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Original Research

Development of treatment-specific outcome prediction models for intracranial aneurysm after coiling or clipping

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ABSTRACT

Background: Treatment-specific outcome prediction after intracranial aneurysm repair remains limited in resource-constrained settings, where complex case and access to endovascular care may differ among centers. We aimed to develop preliminary treatment-specific prediction models for in-hospital outcomes after endovascular coiling or microsurgical clipping in an comprehensive stroke center.

Methods: Consecutive patients treated with coiling or clipping were analyzed. In-hospital endpoints were mortality, good functional outcome defined as Glasgow Outcome Scale-Extended (GOSE) 5–8, and recovery of Glasgow Coma Scale (GCS) to premorbid baseline. Separate multivariable logistic regression models were developed for each treatment-outcome pair after multiple imputation, bidirectional Akaike information criterion selection, and multicollinearity assessment. Discrimination was quantified using area under the curve (AUC), and bootstrap internal validation (500 resamples) was used to estimate optimism-corrected performance.

Results: The retrospective cohort (n = 436; 224 coiling, 212 clipping) was predominantly ruptured (86.9 %). In-hospital mortality was 11.2 % after coiling and 16.5 % after clipping. Good GOSE occurred in 47.3 % and 37.7 %, respectively, and GCS recovery occurred in 79.0 % and 65.1 %, respectively. Apparent AUCs for coiling and clipping were 0.826 and 0.815 for mortality, 0.707 and 0.793 for good GOSE, and 0.768 and 0.765 for GCS recovery. Notably, the retained predictor structure differed by treatment modality: coiling mortality retained age, hypertension, World Federation of Neurosurgical Societies (WFNS) grade, and dome height, whereas the better-performing clipping models incorporated GCS < 15, Intraoperative Monitoring (IOM) availability, aneurysm location, daughter aneurysm, and neck-related morphology. Bootstrap correction preserved the same overall performance ranking, with mortality models remaining the strongest and the coiling good-GOSE model the weakest.

Conclusion: The National Brain Center – General Aneurysm Risk Utility for Decision Aid (NBC-GARUDA) provides preliminary treatment-specific in-hospital risk estimates, with the strongest performance observed for outcome prediction. However, discrimination was heterogeneous and weaker for the coiling favorable-outcome models; therefore, the calculator should be regarded as exploratory pending independent temporal and external validation.

1. Introduction

Intracranial aneurysms occur in roughly 1–2 % of individuals and carry an annual rupture risk of around 1 %, with rupture leading to subarachnoid hemorrhage (SAH) that incurs around 40 % mortality and around 30 % long-term disability [1]. Treatment of intracranial

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aneurysms centers on aneurysm obliteration either by microsurgical clipping or endovascular coiling, a decision guided by aneurysm complexity and patient factors [2]. In landmark trials of ruptured aneurysms, coiling yielded significantly higher one-year independent survival than clipping [3]. Likewise, meta-analyses in unruptured aneurysms show that clipping achieves higher long-term complete occlusion rates, whereas coiling is associated with fewer perioperative complications and shorter hospital stays [4]. Both modalities can yield high rates of favorable outcomes [5], but each has distinct trade-offs that must be weighed in surgical decision-making.

In low- and middle-income countries (LMICs) and developing countries, the aneurysm characteristics and treatment differ from those in high-income settings [6]. Approximately two-thirds of global aSAH cases occur in LMICs [7], yet these regions often lack access to endovascular therapy [8,9]. A recent review found that in high-income countries roughly 35 % of aSAH patients receive coiling, whereas reported developing countries cohorts almost exclusively use surgical clipping [6]. Advanced intraoperative resources are even more limited, only 10 % of centers in LMICs use intraoperative neuromonitoring (IOM) compared to 41 % in high-income centers [10] and neurosurgeon availability is far lower (around 0.12–0.37 per 100,000 in low/mid-income compared to 2.44 per 100,000 in high-income regions) [11]. Patients in developing countries also face barriers to care, including low awareness, delayed presentation, and high out-of-pocket cost [12].

Given these disparities, there is a critical need for context-appropriate decision support. In high-income practice, prognostic nomograms and web-based calculators have been developed to predict post-aneurysm outcomes and aid surgical planning [13]. Risk stratification for intracranial aneurysms has been supported by several established instruments, including PHASES for rupture risk prediction [14], ELAPSS for aneurysm growth prediction [15], and UIATS for structured treatment decision guidance in unruptured aneurysms [16]. In aSAH, early clinical grading and prognostication have been facilitated by PAASH [17], while broader outcome models have been provided by SAFIRE [18] and the SAHIT [19] multinational cohort tools. A more recent point-based tool, the GAHR score, incorporated aneurysm treatment (clipping or coiling) among its predictors and mapped total points to an estimated probability of in-hospital mortality [20]. However, treatment selection between endovascular coiling and microsurgical clipping remains consequential, with differential patterns of dependency-free survival having been demonstrated in patients suitable for either approach, and existing tools have generally been oriented toward single domain prediction or have not been designed to provide parallel, bedside, percentage-based estimates for both coiling and clipping across multiple clinically interpretable endpoints. To address this gap, a predictive model was developed from an Indonesian comprehensive stroke center divided into coiling and clipping subgroups, with separate multivariable logistic regression models created for mortality, good functional outcome, and recovery of Glasgow Coma Scale (GCS) to baseline for each intervention, yielding six predicted probabilities that are displayed in a web calculator. We aimed to incorporate clinical, comorbidity, aneurysm morphology, and care-process predictors to improve practical decision support tailored to a limited resources setting.

2. Methods

2.1. Study design and population

We conducted a model-development study using consecutive patients treated for intracranial aneurysms with either microsurgical clipping or endovascular coiling. Each patient's index treatment episode was used. Records were screened for completeness of outcomes; observations without ascertainment of in-hospital mortality, post-operative Glasgow Outcome Scale–Extended (GOSE), or post-operative GCS recovery to baseline were excluded prior to modeling. Data were curated from the institutional aneurysm registry according to a prespecified analysis plan and locked prior to model exploration.

Six binary endpoints were modeled, stratified by intervention to preserve clinical interpretability: mortality during the index admission after coiling and after clipping; good functional outcome defined as GOSE 5–8 after coiling and after clipping; and recovery of GCS to the pre-morbid baseline after coiling and after clipping. Outcomes were coded as 1 if the event of interest was present and 0 otherwise. All three outcomes were in-hospital outcomes assessed during the index admission. Mortality was defined as death before discharge. Good functional outcome (GOSE 5–8) and recovery of GCS to premorbid baseline were assessed using the final in-hospital neurological evaluation recorded before discharge, according to the unit's routine postoperative schedule.

2.2. Predictors and variable definitions

Candidate predictors were defined a priori based on clinical relevance and data availability. Demographic and clinical variables included age (years), hypertension, diabetes, cardiovascular disease (CVD), current smoking, family history of aneurysm or subarachnoid hemorrhage, hemiparesis at presentation, ruptured aneurysm at presentation, ptosis, seizure prior to operation, multiple aneurysms, World Federation of Neurosurgical Societies (WFNS) grade recorded as an ordinal variable I–V, and admission GCS (3–15). Perioperative exposure included the availability of IOM. Morphological variables comprised dome height (mm) and neck width (mm), from which two derived metrics were constructed: the dome-to-neck ratio and an indicator for neck width > 4 mm. An indicator for daughter sac was recorded when present. For the location term in the clipping GOSE model, aneurysm site was encoded as mutually exclusive categories (AChA, ACom, Basilar, ICA, MCA, and PCoA) using indicator coding with the remaining sites as reference where applicable. A derived binary indicator GCS < 15 was defined as 1 when admission GCS ≤ 14 and 0 otherwise.

2.3. Handling of missing data

After removing observations with unobserved outcomes, remaining missingness among predictors was addressed under a Missing-At-Random assumption using Multiple Imputation by Chained Equations (MICE). Conditional models were matched to variable type: Predictive Mean Matching for continuous variables, logistic regression for binary variables, polytomous logistic regression for nominal categorical variables, and proportional odds logistic regression for ordinal variables such as WFNS. The imputation model included all candidate predictors and the outcomes (for imputation purposes only). Multiple imputed datasets were generated with iterative cycling of conditional models until convergence; diagnostics included inspection of trace plots and distributional checks to verify stability. Model estimation was performed within each imputed dataset and combined using Rubin's rules to obtain pooled coefficients, standard errors, and performance estimates.

2.4. Model development

For each intervention–outcome pair, a multivariable logistic regression model was developed. Initial exploration used bidirectional stepwise selection with the Akaike Information Criterion (stepAIC), allowing both forward entry and backward removal of terms to balance explanatory value and parsimony. The stepwise search operated within each imputed dataset using the full set of candidate predictors defined above. Following selection, multicollinearity was examined with the Variance Inflation Factor (VIF); a threshold of approximately 5 was used to trigger review for redundancy. When collinearity persisted, clinically redundant or unstable terms were removed and the model re-estimated. The final specification for each of the six models retained variables that were consistently selected across imputations and considered clinically plausible within the final multivariable models. The logistic formula

was:

$$\text{logit}(p) = \beta 0 + \sum_{j=1}^{k} \beta j X j, \; p = \frac{1}{1 + exp(-\text{logit}(p))}$$

Internal validation was performed using bootstrap resampling (500 iterations) to derive optimism-corrected discrimination. In each bootstrap sample, the final model was refitted, the AUC was calculated in the bootstrap sample, and the AUC of that same bootstrap-fitted model was then evaluated in the original dataset. Optimism was defined as the mean difference between these two AUCs across resamples. The optimism-corrected AUC was obtained by subtracting the mean optimism from the apparent AUC in the development dataset.

2.5. Performance, Thresholding, and Implementation

Model discrimination was quantified using the AUC, with 95 % confidence intervals estimated by DeLong's method within each imputed dataset and pooled thereafter. Receiver operating characteristic (ROC) curves were plotted for each model specification and intervention–outcome pair. For classification, the operating point was chosen

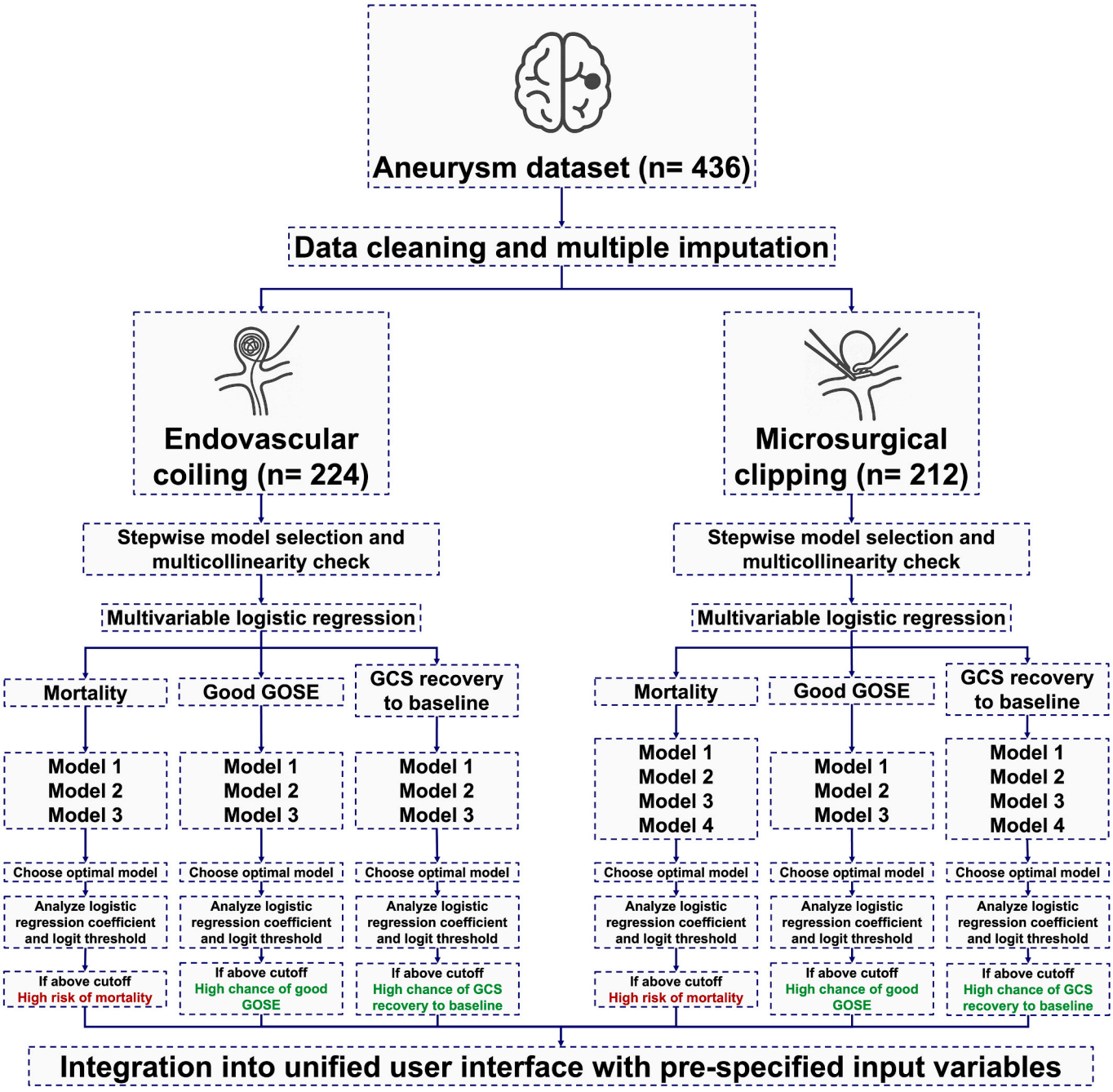

Fig. 1. Analytical workflow of the model development. The aneurysm dataset (n = 436) was divided into patients treated with endovascular coiling (n = 224) and microsurgical clipping (n = 212). Following data cleaning and multiple imputation, each subgroup underwent stepwise model selection with multicollinearity testing. Multivariable logistic regression analyses were performed for three outcomes (mortality, good Glasgow Outcome Scale–Extended (GOSE), and Glasgow Coma Scale (GCS) recovery to baseline) yielding multiple candidate models (M1–M4). The optimal model for each outcome was selected based on area under the curve (AUC), sensitivity, specificity, and accuracy, and the logit cutoff was determined using Youden's Index. The final coefficients were converted into point-based scoring systems and integrated into a unified user interface.

using Youden's Index to optimize sensitivity plus specificity, and we report sensitivity, specificity, and overall accuracy at this cutoff. Among candidate model specifications, the final model was selected on the basis of discrimination and clinical interpretability within the study cohort. For deployment, decision labels in the calculator are generated by comparing the computed logit, against a prespecified model-specific logit threshold: values equal to or above the threshold yield "High Risk of Mortality" for the mortality models and "High Chance of Good GOSE" or "High Chance of GCS Recovery to Baseline" for the favorable outcome models; values below the threshold yield the corresponding "Low" labels. To enhance bedside usability, we additionally derived points-based scores from each final model by normalizing coefficients: each β_j was divided by the smallest non-zero absolute $|\beta|$ in that model and rounded to produce an integer weight, preserving relative effect sizes. The production calculator implements the pooled coefficients and intercepts client-side in JavaScript, computes derived predictors automatically (GCS $<$ 15, dome-to-neck ratio, neck $>$ 4 mm), outputs the predicted probabilities for all six endpoints, and displays the fixed performance characteristics (AUC, sensitivity, and specificity) corresponding to the chosen thresholds. No patient data are transmitted off-device; all computation occurs within the browser. The complete analytical pipeline from data preprocessing to model integration is summarized in Fig. 1. Because an independent temporal or external validation cohort was not available, model performance was primarily assessed within the development dataset; however, bootstrap internal validation was used to derive optimism-corrected AUCs, and the corresponding optimism estimates are also reported.

2.6. Statistical Software

All analyses were performed using R (R Foundation for Statistical Computing, Vienna, Austria). Continuous data were expressed as mean $\pm$ standard deviation or median with interquartile range, and categorical variables as frequencies and percentages. Missing predictor data were handled by MICE using predictive mean matching for continuous variables, logistic regression for binary variables, polytomous logistic regression for nominal variables, and proportional odds logistic regression for ordinal variables, generating ten imputed datasets with diagnostic inspection for convergence. Multivariable logistic regression was used to model each of the six binary outcomes (mortality, good GOSE, and GCS recovery for both coiling and clipping). Variable selection employed bidirectional stepAIC, while multicollinearity was examined through the Variance Inflation Factor, with a threshold of five used to identify redundancy. Model performance was evaluated by the AUC with 95 % confidence intervals estimated by DeLong's method, and classification accuracy was determined by sensitivity, specificity, and overall accuracy calculated at the Youden Index–derived optimal cutoff. Bootstrap internal validation with 500 resamples was performed to derive optimism-corrected AUCs and the corresponding optimism estimates for the six final models. Pooled coefficients across imputations were used to construct the final models, from which normalized β coefficients were derived to generate point-based scoring weights for the web-based, the National Brain Center – General Aneurysm Risk Utility for Decision Aid (NBC-GARUDA) calculator. All statistical hypothesis tests were conducted utilizing a two-sided criterion, with the level of statistical significance established at $\leq$ 0.05.

2.7. Ethical consideration

This study was reviewed and approved by the Health Research Ethics Committee of the National Brain Center Hospital Mahar Mardjono, East Jakarta (Approval No. DP.04.03/D.XXIII.9/266/2025). The study was conducted in accordance with the ethical principles of the Declaration of Helsinki. Given the retrospective nature of the study and the use of anonymized secondary data, the requirement for written informed consent was waived by the ethics committee in accordance with local regulations. All data were handled confidentially, and no identifiable personal information was accessed or disclosed.

3. Results

Baseline demographic, clinical, and morphological characteristics are summarized in Table 1. Patients in the clipping group were older than those in the coiling group ($p = 0.014$) and had a longer length of stay ($p < 0.001$). Admission GCS and WFNS grade differed between groups (GCS $p = 0.005$; WFNS $p = 0.010$), whereas presenting symptoms and medical history were similar. On imaging, clipped aneurysms had larger dome height ($p = 0.009$) and wider neck measurements ($p < 0.001$), while a dome to neck ratio greater than 2 was more frequent in the coiling group (29.5 % vs 19.8 %; $p = 0.020$). Treatment distribution differed by anatomical location, with anterior circulation aneurysms more often clipped and posterior circulation aneurysms more often coiled ($p = 0.007$). Among clipped patients, CSF diversion and IOM were used in 60.8 % and 25.5 %, respectively. Postoperative and discharge GCS were higher after coiling (both $p \leq 0.002$). Mortality did not differ significantly ($p = 0.105$), whereas good functional outcome (GOSE 5–8) and recovery of GCS to baseline were more frequent after coiling ($p = 0.043$ and $p = 0.001$). Overall, the cohort was dominated by ruptured aneurysms (379/436, 86.9 %), whereas unruptured aneurysms accounted for 57/436 cases (13.1 %). Accordingly, the present models should be interpreted as being driven predominantly by ruptured aneurysm presentations.

Model discrimination improved with increasing specification for all outcomes (Supplementary File Table S1), with ROC curves shown in Fig. 2. For mortality after coiling, AUC increased from 0.673 in the simplest model to 0.826 in the final model including dome height, achieving high sensitivity at the Youden cutoff. For mortality after clipping, the extended model incorporating IOM and dome metrics achieved the best discrimination (AUC 0.815) with balanced sensitivity and specificity. A sensitivity prioritized specification achieved higher sensitivity but reduced specificity. For good functional outcome, the final coiling model achieved only moderate discrimination (AUC 0.707) and low specificity at the selected cutoff (50.0 %), whereas the clipping model demonstrated stronger and more balanced performance (AUC 0.793; specificity 77.3 %). For recovery of GCS to baseline, the coiling model showed a marked imbalance between sensitivity and specificity, with low sensitivity (49.7 %) despite high specificity (91.5 %), whereas the clipping model yielded a more balanced profile. Predicted probability density and separation plots for all final models are presented in Fig. 3.

Final model coefficients, operating cutoffs, and integer point translations are reported in Table 2. For mortality after coiling, higher age, hypertension, higher WFNS grade, and larger dome height were associated with increased risk. For clipping, cardiovascular disease, family history, and admission GCS less than fifteen were associated with higher mortality, whereas smoking and IOM showed inverse associations. For good functional outcome, older age, hemiparesis, higher WFNS grade, and rupture reduced the probability after coiling, while diabetes was positively associated after clipping and admission GCS less than fifteen and daughter aneurysm were negative predictors. Location effects were heterogeneous. For recovery of GCS to baseline, younger age and absence of diabetes, ptosis, and seizure favored recovery after coiling, whereas larger dome metrics reduced probability; in the clipping models, ptosis and neck related metrics were positive predictors, while cardiovascular disease, lower admission GCS, rupture, and larger dome height were negative. Across the final models, age was retained consistently, whereas neurological severity entered differently by modality, with WFNS grade contributing to coiling models and admission GCS thresholding contributing more prominently to clipping models. Several predictors appeared modality-specific. IOM availability, aneurysm location, daughter aneurysm, and neck-related morphology were retained only in clipping models, whereas hemiparesis, seizure, and

Table 1
Baseline demographic, clinical, and morphological characteristics of patients undergoing coiling and clipping for intracranial aneurysms.

	Coiling (n = 224)	Clipping (n = 212)	p value	Total (n = 436)
Age (years)	50.74 ± 12.32	53.61 ± 12.00	**0.014***	52.13 ± 12.24
< 65 [n (%)]	196 (87.5)	172 (81.1)	0.067	368 (84.4)
≥ 65 [n (%)]	28 (12.5)	40 (18.9)		68 (15.6)
Female [n (%)]	129 (57.6)	138 (65.1)	0.108	267 (61.2)
LOS (days)	12.07 ± 10.43	17.02 ± 10.68	**<0.001***	14.48 ± 10.83
History				
Stroke [n (%)]	26 (11.6)	25 (11.8)	0.952	51 (11.7)
CVD [n (%)]	11 (4.9)	15 (7.1)	0.340	26 (6.0)
Hypertension [n (%)]	134 (59.8)	130 (61.3)	0.749	264 (60.6)
Diabetes [n (%)]	16 (7.1)	22 (10.4)	0.231	38 (8.7)
Smoking [n (%)]	16 (7.1)	17 (8.0)	0.730	33 (7.6)
Family history [n (%)]	3 (1.3)	5 (2.4)	0.428	8 (1.8)
Presenting symptom				
Headache [n (%)]	202 (90.2)	179 (84.4)	0.071	381 (87.4)
Hemiparesis [n (%)]	58 (25.9)	64 (30.2)	0.318	122 (28.0)
Seizure [n (%)]	31 (13.8)	27 (12.7)	0.735	58 (13.3)
Ptosis [n (%)]	16 (7.1)	16 (7.5)	0.871	32 (7.3)
Setting				
Emergency [n (%)]	151 (67.4)	154 (72.6)	0.234	305 (70.0)
Outpatient clinic [n (%)]	73 (32.6)	58 (27.4)		131 (30.0)
GCS at admission	13.48 ± 2.48	12.75 ± 2.98	**0.005***	13.13 ± 2.75
GCS 15 [n (%)]	144 (64.3)	111 (52.4)	**0.012***	255 (58.5)
GCS < 15 [n (%)]	80 (35.7)	101 (47.6)		181 (41.5)
WFNS grade				
I [n (%)]	146 (65.2)	114 (53.8)	**0.010***	260 (59.6)
II [n (%)]	17 (7.6)	20 (9.4)		37 (8.5)
III [n (%)]	13 (5.8)	12 (5.7)		25 (5.7)
IV [n (%)]	47 (21.0)	61 (28.8)		108 (24.8)
V [n (%)]	1 (0.4)	5 (2.4)		6 (1.4)
Onset to admission				
> 24 h since onset [n (%)]	174 (77.7)	139 (65.6)	**0.005***	313 (71.8)
≤ 24 h since onset [n (%)]	50 (22.3)	73 (34.4)		123 (28.2)
Dome size (mm)	4.61 ± 2.67	5.43 ± 3.92	0.10	5.01 ± 3.36
Dome height (mm)	5.13 ± 3.19	5.98 ± 3.55	**0.009***	5.54 ± 3.39
Neck size	2.83 ± 1.31	3.80 ± 3.66	**<0.001***	3.30 ± 2.76
< 4 mm [n (%)]	196 (87.5)	152 (71.7)	**<0.001***	348 (79.8)
≥ 4 mm [n (%)]	28 (12.5)	60 (28.3)		88 (20.2)
Dome to neck ratio	1.85 ± 1.05	1.73 ± 1.96	0.443	1.79 ± 1.56
≤ 2 [n (%)]	158 (70.5)	170 (80.2)	**0.02***	328 (75.2)
> 2 [n (%)]	66 (29.5)	42 (19.8)		108 (24.8)
Anatomic location				
Anterior [n (%)]	184 (82.1)	193 (91.0)	**0.007***	377 (86.5)
Posterior [n (%)]	20 (8.9)	5 (2.4)		25 (5.7)
Combined [n (%)]	20 (8.9)	14 (6.6)		34 (7.8)
Location of aneurysm				
ACA [n (%)]	11 (4.9)	12 (5.7)	**0.005***	23 (5.3)
AChA [n (%)]	4 (1.8)	3 (1.4)		7 (1.6)
ACom [n (%)]	76 (33.9)	56 (26.4)		132 (30.3)
Basilar [n (%)]	4 (1.8)	5 (2.4)		9 (2.1)
ICA [n (%)]	15 (6.7)	10 (4.7)		25 (5.7)
MCA [n (%)]	22 (9.8)	38 (17.9)		60 (13.8)
PCA [n (%)]	6 (2.7)	0 (0)		6 (1.4)
PCoA [n (%)]	76 (33.9)	88 (41.5)		164 (37.6)
PICA [n (%)]	4 (1.8)	0 (0)		4 (0.9)
Vertebral [n (%)]	5 (2.2)	0 (0)		5 (1.1)
Vertebrobasilar [n (%)]	1 (0.4)	0 (0)		1 (0.2)
Multiple aneurysm [n (%)]	20 (8.9)	14 (6.6)	0.366	34 (5.7)
Ruptured aneurysm [n (%)]	192 (85.7)	187 (88.2)	0.440	379 (86.9)
Daughter aneurysm [n (%)]	32 (14.3)	33 (15.6)	0.708	65 (14.9)
Number of aneurysm				
1 [n (%)]	204 (91.1)	198 (93.4)	0.362	402 (92.2)
2 [n (%)]	15 (6.7)	11 (5.2)		26 (6.0)
3 [n (%)]	5 (2.2)	3 (1.4)		8 (1.8)
CSF diversion [n (%)]	54 (24.1)	129 (60.8)	**<0.001***	183 (42.0)
IOM [n (%)]	0 (0)	54 (25.47)	**<0.001***	54 (12.4)
GCS post operative	12.59 ± 3.37	10.66 ± 3.75	**<0.001***	11.65 ± 3.68
GCS discharge	12.95 ± 3.98	11.66 ± 4.52	**0.002***	12.32 ± 4.30
Mortality [n (%)]	25 (11.2)	35 (16.5)	0.105	60 (13.8)
Good GOSE (5–8) [n (%)]	106 (47.3)	80 (37.7)	**0.043***	186 (42.7)
GCS recovery to baseline [n (%)]	177 (79.0)	138 (65.1)	**0.001***	315 (72.2)

Abbreviations: ACA: Anterior Cerebral Artery; AChA: Anterior Choroidal Artery; ACom: Anterior Communicating Artery; CVD: Cardiovascular Disease; CSF: Cerebrospinal Fluid; GCS: Glasgow Coma Scale; GOSE: Glasgow Outcome Scale – Extended; ICA: Internal Carotid Artery; IOM: Intraoperative Monitoring; LOS: Length of Stay; MCA: Middle Cerebral Artery; PCA: Posterior Cerebral Artery; PCoA: Posterior Communicating Artery; PICA: Posterior Inferior Cerebellar Artery; WFNS: World Federation of Neurosurgical Societies.

multiple aneurysms appeared only in coiling models. The retained predictors were broadly directionally consistent with clinical expectations, particularly for age, neurological severity, rupture status, and selected morphological variables. However, several predictor-level estimates showed wide confidence intervals, indicating substantial uncertainty and limiting variable-level interpretation.

Bootstrap internal validation yielded modest optimism across all six final models, ranging from 0.015 to 0.055 (Table 3). The corresponding optimism-corrected AUCs were 0.782 and 0.762 for mortality after coiling and clipping, 0.691 and 0.750 for good GOSE after coiling and clipping, and 0.713 and 0.723 for GCS recovery after coiling and clipping, respectively. Mortality models remained the strongest after optimism correction, whereas the coiling model for good GOSE remained the weakest.

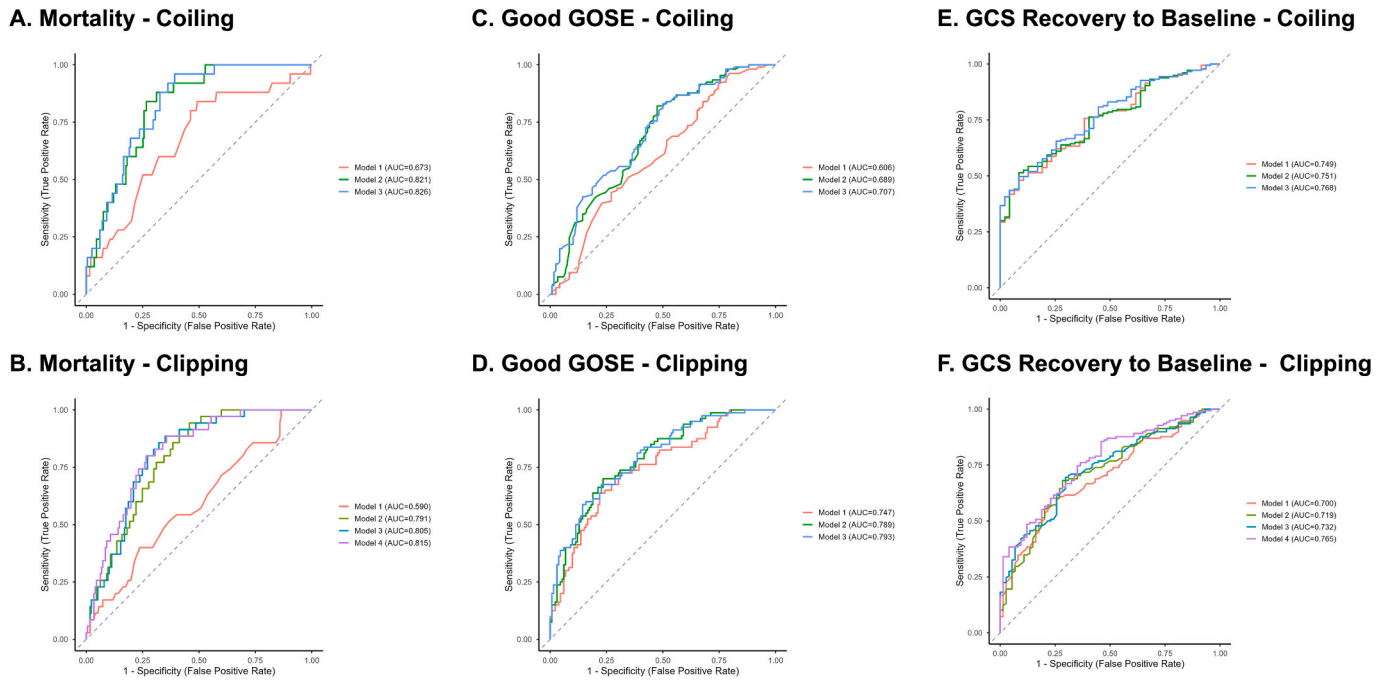

Fig. 2. Receiver operating characteristic curves for NBC-GARUDA models, stratified by intervention and outcome. Receiver operating characteristic (ROC) curves are presented for six intervention outcome pairs: (A) Mortality after coiling. (B) Mortality after clipping. (C) Good GOSE after coiling. (D) Good GOSE after clipping. (E) GCS recovery to baseline after coiling. (F) GCS recovery to baseline after clipping. Each panel shows the ROC curves for sequential model specifications identified during model development (Model 1 through Model 3 or Model 4 as annotated on the figure) with corresponding apparent area under the curve values displayed in the legend. The diagonal dashed line denotes the line of no discrimination.

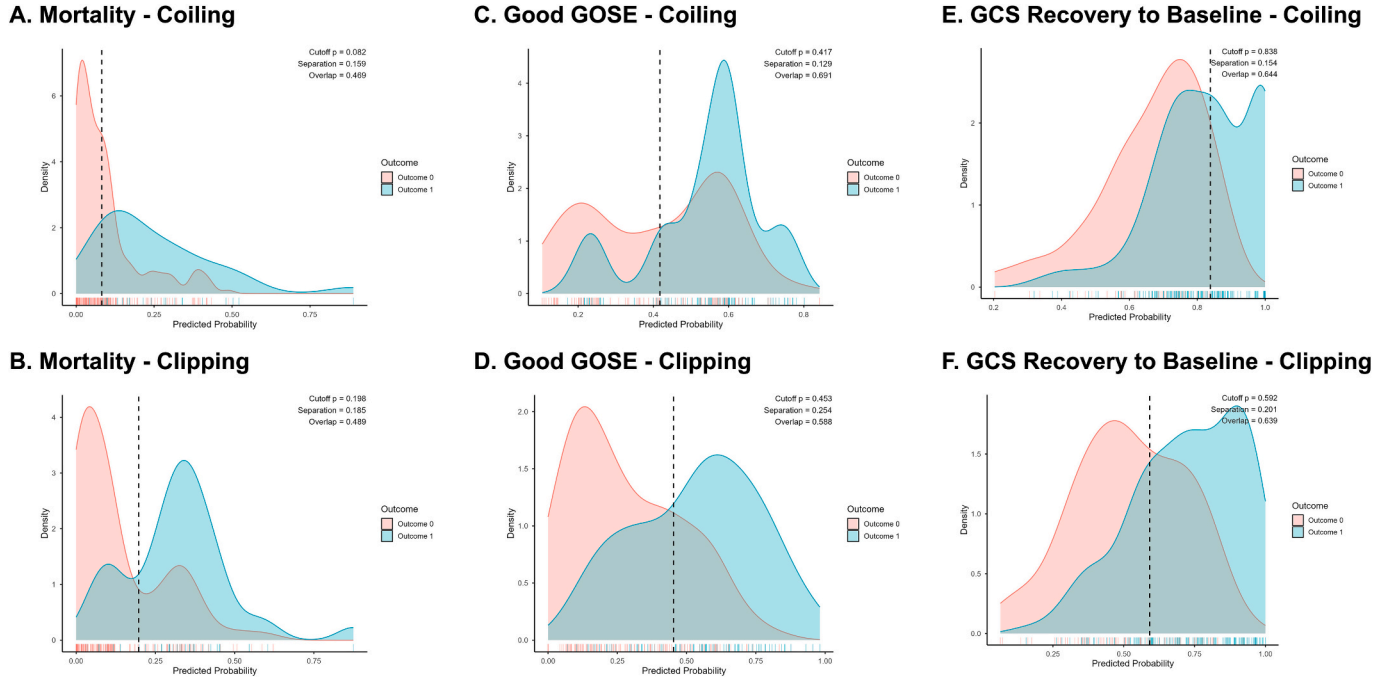

Fig. 3. Predicted probability density and separation plots for NBC-GARUDA models, stratified by intervention and outcome. Kernel density estimates of model predicted probabilities are shown for the six intervention outcome pairs: (A) Mortality after coiling. (B) Mortality after clipping. (C) Good GOSE after coiling. (D) Good GOSE after clipping. (E) GCS recovery to baseline after coiling. (F) GCS recovery to baseline after clipping. Red shaded density corresponds to Outcome = 0 (event absent) and teal shaded density corresponds to Outcome = 1 (event present). A rug plot along the x axis indicates individual observations and their predicted probability. The vertical dashed line indicates the operating cutoff probability derived by the Youden index for that model.

4. Discussion

The present findings should be interpreted cautiously as preliminary model-development results rather than evidence of a validated clinical decision tool. Predictive performance was heterogeneous across outcomes. The mortality models and the clipping model for good functional

Table 2
Final model coefficients, odds ratios, point allocations, and apparent model performance in predicting mortality, good GOSE, and GCS recovery after coiling and clipping.

Outcome	Intervention	Variable	Coefficient	Points	OR (95 %CI)
Mortality	Coiling	(Intercept)	−5.073	−168991	
Mortality	Coiling	Age	0.022	737	1.02 (0.98–1.07)
Mortality	Coiling	Hypertension	1.008	33,585	2.74 (0.95–9.36)
Mortality	Coiling	WFNS Grade	0.525	17,478	1.69 (1.22–2.38)
Mortality	Coiling	Onset to Admission	0	−1	1 (1–1)
Mortality	Coiling	Dome Height	0.061	2023	1.06 (0.99–1.14)
Model summary	**Apparent AUC = 0.826 (0.759–0.894); Cutoff(p) = 0.082; Sens = 0.96; Spec = 0.608; Logit = -2.412**				
Mortality	Clipping	(Intercept)	−1.213	−34951	0.3 (0.02–3.47)
Mortality	Clipping	Age	−0.018	−505	0.98 (0.95–1.02)
Mortality	Clipping	CVD	1.547	44,589	4.7 (0.95–22.38)
Mortality	Clipping	Smoking	−1.9	−54763	0.15 (0–1.27)
Mortality	Clipping	Family History	2.142	61,730	8.51 (0.64–162.44)
Mortality	Clipping	Onset to Admission	0	−1	1 (1–1)
Mortality	Clipping	GCS < 15 at Admission	1.537	44,305	4.65 (1.82–13.56)
Mortality	Clipping	IOM Availability	−1.329	−38321	0.26 (0.06–0.87)
Mortality	Clipping	Dome Height	0.081	2322	1.08 (0.93–1.25)
Mortality	Clipping	Dome to Neck Ratio	−0.27	−7795	0.76 (0.38–1.28)
Model summary	**Apparent AUC = 0.815 (0.747–0.882); Cutoff(p) = 0.198; Sens = 0.8; Spec = 0.734; Logit = -1.401**				
Good GOSE	Coiling	(Intercept)	2.19	167	8.94 (2.22–39.66)
Good GOSE	Coiling	Age	−0.013	−1	0.99 (0.96–1.01)
Good GOSE	Coiling	Hemiparesis	−0.625	−48	0.54 (0.27–1.03)
Good GOSE	Coiling	WFNS Grade	−0.493	−37	0.61 (0.47–0.78)
Good GOSE	Coiling	Ruptured Aneurysm	−0.703	−53	0.5 (0.21–1.12)
Model summary	**Apparent AUC = 0.707 (0.640–0.774); Cutoff(p) = 0.417; Sens = 0.83; Spec = 0.5; Logit = -0.334**				
Good GOSE	Clipping	(Intercept)	2.781	699,709	16.14 (2.21–136.72)
Good GOSE	Clipping	Age	−0.043	−10746	0.96 (0.93–0.99)
Good GOSE	Clipping	Diabetes	1.439	362,058	4.22 (1.44–13.18)
Good GOSE	Clipping	Onset to Admission	0	1	1 (1–1)
Good GOSE	Clipping	GCS < 15 at Admission	−1.363	−342872	0.26 (0.12–0.52)
Good GOSE	Clipping	Aneurysm Location at AChA	1.272	319,962	3.57 (0.23–98.59)
Good GOSE	Clipping	Aneurysm Location at Acom	−0.608	−152984	0.54 (0.13–2.47)
Good GOSE	Clipping	Aneurysm Location at Basilar	0.383	96,328	1.47 (0.11–23.31)
Good GOSE	Clipping	Aneurysm Location at ICA	−18.619	−4683970	0 (0–391749848.7)
Good GOSE	Clipping	Aneurysm Location at MCA	−1.061	−266807	0.35 (0.07–1.75)
Good GOSE	Clipping	Aneurysm Location at PCoA	−0.411	−103336	0.66 (0.16–2.94)
Good GOSE	Clipping	Daughter Aneurysm	−0.856	−215336	0.42 (0.15–1.11)
Model summary	**Apparent AUC = 0.793 (0.732–0.854); Cutoff(p) = 0.453; Sens = 0.675; Spec = 0.773; Logit = -0.19**				
GCS Recovery to Baseline	Coiling	(Intercept)	3.198	55,072	24.47 (3.83–187.5)
GCS Recovery to Baseline	Coiling	Age	−0.033	−576	0.97 (0.94–1)
GCS Recovery to Baseline	Coiling	Onset to Admission	0	1	1 (1–1)
GCS Recovery to Baseline	Coiling	Diabetes	−1.143	−19691	0.32 (0.09–1.11)
GCS Recovery to Baseline	Coiling	Ptosis	−0.94	−16198	0.39 (0.09–1.8)
GCS Recovery to Baseline	Coiling	Seizure	−0.977	−16834	0.38 (0.13–1.1)
GCS Recovery to Baseline	Coiling	Multiple Aneurysm	0.621	10,698	1.86 (0.47–9.88)
GCS Recovery to Baseline	Coiling	Dome Height	−0.029	−502	0.97 (0.91–1.03)
GCS Recovery to Baseline	Coiling	Dome to Neck Ratio	−0.232	−3991	0.79 (0.55–1.14)
Model summary	**Apparent AUC = 0.768 (0.7–0.835); Cutoff(p) = 0.838; Sens = 0.497; Spec = 0.915; Logit = 1.646**				
GCS Recovery to Baseline	Clipping	(Intercept)	3.334	100	28.06 (2.86–341.18)
GCS Recovery to Baseline	Clipping	Age	−0.033	−1	0.97 (0.94–1)
GCS Recovery to Baseline	Clipping	CVD	−1.032	−31	0.36 (0.09–1.26)
GCS Recovery to Baseline	Clipping	Ptosis	2.939	88	18.9 (3.24–365.59)
GCS Recovery to Baseline	Clipping	GCS < 15 at Admission	−0.517	−16	0.6 (0.3–1.17)
GCS Recovery to Baseline	Clipping	IOM Availability	0.843	25	2.32 (1.05–5.48)
GCS Recovery to Baseline	Clipping	Ruptured Aneurysm	−1.542	−46	0.21 (0.04–0.76)
GCS Recovery to Baseline	Clipping	Dome Height	−0.179	−5	0.84 (0.73–0.94)
GCS Recovery to Baseline	Clipping	Dome to Neck Ratio	0.399	12	1.49 (1–2.5)
GCS Recovery to Baseline	Clipping	Neck > 4 mm	0.646	19	1.91 (0.84–4.5)
Model summary	Apparent AUC = 0.765 (0.7–0.829); Cutoff(p) = 0.592; Sens = 0.761; Spec = 0.635; Logit = 0.37				

ORs and 95 % confidence intervals are shown to describe the direction and uncertainty of retained predictors. These estimates are presented for interpretive purposes within a prognostic prediction model and should not be overinterpreted as independent causal associations.
Abbreviations: AChA: Anterior Choroidal Artery; ACom: Anterior Communicating Artery; AUC: Area Under the Receiver Operating Characteristic Curve; CVD: Cardiovascular Disease; GCS: Glasgow Coma Scale; GOSE: Glasgow Outcome Scale – Extended; ICA: Internal Carotid Artery; IOM: Intraoperative Monitoring; MCA: Middle Cerebral Artery; PCoA: Posterior Communicating Artery; WFNS: World Federation of Neurosurgical Societies.

Table 3
Bootstrap internal validation of final models.

Model	Apparent AUC	Optimism-corrected AUC	Optimism
Mortality (Coiling)	0.826	0.782	0.044
Mortality (Clipping)	0.815	0.762	0.052
Good GOSE (Coiling)	0.707	0.691	0.015
Good GOSE (Clipping)	0.793	0.750	0.044
GCS Recovery to Baseline (Coiling)	0.768	0.713	0.055
GCS Recovery to Baseline (Clipping)	0.765	0.723	0.041

Bootstrap internal validation with 500 resamples was used to derive the optimism-corrected AUC. Optimism was defined as the mean difference between the AUC of the model refitted in each bootstrap sample and the AUC of that same bootstrap-fitted model when evaluated in the original dataset. The optimism-corrected AUC was calculated as the apparent AUC minus the estimated optimism.
Abbreviations: AUC: Area Under the Receiver Operating Characteristic Curve; GCS: Glasgow Coma Scale; GOSE: Glasgow Outcome Scale–Extended.

outcome showed the most acceptable discrimination within the study cohort. In contrast, the coiling model for good functional outcome demonstrated only moderate discrimination and low specificity, while the coiling model for GCS recovery showed low sensitivity despite high specificity. Although several retained predictors showed directions that were clinically plausible, individual effect-size estimates should be interpreted cautiously. The present study was designed to develop preliminary prognostic models rather than to establish independent etiologic associations, and several variable-level estimates were imprecise, as reflected by wide confidence intervals, likely owing to sparse data in some subgroups and the modest size of certain outcome strata. These limitations of the current coiling models indicate that the calculator should be viewed as exploratory rather than prescriptive. Bootstrap internal validation demonstrated only modest-to-moderate optimism, and the corrected AUCs preserved the same overall ranking of model performance, with mortality models remaining the most robust and the coiling good-GOSE model remaining the weakest. The modality-specific heterogeneity in discrimination likely reflects both case-mix differences and unmeasured treatment-related factors. Coiling patients in this cohort generally had a more favorable neurological profile, which may have reduced separability for good GOSE and GCS recovery.

Our findings align with established evidence that endovascular coiling often yields better short-term functional outcomes than surgical clipping in patients eligible for both treatments [5]. This has been consistently shown in major trial of ruptured intracranial aneurysms [21], reflecting the less invasive nature of coiling. In contrast, neurosurgical clipping provides more durable aneurysm obliteration. Long-term follow-ups have repeatedly found lower rates of aneurysm recurrence and need for retreatment after clipping [22,23]. In practical terms, this trade-off is reflected in guideline recommendations: when patient and aneurysm characteristics do not strongly favor one approach, consensus guidelines typically advise coiling as the first-line option [24,25]. Notably, a 2025 study of MCA aneurysms confirmed this pattern. While coiling is a viable alternative, experienced surgical teams still achieve higher rates of complete occlusion and superior long-term durability with clipping [26]. Together, these data suggest that coiling versus clipping decisions should be individualized, taking into account both the immediate benefits of less invasive therapy and the long-term need for durable aneurysm closure.

Several decision-support tools and scores have been proposed for intracranial aneurysm management, though few focus specifically on choosing coiling versus clipping (Table 4). For unruptured aneurysms, the multidisciplinary UIATS was developed to harmonize the treatment decision-making by incorporating several clinical and aneurysm factors [27]. UIATS quantifies many relevant variables (patient age, comorbidities, aneurysm size/location, etc.) to generate a recommendation for observation versus intervention. However, it has only modest predictive power for outcomes; for example, an external validation found UIATS had high sensitivity but low specificity for detecting aneurysms that would grow or rupture [27]. In the ruptured aneurysm setting, other efforts include the 2024 SHARP model, which provides individualized outcome estimates under coiling or clipping but is based on ISAT trial data [21]. Importantly, Yoshiyama et al. recently derived an explicit coiling-vs-clipping scoring system using a Japanese stroke registry: they identified separate sets of risk factors for poor outcome with each modality and proposed a simple point system to guide treatment [28]. These existing tools illustrate proof-of-concept that quantitative calculators can inform aneurysm treatment choices. However, all have been developed in high-resource settings (Japan, Europe, trial populations) and primarily address specific contexts (unruptured UIATS; ruptured SaH in ISAT). Furthermore, Rilianto et al. developed and validated the GAHR score, a simple four-variable clinical model incorporating aSAH grade, aneurysmal treatment modality, cardiovascular comorbidity, and respiratory failure, which demonstrated good discrimination for predicting in-hospital mortality after aSAH (AUC 0.83) [20].

In clinical practice, coiling or clipping decisions are made by multidisciplinary teams weighing multiple factors. For example, patient age and neurological grade influence the choice. Older patients or those presenting in poor clinical condition are often steered toward coiling, since the minimally invasive approach mitigates perioperative risk [29]. Similarly, aneurysm factors play a role. Posterior circulation or dissecting aneurysms are often managed with coiling when feasible [30,31], whereas smaller [32] or giant [33] aneurysms, wide-neck aneurysms [34], MCA aneurysms [35], or cases with an accompanying intracerebral hematoma [36] typically favor surgical clipping. In fact, published consensus statements note that when no single approach is clearly indicated by anatomy or patient factors, endovascular coiling is generally advised over clipping [24,25]. Our model is designed to complement this decision process by quantifying the individualized benefits of each treatment (as shown in Fig. 4). Importantly, we emphasize that such a tool is not prescriptive. Rather, it aims to support the multidisciplinary discussion. By making the expected outcome trade-offs explicit for each patient profile, it can make the decision more transparent, but the final choice should always remain in the context of clinical judgment.

Our focus on developing country settings highlights issues that may not be captured in existing tools. In many developing neurosurgical centers, resource constraints strongly influence aneurysm management. For example, a recent survey of African neurosurgery units found that while over 61 % of centers could perform surgical clipping, only about 22 % had the capacity for endovascular aneurysm treatment. Similarly, 64 % of surveyed centers reported having no dedicated neurointerventionalist at all [37]. Such disparities mean that the availability of coiling can be inconsistent, and patients may face significant delays or transfers for endovascular therapy. Cost is another critical factor. The equipment and consumables for coiling are often much more expensive than those for clipping. Indeed, a prospective study in Pakistan found equivalent 6-month outcomes between coiled and clipped SAH patients (81 % vs 83 % good outcome), but the mean total cost for coiling was roughly 62 % higher than for clipping [38]. In Indonesia, limited availability and higher costs constrain aneurysm care, as medical equipment including endovascular devices is priced up due to import duties that act as a luxury tax [39]. Referral for endovascular therapy is frequently constrained by uneven access to angiography suites, as shown in Indonesia where neurointerventional capacity is concentrated in Java and, as of 2020, only 54 facilities (out of 416 districts) were identified, leaving many regions underserved [40]. In practical terms, this implies that an aneurysm for which coiling and clipping are equally suitable might be treated differently depending on the patient's financial resources or hospital supply. Accordingly, a bedside decision aid that emphasizes clinical and examination based predictors is pragmatic for triage when cross-sectional imaging and digital subtraction angiography

Table 4
Comparative overview of aneurysm-related prediction and decision-support tools.

Tool	Predicted outcome(s)	Population	Region	Key predictor domains	Separate coiling and clipping	Model derivation approach	Key distinction
PHASES [14]	5-y rupture risk	Patients with UIAs	USA, Canada, Finland, Japan, the Netherlands, and other European countries	Population/ geography, HTN, age, aneurysm size, earlier SAH, site	No	Pooled IPD survival model using Kaplan–Meier estimates and Cox regression	Natural-history rupture model; not a post-treatment outcome model
ELAPSS [15]	3-/5-y aneurysm growth risk	Patients with UIAs	Finland, Japan, and North America/ Europe	Earlier SAH, location, age, population, size, shape	No	Aneurysm-level multivariable Cox model for growth; converted to a 3-/5-y score	Growth-risk model; not a treatment-specific post-procedural outcome model
UIATS [16]	Treatment recommendation for UIA (repair vs conservative), not direct outcome prediction	Patients with UIAs	International expert consensus panel	Patient, aneurysm, and treatment-related factors	No	Multidisciplinary Delphi-consensus framework with weighted factors	Consensus decision framework; no paired post-treatment probabilities
PAASH [17]	Admission prognostic grade / poor outcome after aSAH	Patients with aSAH at admission	Netherlands	Admission neurological severity (GCS-based)	No	GCS-based admission prognostic grading scale; externally validated against WFNS	Severity/ prognostic grading scale; not a treatment-selection model
SAFIRE [18]	2-mo poor functional outcome (mRS 4–6)	Patients with aSAH	Netherlands	Aneurysm size, age, modified Fisher grade, rWFNS grade	No	Multivariable regression model derived in a prospective single-center cohort, with temporal and external validation; simplified into the SAFIRE scale	Early aSAH prognostic model; no paired coiling/ clipping estimates
SAHIT [19]	3-mo mortality and functional outcome	Multinational aSAH trial/ registry/cohort repository	Unspecified 20 countries	Age, premorbid HTN, neurological grade; extended models add clot volume, aneurysm size/site, treatment modality	No	Logistic-regression models (core, neuroimaging, full) derived from pooled multinational data	aSAH prognostic models; no paired coiling/clipping output
SHARP [21]	2-mo favorable functional outcome and 10-y retreatment/ rebleeding-free outcome	ISAT-derived aSAH population suitable for either treatment	Predominantly UK	Trial-derived clinical and aneurysm predictors with treatment-benefit modeling	Yes	Treatment-benefit modeling using ordinal logistic regression for functional outcome and Cox regression for durability, with interactions	Derived in a randomized-trial population suitable for both treatments
Yoshiyama et al. [28]	Discharge poor outcome (mRS > 2) and in-hospital mortality	JSDB registry	Japan	Modality-specific clinical and aneurysm predictors	Yes	Post hoc registry-based multivariable logistic regression for discharge poor outcome and in-hospital mortality; converted to modality-specific scores	Registry-based Japanese aSAH treatment-selection score
NBC-GARUDA (this present study)	In-hospital mortality, good GOSE, and GCS recovery to baseline	Indonesian single-center cohort	Indonesia	Clinical, comorbidity, aneurysm morphology, and care-process variables	Yes	Separate multivariable logistic regression models after MICE, bidirectional stepAIC, and VIF assessment; thresholds chosen by Youden index	No independent temporal or external validation yet; bootstrap internal validation only

Abbreviations: aSAH: aneurysmal subarachnoid hemorrhage; GCS: Glasgow Coma Scale; GOSE: Glasgow Outcome Scale–Extended; HTN: hypertension; IPD: individual patient data; ISAT: International Subarachnoid Aneurysm Trial; JSDB: Japan Stroke Data Bank; mRS: modified Rankin Scale; MICE: Multiple Imputation by Chained Equations; mo: month; rWFNS: resuscitated World Federation of Neurosurgical Societies grade; SAH: subarachnoid hemorrhage; stepAIC: stepwise Akaike Information Criterion; UIA: unruptured intracranial aneurysm; UIAs: unruptured intracranial aneurysms; VIF: Variance Inflation Factor; WFNS: World Federation of Neurosurgical Societies; y: year.

are not promptly available, consistent with national reviews that call for wider distribution of neurologists and neurointerventionists and for foundational imaging capacity across hospitals. At the same time, there is growing evidence that coiling can be effectively performed in developing countries when infrastructure exists. One Indian tertiary center reported functional outcomes after coiling that were comparable to global standards (91.7 % independence) [41]. These observations underscore that a decision tool should incorporate not only clinical factors but also system realities (availability, cost, expertise). Our model does not explicitly include cost as a variable, but it brings attention to the predicted outcome differences, which can be interpreted alongside cost considerations by practitioners.

This study has several limitations. It represents a model-development study without independent temporal or external validation. Although bootstrap internal validation was performed to estimate optimism-corrected discrimination, the models were still developed within a

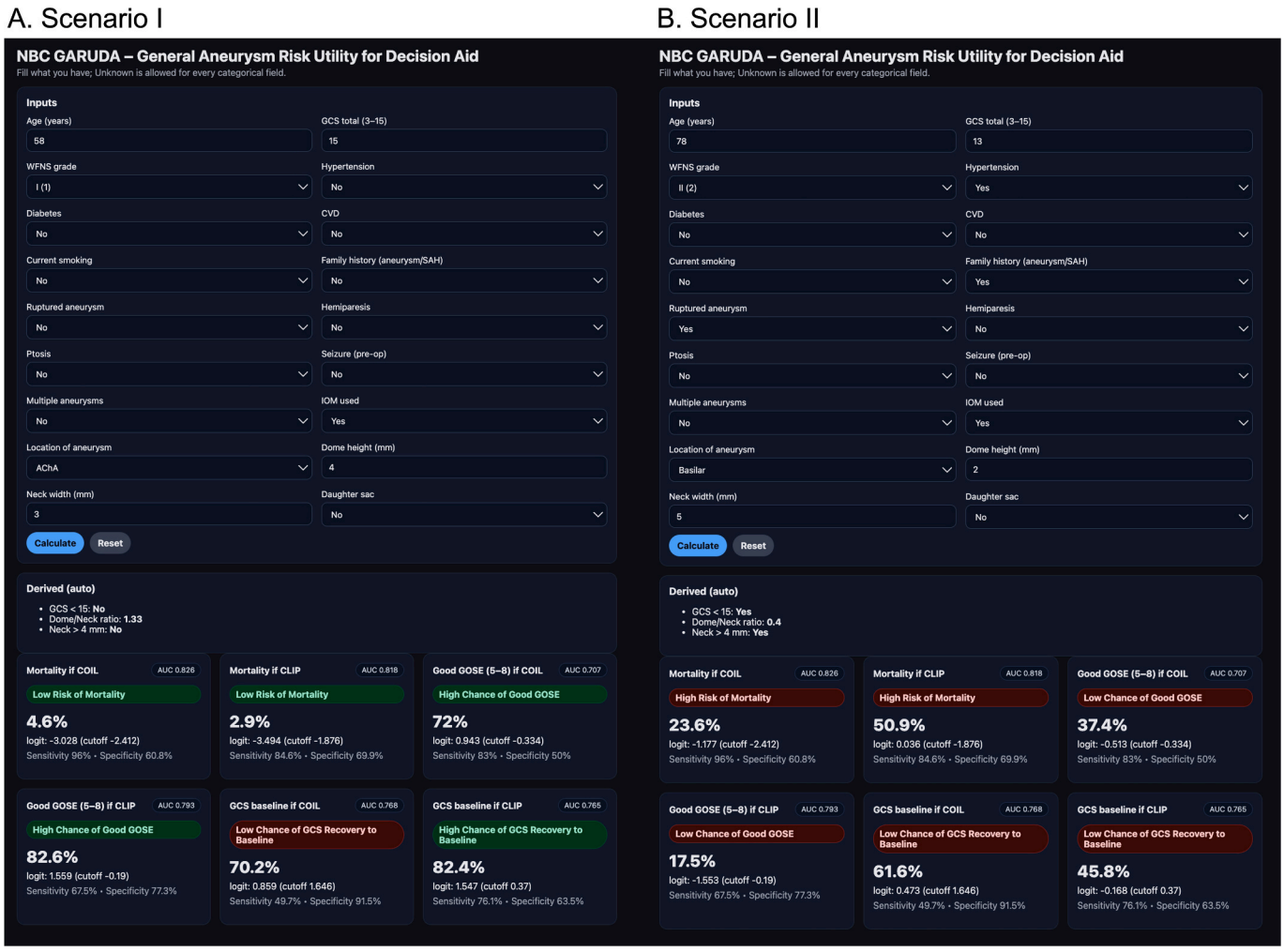

Fig. 4. Proof-of-concept interface of the NBC-GARUDA web calculator in two illustrative clinical scenarios.(A) A 58-year-old patient with intact GCS fifteen, unruptured anterior choroidal artery aneurysm, narrow neck, favorable dome to neck ratio, and intraoperative neuromonitoring available. The calculator displays six predicted endpoints for both coiling and clipping: probability of in-hospital mortality, probability of good functional outcome defined as GOSE 5–8, and probability of return of GCS to baseline. Predicted probabilities are as follows: mortality 4.6 % with coiling and 2.9 % with clipping; good GOSE 72.0 % with coiling and 82.6 % with clipping; recovery of GCS to baseline 70.2 % with coiling and 82.4 % with clipping. (B) A 78-year-old patient with GCS thirteen, ruptured basilar aneurysm, neurological deficit, wide neck with low dome to neck ratio, and daughter sac present. The same six endpoints are presented for both treatment options. Predicted probabilities are as follows: mortality 23.6 % with coiling and 50.9 % with clipping; good GOSE 37.4 % with coiling and 17.5 % with clipping; recovery of GCS to baseline 61.6 % with coiling and 45.8 % with clipping. The calculator is shown to illustrate the structure of the model output and should not be interpreted as a validated stand-alone clinical decision system. https://bryangervais.github.io/garuda-calculator/.

single cohort, and performance in future patients may differ from the apparent and internally corrected estimates reported here. The predictor set was restricted, excluding relevant factors such as operator experience, institutional characteristics, patient preferences, and cerebral vasospasm due to incomplete documentation, which may have reduced predictive accuracy. Unavailable factors such as procedural complexity, adjunctive device use, vasospasm, hydrocephalus, and operator-level strategy may also have contributed. In addition, the cohort was predominantly composed of ruptured aneurysms, so subgroup-specific performance in unruptured aneurysms could not be robustly assessed. Separate rupture-status-specific validation will therefore be important in future work. In the absence of an external comparator cohort, real-world calibration could not be assessed. As a simplified model, this tool should be used only as a decision aid within comprehensive clinical judgment, and further multicenter validation and refinement are required before clinical application. From a service-planning perspective, the present models suggest that improving referral timeliness, perioperative support for clipping, and standardized capture of endovascular procedural variables may be more immediately actionable than treatment availability alone.

5. Conclusion

The NBC-GARUDA, a transparent score and bedside calculator, estimates individual probability of inpatient mortality, good functional outcome, and recovery of GCS after coiling or clipping. Discrimination was variable across outcomes, with stronger performance for mortality models and weaker performance for the coiling models predicting good functional outcome and GCS recovery. Designed for health systems with constrained workforce and variable access to endovascular therapy, this preliminary model may serve as a locally derived proof of concept, but it should not yet be used as a stand-alone tool for counselling or treatment selection. External and prospective validation across centers is required together with impact analyses and periodic recalibration. Future enhancement will incorporate machine learning on digital subtraction angiography images to extract morphological and flow related features with the aim of further improving predictive performance and individualized recommendations.

Ethical approval

The study was reviewed and approved by the Health Research Ethics Committee of the National Brain Center Hospital Mahar Mardjono Jakarta (Approval No. DP.04.03/D.XXIII.9/266/2025) on 3 December 2025.

CRediT authorship contribution statement

Bryan Gervais de Liyis: Writing – original draft, Project administration, Methodology, Data curation, Conceptualization. **Muhammad Iqhrammullah:** Resources, Methodology, Formal analysis. **Muhammad Kusdiansah:** Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration. **Muhammad Hafif:** Writing – original draft, Project administration, Investigation, Data curation. **Bambang Tri Prasetyo:** Resources, Methodology, Investigation, Data curation. **Ricky Gusanto Kurniawan:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology. **Beny Rilianto:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources. **Abrar Arham:** Writing – review & editing, Validation, Supervision, Methodology.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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At this stage, NBC-GARUDA is a preliminary, exploratory, single-center model-development study that provides treatment-specific risk estimates, but it is not yet a validated stand-alone clinical decision tool. The calculator can be accessed here https://bryangervais.github.io/garuda-calculator/

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jocn.2026.112073.

References

[1] Al-Jehani H, Mousa AH. Microsurgical clipping versus endovascular coiling for the treatment of anterior circulation intracranial aneurysms: a systematic review. Discov Med 2025;2:27. https://doi.org/10.1007/s44337-025-00509-0.
[2] Belavadi R, Gudigopuram SVR, Raguthu CC, Gajjela H, Kela I, Kakarala CL, et al. Surgical clipping versus endovascular coiling in the management of intracranial aneurysms. Cureus 2021;13:e20478.
[3] Molyneux AJ, Kerr RSC, Yu L-M, Clarke M, Sneade M, Yarnold JA, et al. International subarachnoid aneurysm trial (ISAT) of neurosurgical clipping versus endovascular coiling in 2143 patients with ruptured intracranial aneurysms: a randomised comparison of effects on survival, dependency, seizures, rebleeding, subgroups, and. Lancet (London, England) 2005;366:809–17.
[4] Hammed A, Al-Qiami A, Alomari O, Otmani Z, Hammed S, Sarhan K, et al. Preventive clipping versus coiling in unruptured intracranial aneurysms: a comprehensive meta-analysis and systematic review to explore safety and efficacy. Neurol Sci Off J Ital Neurol Soc Ital Soc Clin Neurophysiol 2025;46:2499–522.
[5] de Liyis BG, Surya SC, Tini K. Effectivity and safety of endovascular coiling versus microsurgical clipping for aneurysmal subarachnoid hemorrhage: a systematic review and meta-analysis. Clin Neurol Neurosurg 2024;236:108058.
[6] Lim J, Aguirre AO, Baig AA, Levy BR, Ladner LR, Crider C, et al. Global disparities in the presentation and management of aneurysmal subarachnoid hemorrhage: a review and analysis. World Neurosurg 2024;187:202–210.e4.
[7] Hughes JD, Bond KM, Mekary RA, Dewan MC, Rattani A, Baticulon R, et al. Estimating the global incidence of aneurysmal subarachnoid hemorrhage: a systematic review for central nervous system vascular lesions and meta-analysis of ruptured aneurysms. World Neurosurg 2018;115:430–447.e7. https://www.sciencedirect.com/science/article/pii/S1878875018307137.
[8] Lim J, Aguirre AO, Rattani A, Baig AA, Monteiro A, Kuo CC, et al. Thrombectomy outcomes for acute ischemic stroke in lower-middle income countries: a systematic review and analysis. World Neurosurg X 2024;23:100317.
[9] Ospel JM, Diprose WK, Ganesh A, Martins S, Nguyen T, Psychogios M, et al. Challenges to widespread implementation of stroke thrombectomy. Stroke 2024;55:2173–83. https://doi.org/10.1161/STROKEAHA.124.045889.
[10] Lele AV, Shiferaw AA, Theard MA, Vavilala MS, Tavares C, Han R, et al. A global review of the perioperative care of patients with aneurysmal subarachnoid hemorrhage undergoing microsurgical repair of ruptured intracerebral aneurysm. J Neurosurg Anesthesiol 2024;36:164–71.
[11] Gupta S, Gal ZT, Athni TS, Calderon C, Callison WÉ, Dada OE, et al. Mapping the global neurosurgery workforce. Part 1: consultant neurosurgeon density. J Neurosurg 2024;141:1–9. https://thejns.org/view/journals/j-neurosurg/141/1/article-p1.xml.
[12] Ikwuegbuenyi CA, Umutoni A, Atabe Ngwene NN, Ngoma P, Nyalundja AD, Nteranya DS, et al. Public awareness, knowledge of availability, and willingness to use neurosurgical care services in Sub-Saharan Africa: a cross-sectional study. PLoS One 2022;17:e0264955. https://doi.org/10.1371/journal.pone.0264955.
[13] Zhou Z, Wang F, Chen T, Wei Z, Chen C, Xiang L, et al. Pre- and post-operative online prediction of outcome in patients undergoing endovascular coiling after aneurysmal subarachnoid Hemorrhage: Visual and dynamic nomograms. Brain Sci 2023;13.
[14] Greving JP, Wermer MJH, Brown RDJ, Morita A, Juvela S, Yonekura M, et al. Development of the PHASES score for prediction of risk of rupture of intracranial aneurysms: a pooled analysis of six prospective cohort studies. Lancet Neurol 2014;13:59–66.
[15] Backes D, Rinkel GJE, Greving JP, Velthuis BK, Murayama Y, Takao H, et al. ELAPSS score for prediction of risk of growth of unruptured intracranial aneurysms. Neurology 2017;88:1600–6.
[16] Etminan N, Brown RDJ, Beseoglu K, Juvela S, Raymond J, Morita A, et al. The unruptured intracranial aneurysm treatment score: a multidisciplinary consensus. Neurology 2015;85:881–9.
[17] van Heuven AW, Dorhout Mees SM, Algra A, Rinkel GJE. Validation of a prognostic subarachnoid hemorrhage grading scale derived directly from the Glasgow Coma Scale. Stroke 2008;39:1347–8.
[18] van Donkelaar CE, Bakker NA, Birks J, Veeger NJGM, Metzemaekers JDM, Molyneux AJ, et al. Prediction of outcome after aneurysmal subarachnoid Hemorrhage. Stroke 2019;50:837–44.
[19] Jaja BNR, Saposnik G, Lingsma HF, Macdonald E, Thorpe KE, Mamdani M, et al. Development and validation of outcome prediction models for aneurysmal subarachnoid haemorrhage: the SAHIT multinational cohort study. BMJ 2018;360:j5745.
[20] Rilianto B, Prasetyo BT, Kurniawan RG, Rajab NM, Salam S, Sari IM, et al. The GAHR score for prediction of in-hospital mortality patients with aneurysmal subarachnoid hemorrhage. J Clin Neurosci Off J Neurosurg Soc Australas 2025;139:111438.
[21] de Winkel J, Roozenbeek B, Dijkland SA, Dammers R, van Doormaal P-J, van der Jagt M, et al. Personalized decision-making for aneurysm treatment of aneurysmal subarachnoid hemorrhage: development and validation of a clinical prediction tool. BMC Neurol 2024;24:65. https://doi.org/10.1186/s12883-024-03546-x.
[22] Spetzler RF, McDougall CG, Zabramski JM, Albuquerque FC, Hills NK, Nakaji P, et al. Ten-year analysis of saccular aneurysms in the Barrow Ruptured Aneurysm Trial. J Neurosurg 2020;132:771–6.
[23] Molyneux AJ, Birks J, Clarke A, Sneade M, Kerr RSC. The durability of endovascular coiling versus neurosurgical clipping of ruptured cerebral aneurysms: 18 year follow-up of the UK cohort of the International Subarachnoid Aneurysm Trial (ISAT). Lancet (London, England) 2015;385:691–7.
[24] Connolly ESJ, Rabinstein AA, Carhuapoma JR, Derdeyn CP, Dion J, Higashida RT, et al. Guidelines for the management of aneurysmal subarachnoid hemorrhage: a guideline for healthcare professionals from the American Heart Association/American stroke association. Stroke 2012;43:1711–37.
[25] Steiner T, Juvela S, Unterberg A, Jung C, Forsting M, Rinkel G. European stroke organization guidelines for the management of intracranial aneurysms and subarachnoid haemorrhage. Cerebrovasc Dis 2013;35:93–112.
[26] Khamis M, Ibrahim H, Elsayed MA, Tawadros SR, Mohamed MHA, El-Bahy K. Comparative analysis of microsurgical clipping versus endovascular coiling for middle cerebral artery aneurysms: a prospective study at Ain Shams University hospitals. Egypt J Neurosurg 2025;40:2. https://doi.org/10.1186/s41984-024-00338-w.
[27] Molenberg R, Aalbers MW, Mazuri A, Luijckx GJ, Metzemaekers JDM, Groen RJM, et al. The unruptured intracranial aneurysm treatment score as a predictor of aneurysm growth or rupture. Eur J Neurol 2021;28:837–43.
[28] Yoshiyama M, Ikawa F, Hidaka T, Matsuda S, Ozono I, Toyoda K, et al. Development and validation of scoring indication of surgical clipping and endovascular coiling for aneurysmal subarachnoid hemorrhage from the post hoc analysis of japan stroke data bank. Neurol Med Chir (Tokyo) 2021;61:107–16.
[29] Chen C, Qiao H, Cui Z, Wang C, Zhang C, Feng Y. Clipping and coiling of intracranial aneurysms in the elderly patients: clinical features and treatment outcomes. Front Neurol 2023;14. https://www.frontiersin.org/journals/neurology/articles/10.3389/fneur.2023.1282683.
[30] Ariza-Garcia ME, Pérez-Pinto F, Agudelo-Arrieta M, Caballero-Restrepo AF, Riveros-Castillo WM. Endovascular coiling of right vertebral artery saccular aneurysm at non-branching site: a potential and safe treatment option. Interdiscip

Neurosurg 2021;25:101148. https://www.sciencedirect.com/science/article/pii/S2214751921000608.
[31] Hassan F, Osman AAL, Issa AS. Deconstructive endovascular technique for dissecting posterior cerebral artery aneurysms: a single-center case series study. Egypt J Radiol Nucl Med 2024;55:14. https://doi.org/10.1186/s43055-024-01186-2.
[32] Zhao B, Xing H, Fan L, Tan X, Zhong M, Pan Y, et al. Endovascular coiling versus surgical clipping of very small ruptured anterior communicating artery aneurysms. World Neurosurg 2019;126:e1246–50.
[33] Theofanopoulos A, Troude L, Neyazi M, Muhammad S. Review of current treatment modalities and clinical outcome of giant saccular aneurysms of the basilar apex. Brain and Spine 2024;4:103333. https://www.sciencedirect.com/science/article/pii/S2772529424005897.
[34] Won S-Y, Seifert V, Dubinski D, Kashefiolasl S, Dinc N, Bruder M, et al. Short- and midterm outcome of ruptured and unruptured intracerebral wide-necked aneurysms with microsurgical treatment. Sci Rep 2021;11:4982. https://doi.org/10.1038/s41598-021-84339-x.
[35] Ferreira MY, Batista S, Brenner LBO, Marques GN, Maia HG, Palavani LB, et al. Comparing surgical clipping with endovascular treatment for unruptured middle cerebral artery aneurysms: a systematic review and updated meta-analysis. J Neurosurg 2025;142:116–26.
[36] Anxionnat R, Tonnelet R, Derelle AL, Liao L, Barbier C, Bracard S. Endovascular treatment of ruptured intracranial aneurysms: indications, techniques and results. Diagn Interv Imaging 2015;96:667–75. https://www.sciencedirect.com/science/article/pii/S2211568415002090.
[37] Dokponou YCH, Kotecha J, Bandyopadhyay S, Erhabor J, Ooi SZY, Egiz A, et al. Continental survey of access to diagnostic tools and endovascular management of aneurysmal subarachnoid Hemorrhage in Africa. Front Surg 2021;8. https://www.frontiersin.org/journals/surgery/articles/10.3389/fsurg.2021.690714.
[38] Zubair Tahir M, Enam SA, Pervez Ali R, Bhatti A, ul Haq T. Cost-effectiveness of clipping vs coiling of intracranial aneurysms after subarachnoid hemorrhage in a developing country–a prospective study. Surg Neurol 2009;72:351–5.
[39] Mesiano T, Kurniawan M, Saputri KM, Hidayat R, Permana AP, Rasyid A, et al. Endovascular treatment in acute ischemic stroke adoption and practice: a single-center Indonesian experience. Cerebrovasc Dis Extra 2021;11:72–6.
[40] Venketasubramanian N, Yudiarto FL, Tugasworo D. Stroke burden and stroke services in Indonesia. Cerebrovasc Dis Extra 2022;12:53–7. https://doi.org/10.1159/000524161.
[41] Yadav N, Hedaoo K, Patidar J, Parihar VS, Ratre S, Tamaskar A, et al. Real-world outcomes of endovascular management of intracranial aneurysms: insights from a tertiary care hospital in central India. J Clin Interv Radiol ISVIR 2025.