets or complex computational descriptors not always feasible in routine tertiary care environments. Moreover, many previously proposed grading systems were developed in selected cohorts or lack transparent reporting and validation frameworks [8], [17], [18].

Accordingly, there remains a need for simple, reproducible, and clinically applicable rupture risk scores that integrate key morphological features with readily available clinical variables and can be applied across a heterogeneous population of intracranial aneurysms. The purpose of this study was to develop and internally validate an exploratory rupture risk score based on aneurysm morphology and clinical factors in a mixed cohort of intracranial aneurysms, with the aim of improving rupture risk stratification while maintaining methodological transparency and clinical usefulness.

Among the various morphological parameters proposed in the literature, the bottleneck factor was selected for further evaluation because it reflects the geometric relationship between aneurysm dome width and neck width, characteristics that may directly influence intra-aneurysmal flow patterns and wall stress distribution. Previous studies have identified bottleneck factor as a reproducible marker associated with aneurysm instability and rupture risk. In addition, bottleneck factor can be measured directly from standard three-dimensional angiographic reconstructions without requiring advanced computational modeling, making it particularly suitable for routine clinical assessment. Although other parameters such as aspect ratio and size ratio have also been investigated, reported results remain heterogeneous across different aneurysm locations and populations. Therefore, we focused on the bottleneck factor as a simple and clinically applicable morphological parameter while also evaluating the contribution of daughter dome morphology and established clinical risk factors. Based on prior literature, several predefined bottleneck factor thresholds were evaluated. For score construction, the threshold of 1.4 was retained because it demonstrated the strongest association with rupture while remaining within the range most frequently reported in previous morphological studies.

2. Methods

Study design and patient selection

This retrospective observational study included patients diagnosed with intracranial saccular aneurysms treated and/or evaluated at a single tertiary referral center. Consecutive aneurysm cases with available imaging suitable for morphological assessment were included. Fusiform, dissecting, traumatic, and mycotic aneurysms were excluded from analysis. For patients with multiple aneurysms, each aneurysm was analyzed as an independent observation. This approach assumes independence between aneurysms, which may not fully account for within-patient clustering effects. Given the exploratory nature of the study and the relatively limited number of multiple-aneurysm cases, no clustering adjustment was performed.

Rupture status was determined at presentation based on clinical findings and imaging evidence of aneurysmal subarachnoid hemorrhage. The study cohort comprised both ruptured and unruptured aneurysms.

The analytical strategy consisted of three sequential steps. First, ruptured and unruptured aneurysms were compared to identify clinical, morphological, and anatomical features associated with rupture status. Second, variables demonstrating significant associations or considered clinically relevant were incorporated into an exploratory additive rupture risk score. Third, the discriminatory performance and internal validity of the proposed score were evaluated using logistic regression, ROC curve analysis, bootstrap resampling, permutation testing, and multivariable adjustment.

Imaging analysis and morphological measurements

All aneurysm measurements were obtained exclusively from three-dimensional rotational digital subtraction angiography (3D-DSA) studies. Measurements were performed independently by two investigators experienced in cerebrovascular imaging analysis using reconstructed 3D volumes and standardized projection alignment to ensure consistent dome and neck visualization. Any discrepancies were resolved by consensus review. The following geometric parameters were recorded for each aneurysm: dome width, neck width, and bottleneck factor, defined as the ratio between maximum dome diameter and neck width measured at the level of the parent vessel interface on 3D reconstruction.

The presence of a daughter dome was assessed visually on three-dimensional reconstructions and defined as any secondary lobulation or irregular protrusion arising from the aneurysm dome.

Because no universally accepted bottleneck factor cutoff has been established in the literature, several predefined thresholds (1.2, 1.4, 1.6, 1.8, and 2.0) were explored. These values were selected to encompass the range of bottleneck factor thresholds most frequently reported in previous morphological studies of intracranial aneurysms and were explored to assess the consistency of the association between bottleneck factor and rupture status across clinically plausible cutoff values. The purpose of this analysis was not formal cutoff optimization, but rather to assess the stability of the association between bottleneck factor and rupture status across clinically plausible threshold values. The threshold of 1.4 was subsequently retained for development of the exploratory score because it demonstrated the strongest association with rupture in the study cohort while remaining consistent with previously reported morphological ranges.

Clinical and anatomical variables

Clinical variables collected included patient age, sex, arterial hypertension and type 2 diabetes mellitus. Anatomical location of each aneurysm was recorded and categorized according to arterial segment, including the anterior communicating artery (ACoA), posterior communicating artery (PCoA), middle cerebral artery (MCA) and the various segments of the internal carotid artery (ICA).

Statistical analysis

Continuous variables are reported as mean ± standard deviation and categorical variables as counts and percentages. Univariate associations between rupture status and categorical variables were assessed using Fisher's exact test. Continuous variables were analyzed using univariate logistic regression, with odds ratios (ORs), 95% confidence intervals (CIs), and corresponding p values reported.

Based on univariate results and clinical relevance, an exploratory rupture risk score was constructed. The score consisted of three binary components: bottleneck factor >1.4, presence of a daughter dome, and arterial hypertension. Each component contributed one point, yielding a total score ranging from 0 to 3 points.

In addition to univariate analyses, multivariable logistic regression models were constructed to evaluate the independent contribution of score components to rupture status. A primary multivariable model included the three variables incorporated into the exploratory score (bottleneck factor >1.4, daughter dome presence, and arterial hypertension). A secondary extended model further adjusted for age, sex, type 2 diabetes mellitus, and aneurysm location (ACoA, PCoA, and C6 segment of the ICA) to account for potential confounding effects.

Discriminatory performance was assessed using receiver operating characteristic (ROC) curve analysis with calculation of the area under the curve (AUC) for the additive score, the multivariable models, and a partially reconstructed PHASES score based on available cohort variables (age, hypertension, aneurysm size, and location), assuming no prior subarachnoid hemorrhage and a non-high-risk population classification.

Internal validation of the additive score was performed using bootstrap resampling to obtain optimism-corrected 95% confidence intervals for the AUC. Calibration was assessed using the Hosmer–Lemeshow goodness-of-fit test. A two-sided p value <0.05 was considered statistically significant.

3. Results

The study cohort included 259 patients with intracranial aneurysms, of whom 193 were women and 66 were men, with a mean age of 57.4 ± 12.6 years (range 15–90). The most frequent aneurysm location was the MCA (28.6%), followed by the ACoA (22.8%) and the C6 segment of the ICA (19.7%). A total of 113 aneurysms were ruptured and 146 were unruptured at presentation.

Following the descriptive analysis of the study cohort, we first examined the association between aneurysm rupture and predefined bottleneck factor thresholds to evaluate clinically plausible cutoffs for subsequent analyses.

Univariate analysis demonstrated a significant association between aneurysm rupture and multiple predefined bottleneck factor thresholds, with all tested cut-offs showing increased odds of rupture (Table 1). The strongest association was observed for a bottleneck factor threshold >1.4 (OR 5.54, 95% CI 3.19–9.61; p < 0.001), while higher thresholds were also associated with rupture but with progressively lower effect sizes, suggesting a non-linear relationship between bottleneck magnitude and rupture risk.

Table 1 - Univariate association between predefined bottleneck factor thresholds and aneurysm rupture status.

Bottleneck threshold	OR	95% CI	p value (Fisher)
> 1.2	4.476	2.457–8.155	p < 0.001
> 1.4	5.536	3.190–9.609	p < 0.001
> 1.6	4.430	2.620–7.489	p < 0.001
> 1.8	4.163	2.435–7.118	p < 0.001
> 2.0	3.893	2.229–6.800	p < 0.001

Odds ratios (ORs), 95% confidence intervals (CIs), and p values derived from Fisher's exact test are shown for each tested threshold.

Based on the observed association between bottleneck factor thresholds and rupture status, we next performed a comprehensive univariate analysis of clinical, morphological, and anatomical variables to identify additional factors associated with rupture.

Univariate analysis of clinical, morphological, and anatomical variables demonstrated that several factors were significantly associated with aneurysm rupture (Table 2).

Table 2 - Univariate associations between clinical, morphological, and anatomical variables and aneurysm rupture.

Variable	OR	95% CI	p value
Female sex	0.36	0.20-0.65	p = 0.0005
Arterial hypertension	1.84	1.12-3.02	p = 0.0177
Type 2 diabetes	1.06	0.63-1.78	p = 0.817
Daughter dome presence	47.65	11.23-202.20	p < 0.001
Age (per 1 year)	1.01	0.99-1.03	p = 0.332
Dome width (per 1 mm)	1.11	1.04-1.18	p = 0.001
Neck width (per 1 mm)	1.01	0.94-1.09	p = 0.806
Bottleneck factor (per 0.1 increase)	1.10	1.06-1.14	p < 0.001
Location – ACoA (compared to all others)	7.95	3.95-16.00	p < 0.001
Location – PCoA (compared to all others)	2.85	1.17-6.91	p = 0.0289
Location – C6 segment of ICA (compared to all others)	0.21	0.10-0.46	p < 0.001

Fisher's exact test was used to evaluate categorical variables, while univariate logistic regression was applied to continuous parameters. Morphological indices, including bottleneck factor and the presence of a daughter dome, showed the strongest associations with rupture. Among anatomical locations, aneurysms arising from the ACoA and PCoA were associated with higher rupture odds, whereas aneurysms located at the C6 segment of the ICA demonstrated a significantly lower likelihood of rupture. In contrast, age, type 2 diabetes mellitus and neck width were not significantly associated with rupture status.

Variables demonstrating significant associations in univariate analysis, together with clinically relevant covariates, were subsequently selected for the construction of an exploratory rupture risk score.

Based on the results of the univariate analysis, an exploratory rupture risk score was constructed by selecting variables that demonstrated significant associations with rupture as well as clinically relevant covariates. The final score included three binary components: bottleneck factor above the selected threshold of 1.4, presence of a daughter dome, and arterial hypertension. Each variable was assigned one point, resulting in a cumulative score ranging from 0 to 3 points. Variables that did not show a significant association with rupture or were considered redundant with included morphological indices were excluded from score construction.

The exploratory rupture risk score was defined as the sum of three binary variables—bottleneck factor >1.4, presence of a daughter dome, and arterial hypertension—yielding a total score ranging from 0 to 3 points (Table 3).

Table 3 - Definition of the exploratory morphology-clinical rupture risk score.

Score component	Criteria	Points assigned
Bottleneck factor	> 1.4	1
Daughter dome	Present	1
Arterial hypertension	Present	1
Total score	Sum of individual components	0-3

The proposed rupture risk score was significantly associated with aneurysm rupture and moderate discriminatory performance (Table 4). Increasing score values were significantly associated with rupture status, with an odds ratio of 4.12 per 1-point increase (95% CI 2.81–6.04, p < 0.001). A monotonic increase in rupture proportion was observed across score categories, ranging from 11.3% for a score of 0 to 90.9% for a score of 3. Receiver operating characteristic analysis yielded an AUC of 0.78, with an optimism-corrected bootstrap 95% confidence interval of 0.73–0.83. The discriminatory ability of

the score remained significant on permutation testing (p = 0.0002), supporting the internal validity of the proposed model.

Table 4 – Distribution of rupture rates according to additive rupture risk score categories.

Score	N	Ruptured n (%)
0	62	7 (11.3%)
1	80	28 (35%)
2	75	51 (68%)
3	22	20 (90.9%)

A monotonic increase in rupture proportion was observed with increasing score categories.

In multivariable logistic regression including the three score components (Table 5), bottleneck factor >1.4 (OR 4.47, 95% CI 2.39–8.35, p < 0.001) and daughter dome presence (OR 41.06, 95% CI 9.37–179.81, p < 0.001) remained independently associated with rupture status, whereas arterial hypertension showed a borderline association (OR 1.75, 95% CI 0.95–3.20, p = 0.071). The apparent AUC of this model was 0.826.

In an extended multivariable model adjusting for age, sex, type 2 diabetes mellitus, and aneurysm location, bottleneck factor >1.4 (OR 3.33, 95% CI 1.66–6.69, p = 0.0007) and daughter dome presence (OR 40.01, 95% CI 8.43–190.02, p < 0.001) remained independently associated with rupture. Location at the anterior communicating artery was also independently associated with rupture (OR 5.31, 95% CI 2.24–12.62, p < 0.001).

The extended model demonstrated an apparent AUC of 0.884. Bootstrap optimism correction of the extended model yielded an optimism-corrected AUC of 0.868, indicating limited overfitting. Calibration analysis using the Hosmer–Lemeshow goodness-of-fit test demonstrated good calibration of the additive rupture risk score ($\chi^2 = 0.035$, df = 1, p = 0.851), whereas the extended multivariable model showed evidence of miscalibration ($\chi^2 = 20.726$, df = 8, p = 0.0079).

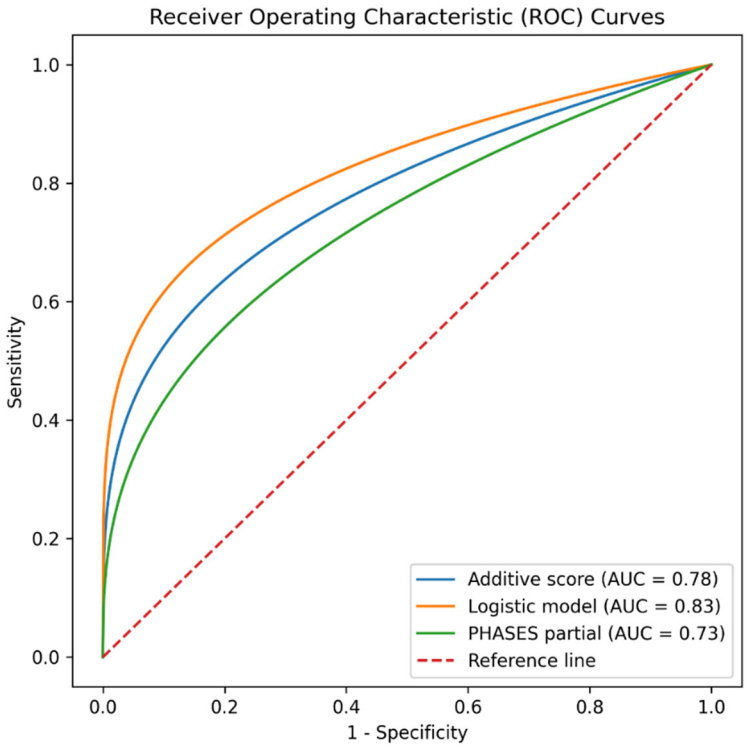
A partially reconstructed PHASES score calculated using available variables (age, hypertension, aneurysm size, and location) yielded an apparent AUC of 0.733 in the present cohort. Detailed multivariable estimates and model discrimination metrics are summarized in Table 5.

Table 5 – Multivariable logistic regression analysis and model discrimination.

Variable	Adjusted OR	95% CI	p value
Bottleneck factor > 1.4	4.47	2.39-8.35	<0.001
Daughter dome presence	41.06	9.37-179.81	<0.001
Arterial hypertension	1.75	0.95-3.20	0.071
Extended multivariable model			
Bottleneck factor > 1.4	3.33	1.66-6.69	0.0007
Daughter dome presence	40.01	8.43-190.02	<0.001
ACoA location	5.31	2.24-12.62	<0.001
Model Discrimination			
Model		AUC	
Additive 0-3 score		0.78	
Logistic (3 variables)		0.826	
Extended model		0.884	
PHASES (partial)		0.733	

Adjusted odds ratios (ORs) with 95% confidence intervals (CIs) are presented for the primary and extended models. Discriminatory performance is summarized using area under the curve (AUC) values. ROC curve analysis comparing the additive score, multivariable models, and the partially reconstructed PHASES score is presented in Figure 1.

Figure 1 - Receiver operating characteristic (ROC) curve analysis comparing model discrimination.



4. Discussion

In this study, we developed and internally validated an exploratory rupture risk score integrating morphological and clinical variables, which was significantly associated with aneurysm rupture and demonstrated moderate discriminatory performance in a heterogeneous cohort of intracranial aneurysms. Because the score components were selected based on univariate associations, the model should be considered exploratory and hypothesis-generating rather than a fully adjusted multivariable predictive model. Multivariable adjustment confirmed the independent association of morphological parameters with rupture status, although the model remains exploratory in nature. Although the extended multivariable model demonstrated higher apparent discrimination, the additive score was intentionally designed for simplicity and ease of implementation rather than maximal statistical performance.

The score integrates one geometry-derived parameter, one marker of morphological irregularity, and one clinical risk factor. All three variables have been previously associated with rupture in different contexts, and their joint inclusion resulted in a stepwise increase in rupture proportion across score categories.

Morphological irregularity emerged as the strongest contributor to rupture risk in the present cohort. The presence of a daughter dome showed the most pronounced univariate association with rupture, consistent with previous reports linking irregular aneurysm shape to altered intra-aneurysmal flow patterns, focal wall stress, and structural instability [12-14], [16]. The very high odds ratio observed for daughter dome presence likely reflects both true biological association and potential sparse-data amplification, as suggested by the wide confidence interval. The relatively small number of aneurysms exhibiting daughter dome morphology may have contributed to the wide confidence intervals observed for this variable. This finding should therefore be interpreted with caution and validated in larger datasets. Prior hemodynamic

and morphological studies have demonstrated that shape-based parameters, including aspect ratio and related dome-to-neck metrics, are closely related to rupture status [13-15]. In this context, the bottleneck factor serves as a simple surrogate for more complex geometric descriptors, capturing critical aspects of aneurysm shape while remaining easy to assess in routine clinical practice.

Among the evaluated bottleneck factor thresholds, a cutoff value of >1.4 showed the strongest association with rupture in this cohort. Although higher thresholds were also significantly associated with rupture, the effect size decreased with increasing cutoff values, suggesting a non-linear relationship between bottleneck magnitude and rupture risk. Retaining the >1.4 threshold for score construction balanced statistical performance with reproducibility and comparability to previously reported morphology-based indices [13-15].

However, the selection of the threshold yielding the strongest observed association introduces an inherent risk of optimism bias and data-driven threshold optimization. Although the evaluated cutoff values were predefined based on ranges reported in previous morphological studies, the final choice of the >1.4 threshold was influenced by the performance observed within the present dataset. Consequently, the reported effect estimates may be somewhat inflated and should be interpreted cautiously. This consideration is particularly relevant given the exploratory nature of the study and the absence of external validation. Future studies should evaluate the stability of this threshold in independent cohorts and determine whether bottleneck factor is best modeled as a continuous variable rather than dichotomized at a specific cutoff.

Arterial hypertension was the only clinical variable retained in the final score. Hypertension has long been recognized as a risk factor for aneurysm formation and rupture, potentially through its effects on hemodynamic stress and vascular wall remodeling [5], [9]. Its inclusion in the score enhances clinical interpretability and underscores the relevance of integrating patient-level risk factors with aneurysm-specific morphological features. Although female sex demonstrated a significant univariate association with rupture, sex was not included in the final score in order to preserve parsimony and avoid inclusion of demographic variables that may reflect referral patterns rather than aneurysm-specific biological instability. Similarly, age and type 2 diabetes mellitus were excluded to minimize model complexity and reduce the risk of overfitting in a single-center cohort.

Anatomical location demonstrated strong associations with rupture in univariate analysis, particularly for aneurysms arising from the anterior communicating artery and posterior communicating artery, in line with prior location-based risk stratification models [9], [11]. However, location was deliberately excluded from the primary score to maintain a morphology- and clinic-centered approach applicable across diverse aneurysm distributions. This decision reflects a trade-off between maximal discriminatory performance and broader applicability, similar to challenges encountered in existing prediction models such as PHASES [11].

Compared with established rupture prediction tools, the present score emphasizes morphological features that can be readily extracted from standard imaging without requiring complex computational modeling. As illustrated in Figure 1, the additive score achieved higher discrimination than the partially reconstructed PHASES model in this cohort while maintaining conceptual simplicity. Population-based models provide valuable guidance at the cohort level; however, their performance may vary across subgroups and aneurysm locations [11]. The proposed score should be viewed as an exploratory adjunct for risk assessment and hypothesis generation rather than a tool intended for independent clinical decision-making. Further validation in external cohorts is required before any consideration of routine clinical application.

Although the extended multivariable model achieved the highest apparent discrimination, calibration analysis suggested poorer agreement between predicted and observed rupture probabilities. In contrast, the simpler additive score demonstrated

good calibration, supporting its potential value as an exploratory framework for future risk stratification studies.

Several limitations should be acknowledged. This study is retrospective and derived from a single-center cohort, which may introduce selection bias. As a tertiary referral center, the case mix may overrepresent complex or symptomatic aneurysms, potentially inflating rupture prevalence and limiting generalizability to screening populations. Posterior circulation aneurysms were underrepresented in this cohort, limiting extrapolation of the findings to this subgroup. Previous history of subarachnoid hemorrhage and multiplicity effects were not incorporated into the score and may influence rupture risk independently. An additional methodological consideration relates to the treatment of multiple aneurysms from the same patient as independent observations. This approach was adopted to maximize the available aneurysm-level information; however, it does not account for potential within-patient clustering. Consequently, aneurysms originating from the same individual may share biological, genetic, or hemodynamic characteristics that could partially violate the assumption of statistical independence. Although the number of patients with multiple aneurysms was relatively limited, some effect estimates and confidence intervals may therefore be influenced by unaccounted clustering.

A critical methodological limitation is the assessment of aneurysm morphology after rupture in ruptured lesions. It is recognized that aneurysm geometry may change during or immediately following rupture as a consequence of wall deformation, partial dome collapse, intraluminal thrombosis, or remodeling of the aneurysm sac. Consequently, some morphological characteristics observed in ruptured aneurysms may represent consequences of rupture rather than pre-existing determinants of instability. For this reason, the present study should be interpreted as identifying factors associated with rupture status in a cross-sectional cohort rather than establishing true prospective predictors of future aneurysm rupture. Prospective longitudinal studies of initially unruptured aneurysms remain necessary to determine the predictive value of the proposed parameters.

Although internal validation using bootstrap and permutation testing supports the robustness of the findings, external validation in independent datasets is required before clinical implementation. Additionally, hemodynamic parameters and advanced three-dimensional shape descriptors were not included and may further refine rupture risk prediction in future studies. Although calibration was assessed using the Hosmer–Lemeshow goodness-of-fit test, more comprehensive calibration analyses, including graphical calibration assessment, were not performed. Consequently, the agreement between predicted and observed rupture probabilities should be interpreted cautiously and warrants further evaluation in external validation studies.

An additional limitation relates to the exploratory evaluation of multiple bottleneck factor thresholds. Although the tested cutoff values were selected a priori based on ranges reported in previous studies, choosing the threshold with the strongest observed association may introduce optimism bias and potentially overestimate the effect size. Consequently, the proposed cutoff should be considered hypothesis-generating and requires validation in independent cohorts.

Residual confounding cannot be excluded. Although the multivariable analyses incorporated several clinically relevant covariates, information regarding certain established aneurysm risk factors was not consistently available within the retrospective dataset and therefore could not be included in the adjustment models. These factors include smoking status, family history of intracranial aneurysms, dyslipidemia, connective tissue disorders, and broader measures of vascular and systemic comorbidity burden. Because several of these variables have previously been associated with aneurysm formation, growth, and rupture, unmeasured confounding may have influenced the magnitude of the reported associations. Consequently, the observed effect

estimates should be interpreted cautiously and require confirmation in prospective studies with more comprehensive clinical characterization.

5. Conclusions

In this retrospective single-center analysis, we developed an exploratory morphology-clinical rupture risk score that demonstrated consistent internal associations and moderate discriminatory performance in a heterogeneous intracranial aneurysm cohort. By combining bottleneck factor, daughter dome presence, and arterial hypertension into a simple additive framework, the proposed model highlights the potential value of integrating routinely measurable morphological parameters with clinical risk factors. From a practical perspective, aneurysms exhibiting both morphological irregularity (daughter dome) and an elevated bottleneck factor may help identify aneurysms deserving closer surveillance and more careful multidisciplinary evaluation, particularly when additional clinical risk factors such as hypertension are present. These findings are hypothesis-generating and require external validation in independent prospective datasets before clinical implementation.

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