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Predicting Candidacy for Neurosurgical Intervention in Stroke: A Nomogram and Decision Tree in a Prospective Cohort of 250 Patients at Bouaké Teaching Hospital, Côte d'Ivoire

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Abstract

Background and Objectives: In resource-limited settings, the decision to operate on a stroke rests on individual experience, with no formal tool. We developed and internally validated a model estimating the probability that a patient meets the criteria for a neurosurgical indication at admission. **Methods:** Prospective cohort of 250 consecutive patients admitted for imaging-confirmed stroke between January 2022 and December 2023. The target outcome was the operative indication recorded in the chart. A logistic regression with backward selection was translated into a nomogram and an integer score, with a classification and regression tree built in parallel. Internal validation replicated the whole process across 1000 bootstrap resamples. **Results:** An indication was made in 107 patients (42.8%). Four variables were independently associated with it: hydrocephalus (adjusted odds ratio 4.15; 95% CI 2.03 - 8.46), mass effect (2.42), intraventricular extension (2.31) and impaired consciousness (2.23). The apparent area under the curve was 0.77 (0.71 - 0.83), the optimism-corrected area 0.73 and the corrected calibration slope 0.84. The model outperformed existing scores (ICH score 0.66; ≤0.60 for the others). The integer score (0 - 5) reproduced a gradient from 15.7% to 95.0%. Of 107 indications, only 45 were operated on, and none of the 15 aneurysmal indications. The decision tree generalised less well (cross-validated area 0.69). **Conclusion:** A four-variable bedside tool estimates the probability of a neurosurgical indication in stroke and outperforms prognostic scores repurposed for

that end. It documents a 58% access gap. External multicentre validation remains necessary.

Keywords

Stroke, Surgical Indication, Nomogram, Decision Tree, Prediction Model, Neurosurgery, Sub-Saharan Africa

1. Introduction

Stroke is the second leading cause of death and the third leading cause of disability worldwide, and sub-Saharan Africa bears a disproportionate share of this burden, marked by a predominance of haemorrhagic forms, onset at a younger age and high case fatality [1]-[10]. In this region, stroke neurosurgery operates against a background of scarcity: limited technical facilities, sometimes delayed imaging, frequent absence of interventional neuroradiology and constrained human resources [7] [9] [11] [12].

The decision to intervene—haematoma evacuation, decompressive craniectomy, ventricular drainage, treatment of an aneurysm—rests on a set of clinical and radiological arguments whose integration remains largely dependent on individual experience. The randomised trials that shape international doctrine (STICH, STICH II, MISTIE III, ENRICH and SWITCH for intracerebral haemorrhage; the pooled analyses of decompressive craniectomy for malignant infarction; ISAT for ruptured aneurysm) were conducted in health systems where access to surgery is not the limiting factor [13]-[19]. Their transportability to low-resource settings is uncertain, and no formal tool helps the frontline practitioner to establish, from admission onwards, the probability that a patient meets the criteria for an operative indication.

Prediction models, when they are transparent, parsimonious and well calibrated, can structure this reasoning, harmonise practice and serve as a teaching and triage aid [20]-[22]. Two formats lend themselves particularly well to bedside use: the nomogram, which translates a regression model into a graphical points scale, and the decision tree (CART), which sets out a sequence of interpretable binary rules [21] [23]. To our knowledge, no decision model has been developed specifically to predict candidacy for neurosurgical intervention in stroke patients in sub-Saharan Africa: the available tools (ICH score, NIHSS, Glasgow Coma Scale, WFNS, modified Fisher) target survival or functional outcome, not the operative decision. This matters, because the surgical decision follows a logic of its own—that of correctable mechanical effect—which a prognostic score captures poorly.

We therefore developed and internally validated, from a prospective cohort of 250 patients managed in a sub-Saharan African neurosurgical department, a tool estimating the probability that a patient is a candidate for neurosurgical interven-

tion using clinical and radiological variables available immediately. We propose two complementary versions of it—a nomogram (with a derived integer score) and a decision tree—and report their discrimination, calibration, clinical benefit and robustness, comparing them with existing prognostic scores. Beyond decision support, the model serves to quantify unmet neurosurgical need objectively, a central dimension in public health and in global neurosurgery. Reporting follows the STROBE recommendations for observational studies and TRIPOD for prediction models [20] [24].

2. Methods

2.1. Study Design and Setting

This is an analysis aimed at developing a prediction model, carried out on a single-centre prospective cohort assembled in the department of neurosurgery of Bouaké Teaching Hospital (Côte d'Ivoire), the tertiary referral centre for the centre of the country. The inclusion criteria, the data collection procedures and the definitions of the variables are set out in Sections 2.2 to 2.4. The present work is reported in accordance with the STROBE recommendations [24] and TRIPOD (development and internal validation of a prediction model) [20].

2.2. Participants

All consecutive patients aged 18 years or over admitted for an imaging-confirmed stroke (computed tomography or magnetic resonance imaging) from 1 January 2022 to 31 December 2023 were included, with the period and individual dates verified against the source database, excluding traumatic or tumour-related haemorrhages and cases without available imaging. The analysis covered all 250 patients in the cohort, none of whom had a missing value on the target outcome or on the four predictors retained in the final model.

2.3. Target Outcome: Candidacy for Neurosurgical Intervention

The outcome to be predicted was the operative indication as recorded in the chart by the neurosurgical team at the end of the admission work-up (binary variable: 0 = no indication; 1 = indication made). An indication corresponded to at least one operative procedure judged appropriate on clinical and radiological grounds: ventricular (external) drainage for obstructive hydrocephalus or intraventricular haemorrhagic extension; haematoma evacuation or decompressive craniectomy for space-occupying mass effect or herniation; decompressive craniectomy for malignant infarction; and treatment of a ruptured aneurysm for subarachnoid haemorrhage. The indication was initially assessed by the on-call neurosurgeon on the basis of the available clinical and imaging data, then discussed jointly with a second neurosurgeon whenever the situation was complex or several therapeutic options were conceivable. It is therefore an expertise-based outcome, reflecting actual practice in a resource-limited setting, and not a universal reference standard: the model predicts the probability that a patient meets the indication criteria

as applied in our centre, and makes no claim about the superiority of surgery over medical treatment. This choice—preferred to surgery actually performed—follows from the purpose of the tool: to estimate the probability that a patient warrants a procedure on clinical and radiological grounds, independently of the actual availability of technical facilities, which is a determinant of access distinct from the medical decision. Surgery actually performed was nevertheless analysed as an alternative target in a sensitivity analysis, precisely in order to expose the gap between indication and delivery. Model development is summarised in Figure 1.

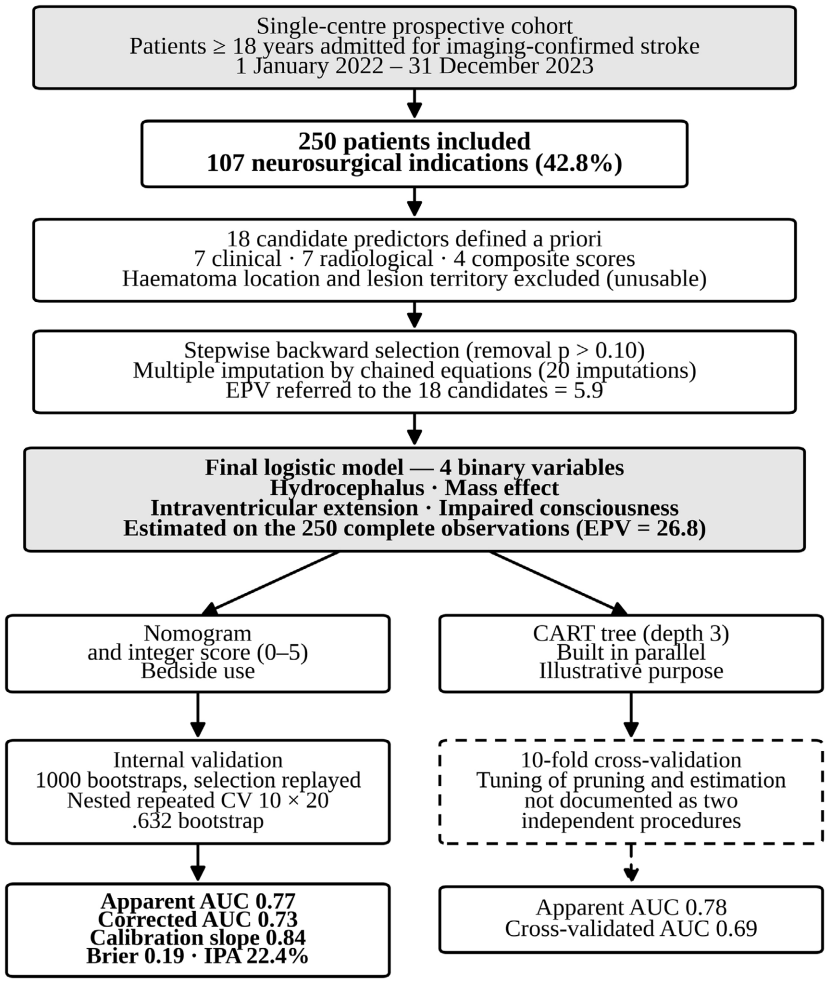


Figure 1. Model development and validation diagram (TRIPOD flow). The 250 patients, with no missing data on the target outcome or on the final predictors, served for the development of the nomogram (4 variables) and of the CART tree, and then for internal validation.

2.4. Candidate Predictors

The predictors, all available at admission, were specified a priori on pathophysiological grounds and for feasibility in a resource-limited setting. The clinical domain comprised age, sex, Glasgow Coma Scale score, impaired consciousness, motor deficit, anisocoria and vomiting; the radiological domain (non-contrast

computed tomography) comprised stroke type, presence of intracerebral haemorrhage, haematoma volume, mass effect, herniation, hydrocephalus and intraventricular extension; the composite scores (ICH score, WFNS, modified Fisher, NIHSS) were also considered. In line with the documented limitations of the database, haematoma location (missing in 148 of the 149 intracerebral haemorrhages) and lesion territory (not recorded in 249 patients) were excluded from the outset. Haematoma volume, herniation, ICH score, WFNS and modified Fisher were coded as zero where they did not apply, with no domain indicator; this coding conflates absence of lesion with absence of measurement. All predictors were ascertained at admission, from the initial clinical examination and the first non-contrast computed tomography. The radiological predictors were read as binary present/absent signs by the neurosurgical team: hydrocephalus as dilatation of the ventricular system reflecting obstruction of cerebrospinal fluid outflow; mass effect as parenchymal compression (effacement of the cortical sulci and basal cisterns, ventricular compression or midline shift); intraventricular extension as the presence of blood within the ventricular system; and herniation as radiological signs of brain displacement across a dural or bony boundary. Impaired consciousness denoted a clinically documented alteration of the level of consciousness at admission, recorded as a binary sign. These classifications were made in the course of routine care, without a separate structured radiology reporting protocol and without independent double reading, so that no inter-observer reproducibility could be measured (a limitation addressed in Section 4.7).

2.5. Model Development

Nomogram. A logistic regression model was developed by stepwise backward selection (removal threshold $p > 0.10$) from the candidate predictors defined a priori. Candidate variables with missing data (Glasgow Coma Scale score, 12.4%; NIHSS, 1.6%; herniation, 3.6%) were handled by multiple imputation by chained equations (20 imputations, iterative predictive regression); the imputation model included all candidate predictors together with the target outcome. Backward selection was performed across the 20 imputed datasets, the removal decision at each step resting on the p-value pooled by Rubin's rules, a predictor being removed when its pooled p-value exceeded 0.10; none of these three variables was, however, retained in the final model. The latter, containing only variables free of missing data, was therefore estimated on the 250 complete observations, without imputation. With 107 events for the four retained predictors, the number of events per variable in the final model was 26.8; referred to the 18 candidate predictors listed above, it stands at 5.9: it is at this level that optimism arises, and that the internal validation procedure described below was designed to capture it. As the four retained predictors were binary, the assumption of logit linearity did not apply; collinearity was checked using the variance inflation factor (VIF). The final model was translated into a nomogram (points assigned in proportion to the coefficients) and then into a simplified integer score intended for bedside use.

Decision tree. A classification and regression tree (CART) was built in parallel on the full set of clinical and radiological predictors, in order to expose any thresholds and interactions. Pruning was carried out by cost-complexity, with the penalty parameter chosen by 10-fold cross-validation maximising the AUC. A deliberately shallow tree (depth 3) was retained for clinical presentation. The choice of the complexity parameter and the estimation of the tree's performance were not documented as two independent procedures in the current version of the code; the AUC of 0.69 must therefore be regarded as a cross-validated estimate, and not as an independent external performance. Candidate variables with missing values were subjected to multiple imputation within the development procedure of the logistic model; the current version of the protocol does not, however, document separately the strategy applied to the CART.

2.6. Internal Validation, Performance and Clinical Benefit

Discrimination was quantified by the area under the ROC curve (AUC), with a 95% confidence interval (DeLong method), and supplemented by the precision-recall curve (average precision). Calibration was assessed using the Hosmer-Lemeshow test, the Brier score, the calibration slope and intercept, and a smoothed calibration curve with a bootstrap confidence interval. Internal validation replicated the entire development process: within each of the 1000 bootstrap resamples, imputation of the candidate variables, backward selection and coefficient estimation were repeated. Optimism was defined as the mean difference between model performance in the bootstrap sample and that obtained when applying it to the original sample [22]. A repeated nested cross-validation (10 folds × 20 repetitions), in which selection was likewise reproduced within each training set, and a 0.632 bootstrap were performed in addition. Clinical benefit was assessed by decision curve analysis (DCA), quantifying the net benefit of the model across a range of probability thresholds, compared with the strategies of operating on all and on none. Finally, the discrimination of the model was compared with that of existing scores (ICH score, NIHSS, Glasgow Coma Scale, WFNS, modified Fisher) repurposed for the prediction of the surgical indication. An exploratory temporal check was carried out by ordering the cohort chronologically and splitting it into the first and last 125 inclusions, the later period serving as an evaluation set; this split was not defined by calendar year, the yearly numbers not being reported separately, and the selection procedure was not re-run on the first 125 patients, so that the resulting figure is exploratory and does not constitute an independent temporal validation. For the tree, performance was estimated by 10-fold cross-validation, subject to the reservation about non-independence stated above.

2.7. Statistical Analysis

Continuous variables are described by their median [interquartile range] and compared using the Mann-Whitney test; categorical variables by counts and per-

centages, compared using the χ^2 test. Associations are expressed as crude and adjusted odds ratios (OR) with 95% confidence intervals. The significance threshold was set at 0.05 (two-sided). Analyses were carried out in Python (pandas, statsmodels, scikit-learn).

2.8. Ethical Considerations

Bouaké Teaching Hospital did not have a constituted ethics committee over the study period. The study was conducted after authorisation by the head of the department of neurosurgery and by the hospital management, in accordance with the principles of the Declaration of Helsinki. It has since received the approval of the Institutional Ethics Committee of the CHU de Bouaké (approval no. CEI/CHU-BKE/102/2026). The data were collected in the course of routine care and analysed in anonymised form; the dispensation from individual informed consent is covered by that approval.

3. Results

3.1. Population and Frequency of the Surgical Indication

A neurosurgical indication was made in 107 of the 250 patients (42.8%). Patients with an indication did not differ from the others in age (median 56 years in both groups) or sex (62% men in both groups), but had more severe neurological and radiological involvement: lower Glasgow Coma Scale score (median 11 vs 12; $p = 0.035$), higher ICH score (median 2 vs 0; $p < 0.001$), larger haematoma volume (median 32 vs 3 mL; $p < 0.001$) and more marked herniation ($p < 0.001$). Intracerebral haemorrhage was more frequent in patients with an indication than in the others (72% vs 50%; $p < 0.001$). The comparative characteristics are shown in Table 1.

Table 1. Patient characteristics according to the presence of a neurosurgical indication.

Characteristic	No indication (n = 143)	Indication (n = 107)	p
Age, median [IQR], years	56 [43 - 66]	56 [45 - 63]	0.98
Male sex, n (%)	89 (62)	66 (62)	1.00
Glasgow Coma Scale score, median [IQR]	12 [10 - 14]	11 [8 - 13]	0.035
NIHSS, median [IQR]	17 [12 - 21]	19 [15 - 23]	0.011
ICH score, median [IQR]	0 [0 - 2]	2 [0 - 3]	<0.001
Haematoma volume, median [IQR], mL	3 [0 - 40]	32 [0 - 49]	<0.001
Herniation, median [IQR], mm	0 [0 - 5]	4 [0 - 7]	<0.001
Intracerebral haemorrhage, n (%)	72 (50)	77 (72)	<0.001
Subarachnoid haemorrhage, n (%)	15 (10)	15 (14)	0.51
Mass effect, n (%)	59 (41)	72 (67)	<0.001

Continued

Hydrocephalus, n (%)	16 (11)	44 (41)	<0.001
Intraventricular extension, n (%)	34 (24)	59 (55)	<0.001
Impaired consciousness, n (%)	52 (36)	68 (64)	<0.001
Anisocoria, n (%)	19 (13)	26 (24)	0.038

IQR: interquartile range; NIHSS: National Institutes of Health Stroke Scale; ICH: intracerebral hemorrhage. Comparisons by Mann-Whitney test (continuous variables) or χ^2 test (categorical variables).

3.2. Univariable Determinants

On univariable analysis, hydrocephalus (OR 5.54; 95% CI 2.90 - 10.59), intraventricular extension (OR 3.94; 2.29 - 6.77), mass effect (OR 2.93; 1.74 - 4.94), impaired consciousness (OR 3.05; 1.81 - 5.14) and intracerebral haemorrhage (OR 2.53; 1.48 - 4.32) were strongly associated with the surgical indication. Haematoma volume, herniation, ICH score and NIHSS were likewise associated, to a lesser degree. By contrast, neither age, nor motor deficit, nor subarachnoid haemorrhage reached the significance threshold (Table 2), any more than did sex and vomiting, whose association is not reported in Table 2.

Table 2. Univariable associations with the neurosurgical indication (crude odds ratios).

Predictor	Crude OR	95% CI	p
Hydrocephalus	5.54	2.90 - 10.59	<0.001
Intraventricular extension	3.94	2.29 - 6.77	<0.001
Impaired consciousness	3.05	1.81 - 5.14	<0.001
Mass effect	2.93	1.74 - 4.94	<0.001
Intracerebral haemorrhage	2.53	1.48 - 4.32	<0.001
Anisocoria	2.09	1.09 - 4.03	0.027
ICH score (per point)	1.65	1.32 - 2.05	<0.001
Herniation (per mm)	1.16	1.07 - 1.25	<0.001
NIHSS (per point)	1.06	1.01 - 1.10	0.009
Haematoma volume (per mL)	1.02	1.01 - 1.03	<0.001
Glasgow Coma Scale score (per point)	0.90	0.82 - 0.98	0.018
Motor deficit	1.77	0.99 - 3.19	0.056
Subarachnoid haemorrhage	1.39	0.65 - 2.99	0.40
Age (per year)	1.00	0.98 - 1.02	0.91

OR: odds ratio; CI: confidence interval. An OR greater than 1 indicates an increased probability of a surgical indication.

3.3. Multivariable Model and Nomogram

After backward selection, four variables remained independently associated with the surgical indication: hydrocephalus (aOR 4.15; 95% CI 2.03 - 8.46; p < 0.001), mass effect (aOR 2.42; 1.35 - 4.36; p = 0.003), intraventricular extension (aOR 2.31; 1.26 - 4.23; p = 0.007) and impaired consciousness (aOR 2.23; 1.25 - 3.96; p = 0.007). The Glasgow Coma Scale score, haematoma volume and the composite scores contributed no independent information once these markers of mechanical effect were taken into account, and were not retained. Collinearity was negligible (all variance inflation factors < 1.8) (Table 3; coefficients, standard errors and variance inflation factors in Table 4). The final model, estimated on the 250 complete observations, was translated into a nomogram (Figure 2): hydrocephalus carries the greatest weight (100 points), ahead of mass effect (62 points), intraventricular extension (59 points) and impaired consciousness (56 points).

The model equation is as follows: logit(p) = −1.83 + 1.42 × hydrocephalus + 0.89 × mass effect + 0.84 × intraventricular extension + 0.80 × impaired consciousness, each variable being coded 0 (absent) or 1 (present); the predicted probability is p = 1/(1 + e^−logit(p)). The equivalent integer score assigns 2 points to hydrocephalus and 1 point to each of the three other variables (total 0 - 5).

Table 3. Final multivariable logistic model (nomogram)—neurosurgical indication (n = 250).

Variable	aOR	95% CI	p	Points
Hydrocephalus	4.15	2.03 - 8.46	<0.001	100
Mass effect	2.42	1.35 - 4.36	0.003	62
Intraventricular extension	2.31	1.26 - 4.23	0.007	59
Impaired consciousness	2.23	1.25 - 3.96	0.007	56
Intercept (β_0)	-	β = −1.83	<0.001	-

aOR: adjusted odds ratio. Points: contribution to the nomogram, standardised from 0 to 100. Apparent AUC 0.77; optimism-corrected AUC 0.73 (optimism 0.041, with selection reproduced in each resample); corrected calibration slope 0.84; Brier score 0.19.

Table 4. Coefficients of the final model, standard errors and variance inflation factors (n = 250).

Variable	β	Standard error	aOR [95% CI]	VIF
Intercept	−1.830	0.285	-	-
Hydrocephalus	1.422	0.364	4.15 [2.03 - 8.46]	1.47
Mass effect	0.886	0.299	2.42 [1.35 - 4.36]	1.78
Intraventricular extension	0.837	0.309	2.31 [1.26 - 4.23]	1.80
Impaired consciousness	0.800	0.294	2.23 [1.25 - 3.96]	1.79

aOR: adjusted odds ratio; VIF: variance inflation factor (all below 2, indicating no problematic collinearity).

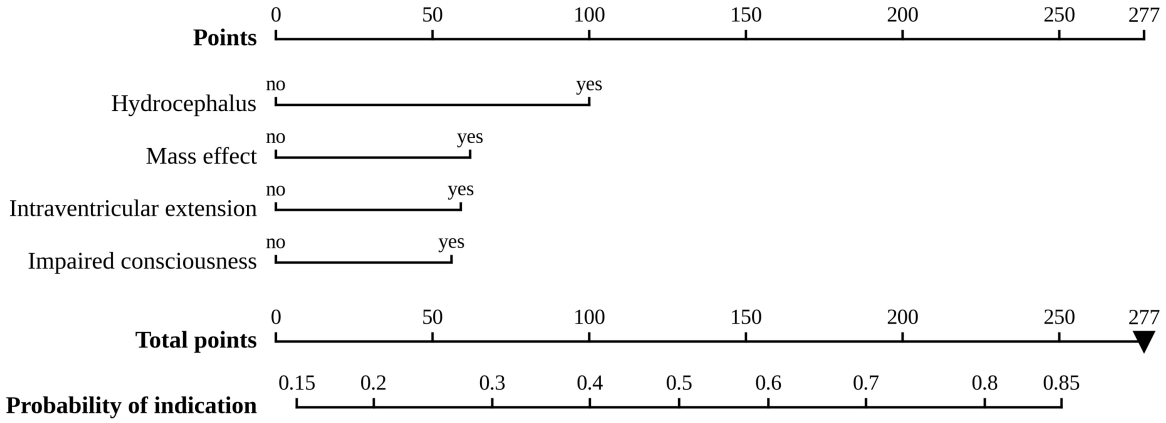


Figure 2. Nomogram for estimating the probability of a neurosurgical indication. The points for each variable are added on the "Total points" rule (maximum attainable 277); the lower rule converts this total into a probability according to logit(p) = −1.830 + 0.01422 × total points.

3.4. Simplified Integer Score

For immediate use without graphical support, an integer score was derived by rounding the contributions: hydrocephalus = 2 points; mass effect, intraventricular extension and impaired consciousness = 1 point each (total 0 to 5). The observed probability of an indication rose monotonically with the score, from 15.7% (0 points) to 95.0% (5 points), in agreement with the predicted probabilities, except at a score of 4, where the observed probability (66.7% in 18 patients) remains eleven points below the predicted value (**Table 5**, **Figure 3**). Evaluated on its own—through its own ROC curve and its own observed-versus-predicted frequencies by score level—the integer score reached an area under the curve of 0.77 and reproduced the risk gradient directly (**Table 5**, **Figure 3**), rather than by inference from the logistic model. The weighting adopted groups the sixteen possible profiles into six levels without ever inverting their order: by construction it therefore guarantees that the score cannot exceed the continuous model, but not that it equals it. The absence of loss is here a finding, ties within a given score level having not degraded concordance.

Table 5. Integer score (0 - 5): gradient of risk of a neurosurgical indication.

Score	n patients	Observed indication, %	Predicted probability, %
0	51	15.7	13.8
1	67	23.9	27.2
2	57	49.1	45.8
3	37	64.9	64.1
4	18	66.7	78.1
5	20	95.0	89.2

Points assignment: hydrocephalus = 2; mass effect = 1; intraventricular extension = 1; impaired consciousness = 1.

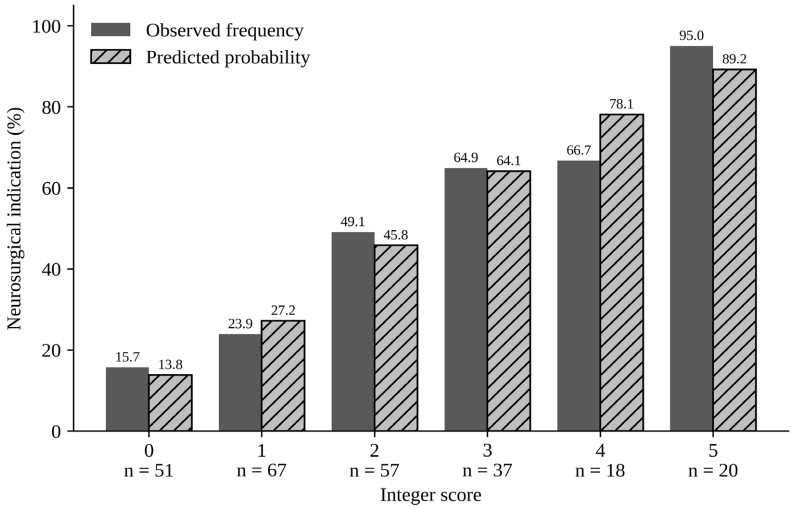


Figure 3. Risk gradient by integer score (0 - 5): agreement between the observed rate of indication and the probability predicted by the model.

3.5. Decision Tree (CART)

The classification tree identified hydrocephalus as the first splitting node, then, in its absence, herniation and the ICH score, and, in its presence, haematoma volume and mass effect—recovering clinically plausible thresholds (volume of about 22 mL, herniation of about 6.5 mm) (**Figure 4**). Despite good apparent performance (AUC 0.78), the tree generalised less well on cross-validation (AUC 0.69), reflecting the overfitting inherent to single trees. The nomogram, being more stable, is therefore proposed as the first-line tool, with the tree serving as a teaching aid for reading thresholds and interactions.

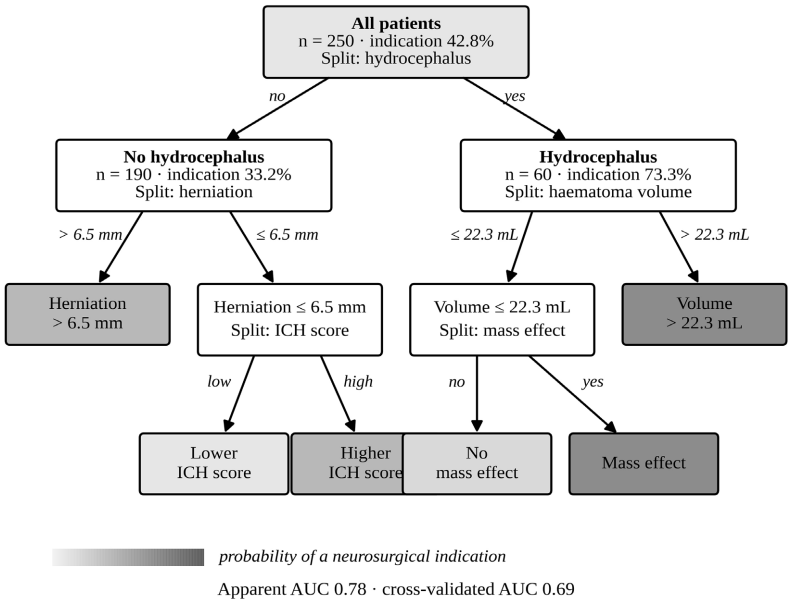


Figure 4. CART decision tree (depth 3). Hydrocephalus is the first node; in its absence, herniation and the ICH score direct the decision; in its presence, volume and mass effect. Cross-validated AUC = 0.69.

3.6. Discrimination, Calibration and Internal Validation

The nomogram showed an apparent AUC of 0.77 (95% CI 0.71 - 0.83) (Figure 5). As internal validation replicated the entire development process, mean optimism was 0.041 and the corrected AUC 0.73; repeated nested cross-validation returned 0.74, and the 0.632 bootstrap estimate likewise 0.74. Across the 1000 resamples, the four predictors of the final model were retained with selection frequencies of 96.8% (hydrocephalus), 88.7% (mass effect), 84.3% (intraventricular extension) and 86.1% (impaired consciousness), and the optimism-corrected estimates are reported with bootstrap 95% confidence intervals (corrected AUC 0.73 [95% CI 0.66 - 0.79]; corrected calibration slope 0.84 [95% CI 0.65 - 1.03]). Discrimination is therefore moderate after an internal validation that reproduces selection—which remains creditable for a tool based on four binary variables available at admission and calculable from memory. Calibration was satisfactory overall: corrected slope 0.84 and corrected intercept −0.01 (ideal values 1 and 0 respectively), a slope below 1 indicating moderate overfitting; a non-significant Hosmer-Lemeshow test ($p = 0.92$, of limited interpretability, the sixteen profiles predicted by the model being very unevenly distributed across the cohort); an observed-to-expected ratio of 1.00, the value expected by construction for a logistic model estimated on its own data; a Brier score of 0.19, corresponding to an index of prediction accuracy of 22.4% relative to the null model; and satisfactory observed-predicted agreement over most of the risk range, the only departure occurring at a score of 4 (Figure 6 and Figure 7). The precision-recall curve (average precision 0.73, for a prevalence of 0.43) confirmed the relevance of the

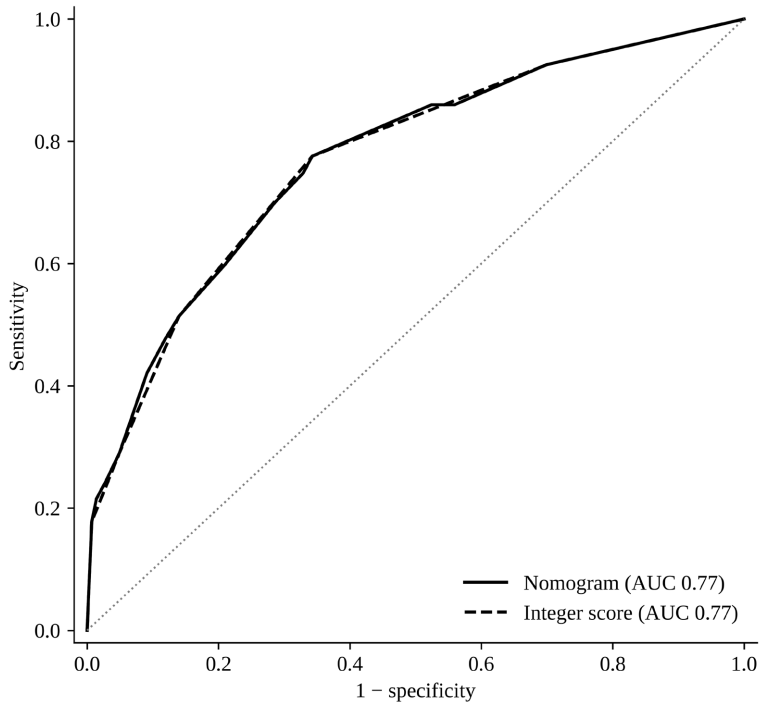


Figure 5. ROC curves of the nomogram and of the integer score for the prediction of the neurosurgical indication.

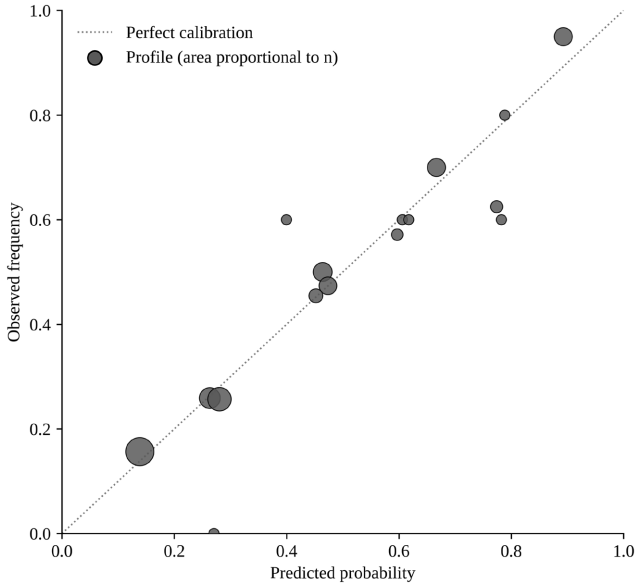


Figure 6. Calibration plot of the nomogram: observed frequencies of indication against predicted probabilities (Hosmer-Lemeshow test p = 0.92, of limited interpretability, the sixteen profiles predicted by the model being very unevenly distributed across the cohort).

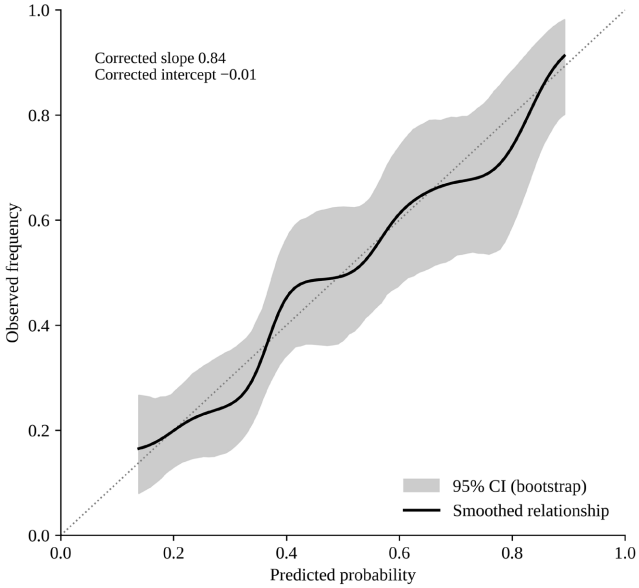


Figure 7. Internal calibration of the logistic model. The solid line represents the smoothed relationship between predicted probabilities and observed frequency; the shaded area represents the 95% confidence interval obtained by bootstrap. The optimism-corrected calibration slope was 0.84 and the corrected intercept −0.01. The whole variable selection process was repeated within each resample.

model in a decision-making context (**Figure 8**). The optimal probability threshold by the Youden index was 0.40; it corresponds to an integer score ≥ 2, whose performance is 77.6% sensitivity and 65.7% specificity—with the single exception of the profile of isolated hydrocephalus, whose predicted probability (0.399) falls just below the threshold, so that the two rules do not classify that profile identically.

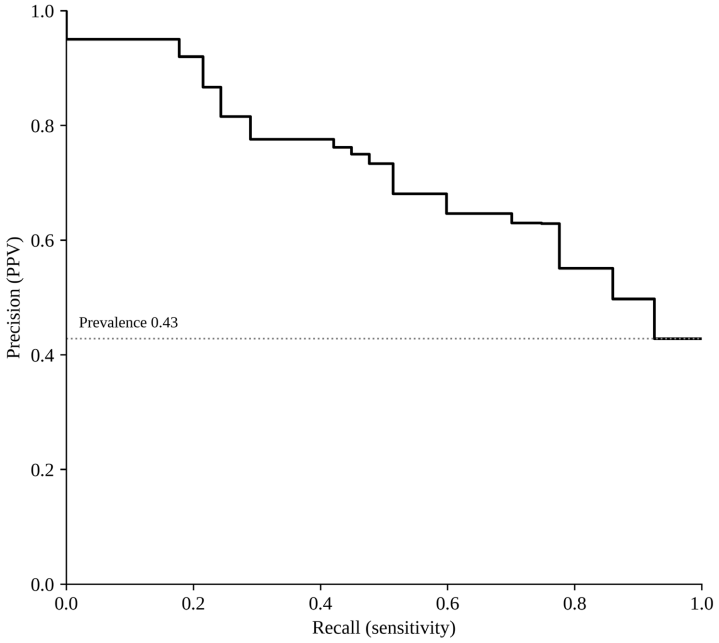


Figure 8. Precision-recall curve of the nomogram (average precision 0.73; prevalence 0.43).

3.7. Clinical Benefit and Comparison with Existing Scores

On decision curve analysis, the nomogram provided a net benefit superior to the strategies of operating on all and on none, and to a model based on the ICH score alone, across the whole range of probabilities it predicts (0.14 to 0.89); beyond these bounds it coincides with one or other of the two reference strategies (**Figure 9**). As the reference outcome is the indication made by the team, this net benefit measures the usefulness of reproducing that decision, and not a demonstrated gain in patient outcome. The nomogram also discriminated the surgical indication better than the classical prognostic scores repurposed for that end: across the cohort the ICH score reached an AUC of only 0.66, the NIHSS 0.60, the Glasgow Coma Scale score 0.58, the WFNS 0.52 and the modified Fisher 0.52, against 0.77 for the nomogram (**Table 6**, **Figure 10**). This comparison must be read with caution and is presented as indicative rather than confirmatory. It sets the apparent AUC of the nomogram (0.77)—not the optimism-corrected AUC (0.73)—against scores none of whose parameters was estimated on the cohort, and the DeLong p-values (all below 0.001) take no account of the uncertainty of predictor selection, so that the statistical significance is anti-conservative. Furthermore, the ICH score is defined only in intracerebral haemorrhage and the WFNS and modified Fisher only in subarachnoid haemorrhage; computed across the whole cohort with out-of-domain values coded as zero, their discrimination is mechanically depressed and is not the quantity a within-population comparison would return. A comparison restricted to the population in which each score is defined is the appropriate analysis and is deferred to external validation. The direction of the difference is nonetheless expected on principle, these scores having been designed to predict mortality or functional outcome, and not surgical candidacy.

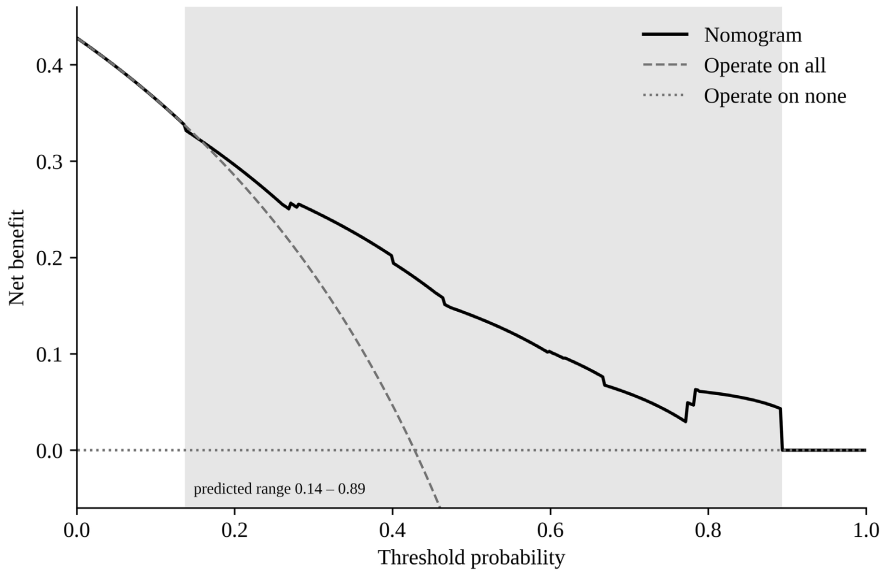


Figure 9. Decision curve analysis. The nomogram (solid line) provides a net benefit superior to the strategies of operating on all and on none and to the model based on the ICH score alone across the whole range of probabilities it predicts (0.14 to 0.89); beyond these bounds it coincides with one or other of the two reference strategies.

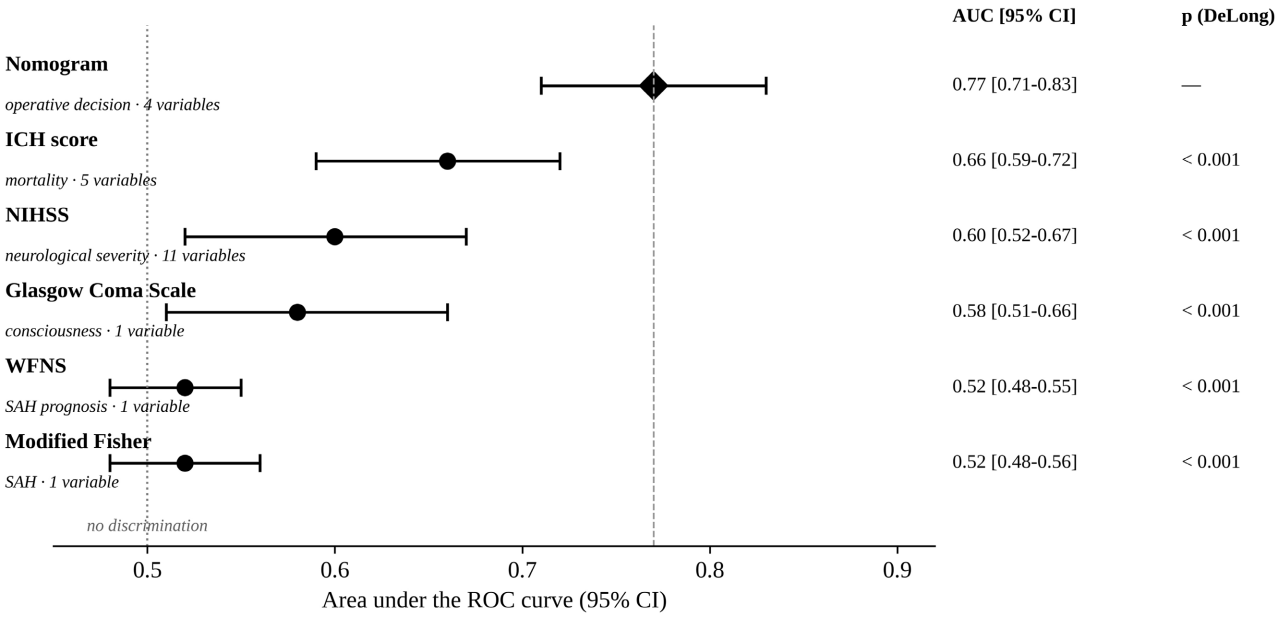


Figure 10. Areas under the ROC curve compared, with 95% confidence intervals. The nomogram (0.77) outperforms the existing scores (ICH score, NIHSS, Glasgow Coma Scale score, WFNS, modified Fisher) repurposed for the prediction of the surgical indication; the original purpose of each tool is recalled beneath its name. The marker at 0.50 corresponds to absence of discrimination. The p values are those of the DeLong test comparing each area with that of the nomogram.

Table 6. Discrimination of the nomogram compared with that of existing scores for the prediction of the neurosurgical indication.

Tool (original purpose)	Variables	AUC	95% CI	p (DeLong)
Nomogram (operative decision)	4	0.77	0.71 - 0.83	-

Continued

ICH score (mortality)	5	0.66	0.59 - 0.72	<0.001
NIHSS (neurological severity)	11	0.60	0.52 - 0.67	<0.001
Glasgow Coma Scale score (consciousness)	1	0.58	0.51 - 0.66	<0.001
WFNS (SAH prognosis)	1	0.52	0.48 - 0.55	<0.001
Modified Fisher (SAH)	1	0.52	0.48 - 0.56	<0.001

AUC: area under the ROC curve. p (DeLong): comparison with the apparent AUC of the nomogram (0.77), not the optimism-corrected AUC (0.73); these p-values do not account for predictor-selection uncertainty, so the statistical significance is anti-conservative and the comparison is indicative only. The existing scores are repurposed from their original aim towards the prediction of the surgical indication, which explains their limited discrimination. The ICH score is defined only in intracerebral haemorrhage (n = 149), and the WFNS and modified Fisher only in the 30 patients with subarachnoid haemorrhage; computed across the whole cohort with out-of-domain values coded as zero, their discrimination is depressed by that coding. A comparison restricted to each score's defining population is the appropriate analysis.

3.8. Operating Thresholds of the Score

The performance of the integer score at its various thresholds offers a range of operating points suited to distinct uses (Table 7). A low threshold (score ≥ 1) favours sensitivity (92.5%), useful so as not to overlook a candidate for referral; an intermediate threshold (score ≥ 2) balances sensitivity (77.6%) and specificity (65.7%); a high threshold (score ≥ 5) achieves 99.3% specificity and a positive predictive value of 95.0% (positive likelihood ratio 25.4), identifying patients in whom the indication is all but certain.

Table 7. Diagnostic performance of the integer score by threshold.

Threshold	Sensitivity, %	Specificity, %	PPV, %	NPV, %	LR+
≥1	92.5	30.1	49.7	84.3	1.3
≥2	77.6	65.7	62.9	79.7	2.3
≥3	51.4	86.0	73.3	70.3	3.7
≥4	29.0	95.1	81.6	64.2	5.9
≥5	17.8	99.3	95.0	61.7	25.4

PPV: positive predictive value; NPV: negative predictive value; LR+: positive likelihood ratio. Prevalence of the indication = 42.8%.

3.9. Sensitivity Analysis: Surgery Actually Performed

When the target was surgery actually performed (45 patients operated on), the same markers of severity remained decisive, but relative weight shifted towards mass effect (aOR 5.00; 2.04 - 12.29) and impaired consciousness (aOR 5.85; 2.41 - 14.24), with hydrocephalus remaining significant (aOR 2.42; 1.08 - 5.44) and in-

traventricular extension losing significance (aOR 1.41; 0.65 - 3.07). This model discriminated even better (AUC 0.83), which is to be expected since operated patients represent the most severe end of the spectrum. The variable set is therefore the same for both targets, but their ranking changes: hydrocephalus, dominant for the indication, falls behind mass effect and impaired consciousness, even though 24 of the 54 procedures performed were ventricular drainages. This shift is consistent with the idea that actual delivery of the procedure depends more on parenchymal and clinical effect than on obstruction to cerebrospinal fluid flow alone; it cautions against reading this analysis as a mere confirmation of the main model.

3.10. Performance by Subgroup

Discrimination was homogeneous by sex (AUC 0.75 in men, 0.79 in women) and age (0.78 below 56 years, 0.75 above). It was highest in intracerebral haemorrhage (AUC 0.77; n = 149), the subgroup that concentrates most indications, and more modest in ischaemia (0.62; n = 65) and subarachnoid haemorrhage (0.62; n = 30)—the six remaining patients having other mechanisms, too few to be analysed separately—where the small number of events and the specific nature of the decision-making mechanisms (craniectomy for malignant infarction, aneurysm treatment) limit the reach of the model. These subgroup performances, based on small numbers, are exploratory.

3.11. Comparison with Machine Learning and Temporal Validation

Two additional checks support the choice of a simple model. First, on the same four variables, two machine-learning methods did no better than logistic regression on repeated cross-validation: random forest AUC 0.73, gradient boosting 0.74, against 0.76 for the logistic regression fitted on those same four variables without fresh selection. As these methods were applied only to the four variables already retained—that is, sixteen possible profiles—this result establishes that no residual interaction among them can be exploited, rather than the general futility of complex approaches upstream of selection. Second, an exploratory temporal validation by chronological splitting of the first 125 and the last 125 inclusions—which must not be read as a validation by calendar year, the exact numbers for 2022 and 2023 not being reported separately—returned an AUC of 0.82 in the later period, despite a higher frequency of indication in the second period. This value, above the apparent AUC of the model developed on the whole cohort, rests on 125 patients and permits no firm conclusion; the drift in frequency between the two periods further calls for calibration to be re-examined at any external validation. As the selection procedure was not re-run on the first 125 patients and the split was not defined by calendar year, this figure cannot be reproduced as a formal temporal validation; it is reported as exploratory only and does not by itself establish temporal robustness.

3.12. Analysis of Discordant Cases

At the threshold of a score ≥ 2, the 24 false negatives (indication made despite a low score) had, by construction, no hydrocephalus and few signs of mechanical effect on computed tomography; a third were infarcts (8/24), whose indication—decompressive craniectomy for malignant infarction—rests on clinical and topographical criteria not captured by the four radiological variables of the model; only 3 of these 24 patients were eventually operated on. The 49 false positives (score ≥ 2 without a retained indication), by contrast, showed signs of mechanical effect (mass effect in 33, impaired consciousness in 34) but had been turned down after overall assessment. The model is therefore least reliable precisely where the decision escapes the mechanical effect visible on computed tomography—foremost among them malignant infarction—which clearly delimits its scope of application.

3.13. Unmet Indications

Of the 107 indications made, only 45 (42%) led to an intervention, leaving 62 unmet indications—close to 6 in 10 patients warranting surgery did not receive it. The gap varied markedly by mechanism (Table 8): it was total for subarachnoid haemorrhage (none of the 15 aneurysmal indications treated, by either clipping or embolisation, for want of interventional neuroradiology); it reached 64% for malignant infarction (5 craniectomies out of 14 indications) and 48% for intracerebral haemorrhage (40 patients operated on out of 77 indications); the remaining indication, of another mechanism, was likewise unmet. These 45 patients underwent 54 procedures, some having received combined operations: 24 external ventricular drainages, 24 decompressive craniectomies and 6 haematoma evacuations. In the 40 patients operated on for intracerebral haemorrhage, 49 procedures were performed—24 drainages, 19 craniectomies and 6 evacuations—the 5 patients operated on for malignant infarction all having undergone decompressive craniectomy. Procedure counts therefore do not add up as counts of distinct patients. This finding, distinct from the predictive performance of the model, illustrates that the medical decision and actual access to surgery constitute two disjoint stages of the care pathway.

Table 8. Met and unmet neurosurgical indications, by stroke type.

Stroke type	Indications	Operated	Unmet	%
Intracerebral haemorrhage	77	40	37	48
Malignant infarction (ischaemia)	14	5	9	64
Subarachnoid haemorrhage	15	0	15	100
Other	1	0	1	100
Total	107	45	62	58

All aneurysm-related indications (subarachnoid haemorrhage) went untreated, for want of interventional neuroradiology capacity and dedicated vascular surgery.

4. Discussion

4.1. Main Findings

From a prospective Ivorian cohort of 250 patients, we developed and internally validated a parsimonious tool estimating the probability that a patient warrants a neurosurgical indication in the course of a stroke. Four variables available at admission—hydrocephalus, mass effect and intraventricular extension on computed tomography, impaired consciousness on examination—suffice to achieve moderate discrimination after an internal validation reproducing selection (apparent AUC 0.77; corrected 0.73) and satisfactory overall calibration (corrected slope 0.84). The nomogram and its integer-score version offer two modes of bedside use; the decision tree provides a teaching-oriented reading of them.

4.2. Pathophysiological Interpretation

The four determinants converge on a single logic: that of the acute mechanical effect of the lesion and of obstruction to cerebrospinal fluid circulation. Hydrocephalus, the heaviest marker (100 points), signals obstruction of the outflow pathways frequently warranting emergency drainage; it is a direct and rapidly correctable threat, which explains why it dominates the model. Intraventricular extension is its haemorrhagic counterpart; mass effect reflects the raised intracranial pressure calling for decompression or evacuation; impaired consciousness is its integrated clinical expression.

It is notable that haematoma volume, the Glasgow Coma Scale score and the composite scores (ICH, NIHSS), although associated with the indication on univariable analysis, disappear from the final model. This does not mean they are irrelevant: once the markers of mechanical effect were taken into account, their information added nothing measurable, the most direct explanation being that it is already captured by those markers, in a form more directly geared to decision-making. A haematoma does not mandate a procedure by its size alone, but through the mass effect and herniation it produces; for decision purposes, impaired consciousness is better summarised by the binary variable than by the continuous Glasgow Coma Scale score, part of whose information overlaps with mass effect and hydrocephalus. In other words, the model gives precedence to correctable mechanical effect over overall severity—which is precisely the logic of the neurosurgical procedure, and not that of prognosis (**Figure 11**, **Table 9**).

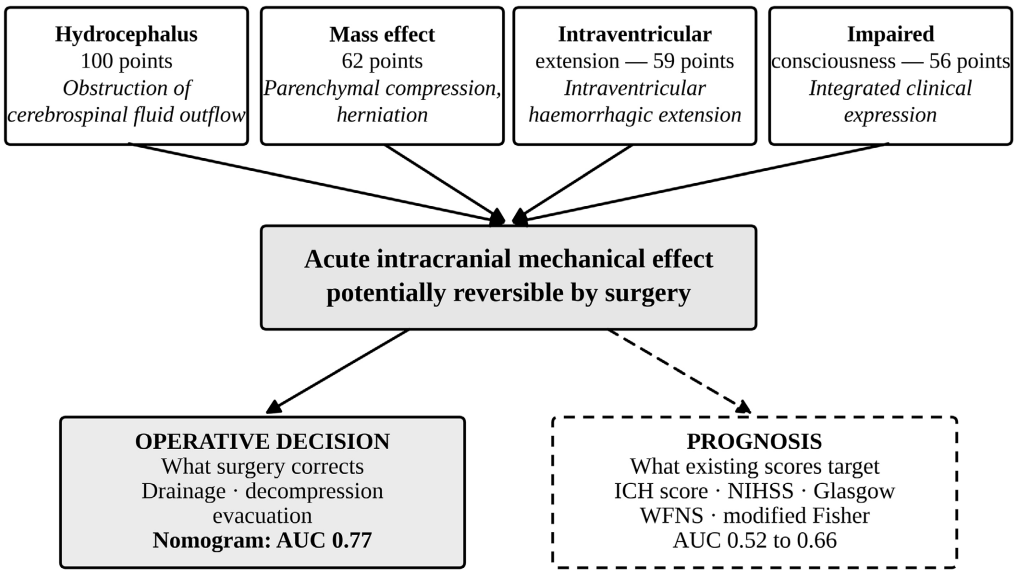
Table 9. Clinical and pathophysiological rationale for the four variables of the model.

Variable	Pathophysiological mechanism	Surgical counterpart
Hydrocephalus	Obstruction of cerebrospinal fluid outflow, acute raised intracranial pressure	Ventricular drainage
Mass effect	Compression of the parenchyma, herniation	Decompression or evacuation
Intraventricular extension	Intraventricular haemorrhagic extension, worsening of raised intracranial pressure	Drainage, evacuation

Continued

Impaired consciousness	Integrated clinical expression of cerebral mechanical effect	Marker of severity bearing on the decision

The four variables are not merely associated statistically with the decision: they reflect the mechanisms that surgery seeks to correct.



Two distinct logics: a score designed to predict death or disability does not predict candidacy for a procedure. This is what warrants a dedicated tool.

Figure 11. Pathophysiological framework of the neurosurgical decision. The four variables of the model are manifestations of one and the same phenomenon—intracranial mechanical effect potentially reversible by surgery—which distinguishes the operative decision from prognosis.

4.3. A Deliberate Parsimony

The model rests on four variables readily obtainable at admission, all binary. This choice follows from statistical selection—the Glasgow Coma Scale score, haematoma volume and the composite scores added no independent information once the markers of mechanical effect were accounted for—but it also answers a requirement of usability. A tool intended for the emergency room of a resource-limited hospital must be applicable from memory, without calculation or computer support. The trade-off between simplicity and performance is favourable here: the four-item integer score, assessed on its own ROC curve, matched the discrimination of the continuous model (AUC 0.77), even though grouping the sixteen profiles into six levels could have caused a loss; the optimism measured by an internal validation that reproduces selection remains contained (0.041 on the AUC, corrected calibration slope 0.84); and two machine-learning methods tested on the same variables did no better (AUC 0.73 - 0.74). This parsimony, far from being a limitation, is a strength for a field instrument: it guarantees transparency, interpretability and transportability.

4.4. Comparison with the Literature and Guidelines

Our determinants overlap with the criteria that structure international trials and guidelines: hydrocephalus and intraventricular extension as indications for drainage, mass effect and impaired consciousness as indications for decompression or evacuation [13]-[19] [25]-[29]. The major trials of intracerebral haemorrhage evacuation (STICH, STICH II, MISTIE III, ENRICH), the pooled analyses of decompressive craniectomy in malignant infarction and the ISAT trial in ruptured aneurysm have specified when surgery improves functional outcome, but all presuppose surgical access that is not guaranteed in our setting, and none provides a transportable decision tool [13]-[16] [18] [19]. Nomograms are in common use in intracerebral haemorrhage; all of them target prognosis—mortality or functional outcome [30], or indeed long-term survival estimated from age, Glasgow Coma Scale score and hydrocephalus [31]. None takes surgical candidacy itself as its target: we do not predict what will become of the patient, but what the team will conclude from examining them.

The comparison with existing scores illuminates this distinctive feature. The classical prognostic scores discriminated the surgical indication only weakly across the cohort (AUC 0.52 to 0.66; an indicative comparison only, for the reasons set out in Section 3.7), below the nomogram (0.77). This is not a shortcoming of those scores but a consequence of their purpose: they quantify a risk of death or disability, not candidacy for a procedure. The surgical decision follows a distinct logic—that of correctable mechanical effect—which warrants dedicated tools rather than the reuse of prognostic scores.

4.5. Practical Implications

Several uses emerge. First, support for triage and referral in peripheral hospitals without a neurosurgeon: a high score identifies early those patients with a high probability of an indication, to be referred without delay to a neurosurgical facility, and allows transfers to be prioritised where transport or admission capacity is limited. Second, a means of harmonising indications between practitioners and of training junior neurosurgeons, useful where expertise is scarce and clinical exposure heterogeneous. Third, a tool for quantifying surgical need at the level of a health system, making it possible to document, as here, the scale of unmet indications. The integer score (0 - 5), which requires no computer support, is particularly suited to use in the emergency room (**Figure 12**).

Two examples illustrate use of the score. A 58-year-old patient presenting with an intracerebral haemorrhage with hydrocephalus, mass effect and impaired consciousness totals 4 points, a predicted probability of about 78%—for an observed frequency of 67% at that level in our cohort: in a peripheral hospital, such a score warrants immediate transfer to a neurosurgical centre. A 62-year-old patient presenting with a limited infarct, without hydrocephalus, mass effect, intraventricular extension or impaired consciousness, totals 0 points, a probability of about 14%: close monitoring is reasonable, with reassessment should deterioration occur.

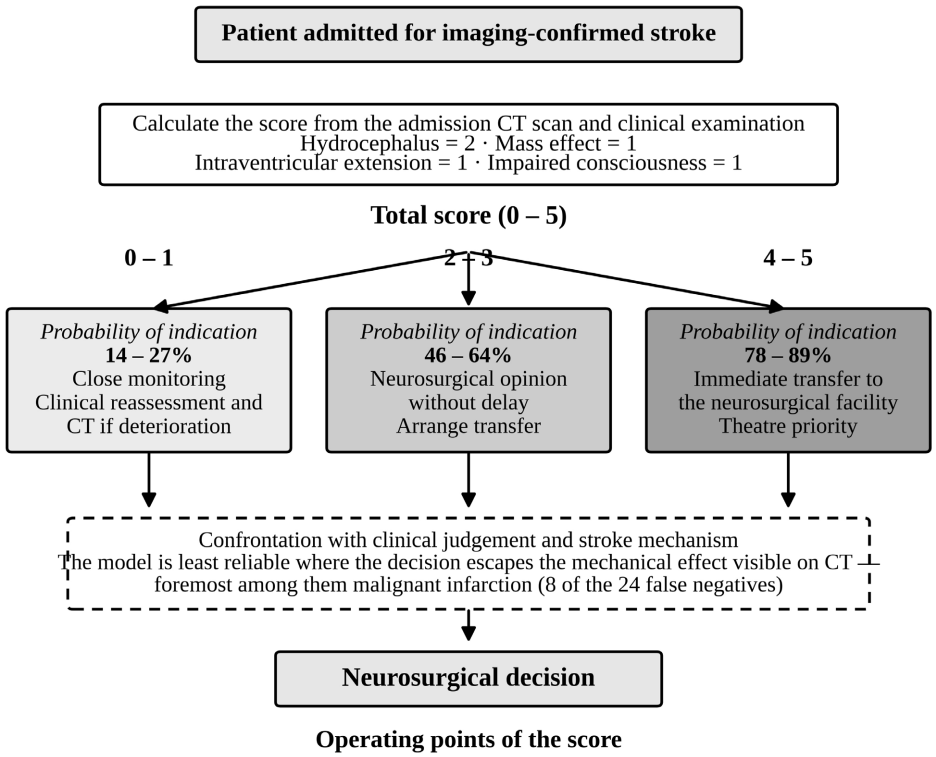


Figure 12. Proposed clinical use algorithm. The thresholds are indicative and to be evaluated prospectively; they do not replace clinical judgement.

These uses can be read directly from a situational grid (Table 10).

Table 10. Potential applications of the score according to the care setting.

Clinical situation	Proposed use of the score
Hospital without a neurosurgeon	Identify rapidly the patients to be transferred and prioritise transfers.
Referral centre	Help rank interventions when several patients are eligible and only one theatre is available.
Training	Harmonise indications between practitioners; teaching aid for residents.
Discussion with families	Document the probability of an indication so as to inform disclosure and shared decision-making.
Audit and planning	Quantify unmet neurosurgical need at the level of a department or a territory.

These proposals must be evaluated prospectively; the model has not yet undergone external validation.

4.6. The Surgical Access Gap: A Global Neurosurgery Issue

The most striking finding goes beyond the performance of the model: fewer than one indication in two was followed by an intervention—close to 6 in 10 patients warranting surgery did not receive it—and every aneurysmal indication went without therapeutic response. This gap is part of the global picture of massively unmet neurosurgical need in low- and middle-income countries, where several million essential operations are lacking each year [32]-[34]. Several non-exclusive factors contribute to this gap in our setting: the absence of interventional neuroradiology and of dedicated vascular surgery (which accounts for the total deficit in subarachnoid haemorrhage), limited availability of operating theatres and equipment, the shortage of specialised human resources (neurosurgeons, neuroanaesthetists), patients' financial constraints and transfer delays. The respective share of these causes could not be documented patient by patient in the present cohort, which is a limitation; their prospective analysis is a direct extension of this work.

This gap gives the work a reach beyond individual decision support. By documenting, patient by patient, the existence of an indication, the tool provides a reproducible instrument for measuring unmet surgical need at the level of a department or a territory—data essential to advocacy, health planning and the sizing of technical facilities. Concrete avenues follow: structuring regional referral networks, strengthening interventional neuroradiology, financing neurosurgical care and specialised training. A prediction model cannot close this gap; but it reveals its scale and can help to document it in a standardised way.

4.7. Strengths and Limitations

The strengths of this work lie in the prospective nature of the cohort, the absence of missing data on the target outcome and on the final predictors, adherence to the TRIPOD recommendations, and an internal validation that replays the whole of development—imputation, selection and estimation—within each resample, the only way of estimating honestly the optimism of a stepwise selection; calibration and clinical benefit are assessed beyond the Hosmer-Lemeshow test alone.

Several limitations must nevertheless be stressed. First, the target outcome—the indication as recorded—reflects the decision of the local team, may incorporate an element of subjectivity and partial circularity with the radiological variables, does not constitute an external reference standard and was not subjected to a measurement of inter-observer reproducibility; conversely, that a model built on the very criteria underpinning the indication does not exceed 0.77 indicates that an appreciable part of the decision escapes explicit radiological markers. Second, validation remains purely internal and does not guarantee the transportability of the model, which will have to be established by external multicentre validation before any clinical use. Third, the single-centre design is open to selection bias: recruited in a referral neurosurgical department, the cohort may over-represent severe forms, and the observed frequency of indication (42.8%) is not neces-

sarily transportable to other levels of care. Fourth, the sample size limits the granularity of subgroups, notably subarachnoid haemorrhage and malignant infarction. Fifth, haematoma location and lesion territory were unusable; volume, herniation and the composite scores are defined only for part of the cohort, so that the corresponding univariable associations and the thresholds of the tree partly separate haemorrhages from infarcts rather than a gradient of severity; the cohort-wide comparison of the ICH score, WFNS and modified Fisher against the nomogram (Table 6) is affected by the same out-of-domain zero-coding and is therefore indicative only, a within-population comparison being deferred to external validation; herniation, coded as zero outside its domain and imputed for its missing values, was subjected to an imputation model learned on a distribution mixing true clinical zeros with absent measurements; and the Glasgow Coma Scale score, missing in 12.4% of patients, may have had its association attenuated by that imputation, so that its elimination cannot be attributed to redundancy alone. Sixth, more complex machine-learning approaches, when tested, brought no gain. Seventh, the study establishes that the model predicts an indication, not that it alters outcome, which is a matter for later prospective evaluation. Finally, the CART tree, presented for illustrative purposes, should not be used in isolation given its overfitting.

A self-assessment of the risk of bias using the PROBAST tool is set out in Table 11 [35].

Table 11. Self-assessment of the risk of bias using PROBAST.

Domain	Risk	Rationale
Participants	Low	Prospective cohort of consecutive patients, with no missing data on the target outcome.
Predictors	Low	Variables defined a priori, available at admission, assessed independently of the outcome.
Outcome	Moderate	Indication based on the decision of the local team; element of subjectivity and partial circularity with imaging.
Analysis	Moderate	EPV = 26.8 for the final model (5.9 referred to the 18 candidate predictors); internal validation reproducing selection within each resample (optimism 0.041); full calibration; decision curve analysis. By contrast, the tuning and the evaluation of the decision tree are not documented as two independent procedures, and the strategy for handling missing data applied to it is not documented separately.

PROBAST: Prediction model Risk Of Bias ASsessment Tool. Overall risk is judged low to moderate, the main points of attention being the outcome, whose transportability external validation will allow to be assessed, and the validation of the decision tree.

4.8. Future Directions

The priority is external multicentre validation, ideally on a West African scale, with recalibration where appropriate; urban and rural centres, with their con-

trasting technical facilities, would provide complementary settings. In line with current frameworks for the appraisal of prediction models (PROBAST, TRIPOD and its update TRIPOD + AI), such a validation will have to examine explicitly the risk of bias, transportability and generalisability [20] [35] [36]. Incorporating time to admission and longitudinal trajectories could enrich the tool. In the longer term, deployment as a mobile application or an online calculator, integrated with the medical record and coupled to monitoring of unmet indications, would link decision support with the steering of service provision. Finally, a prospective evaluation of the impact of the score on actual decisions and on time to treatment would be the final step before wide adoption.

5. Conclusion

In this Ivorian neurosurgical cohort, a parsimonious model based on four clinical and radiological variables estimates reproducibly and with adequate calibration the probability that a patient is a candidate for neurosurgical intervention in the course of a stroke, with a favourable net benefit across the range of probabilities it predicts, and outperforms existing prognostic scores repurposed for that purpose. Available as a nomogram and as an integer score for bedside use, it could structure triage, referral and the prioritisation of transfers in resource-limited settings. It simultaneously reveals a large surgical access gap—close to six indications in ten unmet—which no model can close by itself, but which it makes it possible to document. External multicentre validation is the indispensable next step.

Author Contributions

All authors made a substantial contribution to this work, whether to the design of the study, the collection of the data, the analysis and interpretation of the results, or the drafting and critical revision of the manuscript. All have read and approved the submitted version and take collective responsibility for it.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Ethical Approval

The study was conducted in accordance with the principles of the Declaration of Helsinki and received the approval of the Institutional Ethics Committee of the CHU de Bouaké (approval no. CEI/CHU-BKE/102/2026). As the centre had no constituted ethics committee over the study period itself, the study had initially been authorised by the head of the department of Neurosurgery and by the hospital management (Section 2.8); the dispensation from individual informed consent, the data having been collected in the course of routine care and analysed in

anonymised form, is covered by that approval.

Consent to Publish

The manuscript contains no data, image or clinical detail allowing a patient to be identified. Data were analysed in anonymised form, under the conditions set out in Section 2.8.

Availability of Data and Materials

The data used for this analysis may be obtained from the corresponding author on reasonable request, subject to the regulations applicable to the protection of health data.

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Abbreviations

AUC = area under the ROC curve; CART = classification and regression tree; CI = confidence interval; DCA = decision curve analysis; EPV = events per variable; ICH = intracerebral hemorrhage (score); IQR = interquartile range; LR+ = positive likelihood ratio; NIHSS = National Institutes of Health Stroke Scale; NPV = negative predictive value; PPV = positive predictive value; PROBAST = Prediction model Risk Of Bias ASsessment Tool; SAH = subarachnoid haemorrhage; STROBE = Strengthening the Reporting of Observational Studies in Epidemiology; TRIPOD = Transparent Reporting of a multivariable prediction model for Individual Prognosis Or Diagnosis; VIF = variance inflation factor; WFNS = World Federation of Neurosurgical Societies (grade); aOR = adjusted odds ratio.