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Original Research

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Abstract

Background: Complete occlusion of an intracranial aneurysm (IA) after the deployment of a flow-diverter stent (FDS) is currently unpredictable. The aim of the study was to develop a predictive occlusion score based on pre-treatment clinical and angiographic criteria.

Methods: Consecutive patients with ≥ 6 months follow-up were included from 2008 to 2019 and retrospectively analyzed. Each IA was evaluated by using the Raymond-Roy occlusion classification (RROC) and dichotomized as occluded (A) or residual (B/C), and 80% of patients randomly attributed to the training sample. Feature selection and binary outcome prediction relied on logistic regression, and threshold maximizing class separation selected by a CART tree algorithm. The feature selection was addressed by a genetic algorithm selecting among the 30 pre-treatment available variables.

Results: The study included 146 patients with 154 IAs. Feature selection yielded a combination of six variables with a good cross-validated accuracy on the test sample, a combination we labeled DIANES score (IA's diameter, indication, parent artery diameters ratio, neck ratio, side-branch artery, and sex). A score > -6 maximized the ability to predict a RROC=A with sensitivity of 87% ($_{95\%}$CI: 79%, 95%) and specificity of 82% ($_{95\%}$CI: 64%, 96%) on the training sample. Accuracy was 86% ($_{95\%}$CI: 79%, 94%). In the test sample, sensitivity and specificity were 89% ($_{95\%}$CI: 77%, 98%) and 60% ($_{95\%}$CI: 33%, 86%), respectively. Accuracy was 81% ($_{95\%}$CI: 69%, 91%).

Conclusion: A score was developed as a grading scale for prediction of the final occlusion status of IA treated with FDS.

Introduction

Flow-diverter stents (FDSs) have been widely accepted for the treatment of complex intracranial aneurysms (IAs) (giant/large, large-necked, and/or dissecting/fusiform IAs) and in case of IA recanalization [1]. The effect of FDS is based on two complementary mechanisms that will eventually lead to IA thrombosis: diversion of the blood flow from the IA sac toward the parent artery and endothelialization of the IA's neck promoting a neck sealing. The goal of the treatment is the same as in coils embolization, i.e. a complete obliteration of the IA's sac, assessed by the widely use three-point scale Raymond-Roy occlusion classification (RROC) [2].

However, whether complete IA occlusion will occur after FDS deployment is currently unpredictable. Indeed, the process of IA's sac thrombosis is progressive, with time course ranging from several minutes to several months. In a significant number of cases, there is no occlusion (as high as 24% at 6 months and 15% after one year) [1–3]. This delay generates uncertainties for the patient and the operator, absence of early optimal protection against (re)rupture and loss of intra-aneurysmal access because of the FDS's tight mesh. Pre-treatment predisposing factors of complete IA occlusion would be very helpful in many clinical situations to predict the most likely upcoming flow-diverting effect.

Several studies have already shown the existence of factors predictive of aneurysmal occlusion after FDS placement. However, these studies have very varied methodologies: silicon flow models [4], animal models [4,5], computational fluid dynamics (CFD) models [6,7], digital subtraction angiography (DSA)-based optical flow approach [8], or patient cohort studies [9,10]. To the best of our knowledge there is no pre-treatment predictive score available in the literature for complete occlusion of IAs treated by FDS.

The purpose of our study was to propose a predictive score of complete occlusion of IAs treated with FDS based on initial (i.e.: pre-treatment) clinical and angiographic criteria (DIANES [diameter, indication, artery, neck, exit, sex] score) using machine learning.

Methods

Patients

The data that support the findings of this study are available from the corresponding author upon reasonable request. We retrospectively reviewed in a prospectively maintained database the data of patients consecutively treated in our Institution from October 2008 to December 2019 by means of FDSs for IAs. Approval of the institutional review board was obtained; without patient informed consent required. Exclusion criteria were: not assessable IA (carotid-cavernous sinus fistula, parent artery occlusion), unavailable DSA images, and follow-up < 6 months (loss to follow-up, death).

We systematically reviewed: patients' demographics: age, sex; IAs' characteristics: type, location, configuration (saccular unilobular or complex [10] [fusiform, dysmorphic, multilobular]), sizing, neck ratio (NR) [11] (ratio of diameters of the neck and the parent artery), ruptured or unruptured IA, indication (first treatment, recanalization), presence of a side-branch artery incorporated into the IA, and contrast agent stagnation at venous phase; parent artery' characteristics: diameters (5 mm upstream to the neck and 5 mm downstream), diameters ratio (PDR), curvature of the parent artery in relation to the tangent passing through the neck of the IA (acute angle: concavity, no angle: straightness, obtuse angle: convexity), and inflow angle [12]; as well as devices' characteristics: type, number, and associate coiling.

Management

Prior to the procedure, the neuroradiology team collegially assessed the characteristics of each aneurysm and treatment modalities were discussed at a multidisciplinary meeting (including neurosurgeons and neurointensivists).

All patients received dual-antiplatelet therapy (clopidogrel and aspirin) 5 days before stenting. In case of clopidogrel resistance (assessed by a platelet-aggregation test: Multi-plate [Roche Diagnostics]), patients were treated with ticagrelor for 6 months after the procedure. If the platelet-aggregation test was satisfactory, patients were maintained on dual antiplatelet therapy for at least 6 months after the procedure, followed by aspirin alone during 6 months.

Procedures were performed under general anesthesia through femoral access. The FDSs were deployed using a tri-axial guiding-catheter system (using a 6 French long sheath, a 5 or 6F supple intermediate support catheter and a 0.027" microcatheter). Five commercially available devices were used: the Pipeline Embolization Device (PED, PED Flex [Covidien]), the Silk (Balt), the Flow-Redirection Endoluminal Device (FRED [MicroVention]), the Surpass (Streamline, Evolve [Stryker]) and the p64 (Phenox).

Outcome

MRI was performed at 6-month, DSA at 1-year, and MRI/DSA at last follow-up. The last follow-up is defined as the date with the last available imaging control of the aneurysmal occlusion (by MRI or DSA). Based on their last follow-up, IAs were dichotomized as occluded (RROC=A) or residual (RROC=B/C) [2]. A junior (in-training) and two senior interventional neuroradiologists (with five and twelve years of experience) independently reviewed the follow-up imaging studies, blinded to the clinical data. Discrepancies were settled by consensus agreements. The primary outcome was the last available scoring for patients followed at least 6 months, with only RROC=A scored patients being considered successes.

Statistical analysis

80% of the aneurysm cases were randomly attributed to the learning set while the remaining 20% were kept as an untouched test set. Subsequently, a separate set of 27 newly gathered aneurysms was fused to the randomly selected test set. Quantitative variables were discretized by manually selecting limits maximizing success/failure separation on the training set close to the ones a rpart tree algorithm would have chosen using the “outcome” as variable to be classified, yielding at least 20 cases per interval (subgroups being the result of splitting a variable on the train set, and not each of the intersections of said split variable with the “outcome” variable) and if possible, thresholds being rounded enough to make for a clinically acceptable score. The impurity allowing class separation by an rpart tree was based on the information index [13]. Feature selection and binary outcome prediction relied on elasticnet [14] penalized logistic regression (LR). Class weighting accounted for the unequal number of cases in the success and failure groups.

To enhance the interpretability and performance of the model, a subset of available features may prove more efficient than the full feature range. We chose a genetic algorithm as a means to explore the possible predictor variable combinations more efficiently than stepwise-forward and -backward algorithms commonly used in medicine [15–17]. We ran the variable selection genetic algorithm with a 0/1 numerical encoding (allowing for example a single coefficient for gender=male to represent the gender variable, instead of having 2 opposite coefficients). This well-described algorithm initially draws a number of predictor combinations, and tests the predictive ability of logistic regressions using said combinations of predictors by 10-fold cross validation within the "train" cohort. Only the most efficient combinations are allowed to proceed to the following generation, where a mixture of "mutation" (random addition or deletion of a predictor within a combination) and "crossover" (the random matching of the x-first variables a priory successful combination to the y-last of another combination) creates new combinations to be tested.

The algorithm was allowed to proceed for 200 generations of 40 'genotypes' each (mutation rate: 0.15, maximum features per genotype: 20). The penalization parameter 's' for predictions was set to 0.02, and among the tested performance criteria (mean misclassification error, sum or product of true positive rate and accuracy), prediction area under the curve proved the most efficient (averaged prediction on the validation sample of each cross-validation performed on the training dataset).

To obtain an efficient elasticnet mixing parameter, a grid tuning was subsequently performed for each of the most promising feature sets from the precedent step with a second cross validated penalized and weighted LR, always on the training subset of data. Each of the selected feature sets with its proposed elasticnet mixing parameter was then used in a LR trained on the full training dataset and evaluated by its max (accuracy + true positive rate) over the range of thresholds (where FDS failure is considered as the positive class). The model was transformed into score by extracting beta coefficients, and the threshold chosen to maximize "accuracy + balanced accuracy" on the training set.

The interobserver reliability was assessed by calculation of Kappa (κ) values, categorized as: 0.41-0.6, 0.61-0.8, and 0.81-1 indicating moderate, good, and excellent agreement, respectively.

All statistical analyses were performed using R (3.4.1) and RStudio (1.0.153); packages were: *car*, *caret*, *Hmisc*, *rpart*, *ggplot2*, *questionr*, *corrplot*, *dummies*, *pROC* and *reshape*. Regression was done using *glmnet* embedded in the *mlr* package.

Results

Clinical Characteristics

One hundred and seventy-nine patients were screened for eligibility during the study period. Thirty-three patients were excluded for lost to follow-up (n=25), parent artery occlusion (n=3), death (n=4), and FDS for carotid-cavernous fistula treatment (n=1). The four early (<6 months) deaths were due to: an early hematoma with death at the eighth day after the treatment with FDS and coils of a giant aneurysm of the middle cerebral artery, a complication of dual anti-platelet therapy with death twenty-three days after stenting, a retroperitoneal hematoma requiring the interruption of dual anti-platelet therapy leading to cerebral ischemic and hemorrhagic complication with death on the seventh day, and a fatal hemorrhagic transformation after cerebral infarction. The parent artery occlusions by coils were due to one intra-aneurysmal stent migration in a giant intracavernous aneurysm and two misopening of the FDS. One hundred forty-six patients (one hundred fifty-four IAs) were included in this study. They were randomly assigned to the learning cohort (80%) or the validation cohort (20%). Patients, IAs and parent arteries pre-stenting characteristics are summarized in **Table 1**. The overall median follow-up was 14.4 months (interquartile range [IQR]: 11.9–30.4). The distribution of the devices was as follows: nitinol: n = 18 Silk (11%), n = 2 FRED (1.2%), n = 4 p64 (2.4%) and cobalt-chromium alloy: n = 128 PED (78%), n = 12 Surpass (7.3%). A second telescopic FDS was required in ten cases (6.5%). No procedure required more than two FDS. In 23 cases (14.9%), the coiling of the aneurysmal sac was performed before stenting because of the large diameter of the IA (median diameter: 10 mm, IQR: 6.9–13.9). 117 IAs were assigned to group RROC=A (complete obliteration), 37 IAs were assigned to group RROC=B/C (n=15 for residual neck and n=22 for residual IA, respectively). Interreader agreement for RROC status evaluated at last follow-up by MRI or DSA was considered as excellent with $\kappa = 0.88$ ($_{95\%}$CI: 0.79–0.98) and good for the assessment of side-branch artery and parent artery curvature: $\kappa = 0.78$ ($_{95\%}$CI: 0.62–0.96) and $\kappa = 0.71$ ($_{95\%}$CI: 0.53–0.90), respectively. The median of the last follow-up was 14.9 months (IQR: 12.1–29.8) and the mean was 23.3 months (standard deviation [SD]=18.2 months) in the RROC=A group, and the median of the last follow-up was 13.4 months (IQR: 10.1–30.8) and the mean was 22.0 months (SD=19.5 months) in the RROC=B/C group.

Table 1: Patients, Intracranial Aneurysms and Parent Arteries Initial Characteristics

Parameters	Train	Test
Patients	98	51
Female	77 (79)	44 (86)
Age (years)*	50 (39–56)	54 (45–59)
Intracranial aneurysms (IAs)	102	52
Diameter (mm) *	7 (5–9.88)	6.31 (4.25–12.48)
Neck (mm)*	4.6 (3.5–6.15)	4.82 (3.92–6.73)
Dome-to-neck ratio (DNR)*	1.4 (1.08–1.79)	1.39 (1.14–2)
Locations: Anterior circulation: Carotid-ophthalmic	40	24
Posterior communicating artery	12	4
Supraclinoid ICA	4	0
Cavernous ICA	10	3
ICA Siphon	5	11
Anterior communicating and anterior cerebral arteries	5	3
Middle cerebral artery	5	1
Anterior choroidal artery	1	3
Superior hypophyseal artery	1	2
Posterior circulation: Vertebral artery	8	0
Posterior cerebral artery	4	0
Basilar artery	4	0
Superior and posterior inferior cerebellar arteries	3	1
Type: Saccular	82 (80.4)	45 (86.5)
Dissecting aneurysm	4 (3.9)	1 (1.9)
Large/giant partially thrombosed	8 (7.8)	1 (1.9)
Fusiform	4 (3.9)	0
Blister-like	4 (3.9)	5 (9.6)
Indication: Recanalization	34 (33)	14 (27)
Ruptured IA	27 (26)	12 (23)
Contrast media stagnation	27 (26)	18 (35)
Incorporated side-branch artery: Yes	18 (18)	12 (23)
Diameter (mm)*	1.1 (0.8–1.5)	1.15 (0.97–1.53)
Configuration: Complex	82 (80)	45 (87)
Parent arteries		
Diameters: Upstream (mm)*	3.7 (3.1–4.1)	4.1 (3.57–4.5)
Downstream (mm)*	3.1 (2.62–3.4)	3.2 (2.87–3.6)
Average (mm) *	3.35 (2.91–3.74)	3.65 (3.28–4.03)
Upstream/downstream ratio (PDR) *	1.19 (1.06–1.37)	1.26 (1.14–1.36)
Neck / parent artery diameters ratio (NR)*	1.44 (1.03–1.95)	1.34 (1.07–1.87)

Geometry: Inflow angle (degree °)*	135 (95–163)	135 (103–168)
Convex Curvature	50 (49)	20 (38)

Note: unless otherwise indicated, data are number of patients, with percentage in brackets.

* Data are median with the interquartile range (IQR) in brackets.

ICA = internal carotid artery, n = number, NR = neck ratio, PDR = parent artery diameters ratio.

Training Sample

Six variables were included in the DIANES score. The score ranged from -24 to 4 points (**Table 2**). The median score was -3 (IQR: -7–2) in the overall cohort. Among failed occlusion (RROC=B/C) the median score was -8 (IQR: -10–-5) and -2 (IQR: -4–2) among successful occlusion (RROC=A). In receiver operating characteristic analysis, a score greater than -6 maximized the ability to predict a complete occlusion (RROC=A). The score accuracy was 0.86 ($_{95\%}$CI: 0.79–0.94), with sensitivity of 0.87 ($_{95\%}$CI: 0.79–0.95) and specificity of 0.82 ($_{95\%}$CI: 0.64–0.96) (**Table 3, Fig 1**).

Test Sample and Whole Cohort

In the test sample, a DIANES score greater than -6 was predictive of complete occlusion (RROC=A), with sensitivity of 0.89 ($_{95\%}$CI: 0.77–0.98) and specificity of 0.60 ($_{95\%}$CI: 0.33–0.86). The score accuracy was 0.81 ($_{95\%}$CI: 0.69–0.91) (**Table 3, Fig 1**). In the whole cohort, a DIANES score greater than -6 was predictive of complete occlusion (RROC=A), with sensitivity of 0.88 ($_{95\%}$CI: 0.82–0.94) and specificity of 0.73 ($_{95\%}$CI: 0.58–0.87). The score accuracy was 0.84 ($_{95\%}$CI: 0.78–0.90) (**Table 3, Fig 1**). The DIANES score was able to divide the whole cohort from either side of the threshold value (-6 points) in both success (RROC=A) and failure (RROC=B/C) groups at last follow-up (**Fig 1**). Additional representations have been added to the supplemental material with their accuracies ($_{95\%}$CI) on training and test samples: a recursive partitioning CART tree, a penalized logistic regression LASSO, and a simplified version of the DIANES score.

Table 2: DIANES Score Components and Scoring Parameters

Component	Score
1. **Sex**	
Male	4
2. **Indication**	
Recanalization	-5
3. **Side-branch artery**	
Yes	-8
4. **Aneurysm's diameter (mm)**	
> 8.9	-5
5. **Neck ratio (NR)**	
> 1.1 ; 1.8 ≤	-2
6. **Parent artery diameters ratio (PDR)**	
> 1.3	-4
Threshold (under = predictive of failure)	-6

Note: the score is the sum of the points of the seven criteria. The threshold maximizing class separation (i.e.: RROC=A and RROC=B/C), a score below two was predictive of incomplete occlusion (RROC=B/C).

DIANES score = diameter, indication, artery, neck, exit, sex score, RROC = Raymond-Roy occlusion classification.

Table 3: Sensitivities, Specificities and Predictive Values for the DIANES Score

	Accuracy	**Sensitivity**	**Specificity**	**Positive Predictive Value (PPV)**	**Negative Predictive Value (NPV)**	**AUC**
Training sample	0.86 (0.79, 0.94)	0.87 (0.79, 0.95) [70 / 80]	0.82 (0.64, 0.96) [18 / 22]	0.95 (0.88, 0.99) [70 / 74]	0.64 (0.45, 0.83) [18 / 28]	0.88 (0.80, 0.96)
Test sample	0.81 (0.69, 0.91)	0.89 (0.77, 0.98) [33 / 37]	0.60 (0.33, 0.86) [9 /15]	0.86 (0.72, 0.95) [33 / 37]	0.66 (0.41, 0.93) [9/ 13]	0.73 (0.55, 0.91)
Whole cohort	0.84 (0.78, 0.90)	0.88 (0.82, 0.94) [103 / 117]	0.73 (0.58, 0.87) [27 / 37]	0.91 (0.85, 0.96) [103 / 113]	0.66 (0.51, 0.81) [27 / 41]	0.83 (0.74, 0.91)

Note: Data are percentages; data in parentheses are 95% confidence intervals (CIs); data in brackets are numerator/denominator.

DIANES score = diameter, indication, artery, neck, exit, sex score.

Discussion

The evolution of the clinical practice and the current knowledge in the field of FDS requires a better prediction of IA occlusion after stenting by FDS. Currently, the prediction of IA's thrombosis can either be based on descriptive grading scales using DSA images [18,19], parametric color coding [20] or CFD models [21]. Furthermore, off-label applications of the FDSs have been reported [22] such as ruptured IAs [23], requiring an even more accurate prediction. Moreover, FDSs are associated with an elevated rate (34%) of ipsilateral de novo fluid-attenuated inversion recovery (FLAIR) lesions, most likely due to delayed thromboembolic events from the FDS/IA complex before complete healing of the IA [24].

In our cohort, the DIANES score is associated with long-term aneurysmal sac occlusion in patients treated with FDS. The score is based on six items: two clinical criteria (**i/**sex, **ii/**indication) and four imaging criteria regarding the morphology of the IA (**iii/**side-branch artery, **iv/**diameter, **v/**NR) and the parent artery (**vi/**PDR). These criteria have already been described as predictive in the literature.

Regarding the clinical criteria of the score: **i/**The DIANES score reflects vascular gender differences, with males predicting a higher occlusion rate. Indeed, sex steroid hormones are well-known factors involved in IAs' pathogenesis [25] but their role in vascular remodeling after stenting is poorly known. Moreover, circulating bone marrow-derived endothelial progenitor cells (PCs) play an important role in vascular repair [26] and endothelialization of the FDS's mesh [26]. However, women have lower PCs levels compared to men and are likely to reach a critically low level with aging [27] ; **ii/**In our score, an FDS indication for a recanalized IA is a less favorable situation. Healing of a coiled IA is a dynamic process occurring within the first four weeks after embolization and recanalization occurs in 10-20% of cases [28]. Indeed, although FDSs are a well-recognized treatment of recurrent IAs, it could be hypothesized that several mechanisms underlying the recanalization pathophysiology [28] such as active vascular wall disease, poor quality neointima formation across the neck, or significant transmission of blood pulsation affecting the thrombus stability [5] may also affect the efficacy of the stent.

Regarding the morphological criteria of the score: **iii/**The existence of a side-branch artery arising from the sac has been previously demonstrated as a negative predicting factor for IA's occlusion [9,29] diminishing the 'flow-diverting effect'; **iv/**FDS seems to be a relatively safe and effective technique for large and giant unruptured IAs embolization [30] but the success of occlusion could depend on the neck size [4]. In these cases, occlusion failures could be explained by holes in the neointima lining the FDS [31] ; **v/**In the literature, NR was described as a predictive factor of occlusion [11], whereas larger neck diameters [4,5] and lower dome-to-neck ratios [29] were negative predictive criteria. The NR is a predictor of failure and suggests that a larger defect in the parent artery provides the input for blood flow into RROC B/C IAs. This would result in higher flow in the IA sac, which represents a greater burden for flow diversion and thus less effective treatment of FDS [11]. Ostium enlargement has been correlated with the rate of IA occlusion after flow diversion in animal model studies [4,32]; **vi/**At last, in our score, a higher PDR could also reflect an increased risk of FDS oversizing and poor wall apposition. Oversizing could be associated with lower pore density and metal coverage resulting in increased porosity of the FDS [33] and malapposition [29] results in the risk of endoleak and failure of endothelialization.

During the follow-up period of IAs treated with FDSs, there was no further treatment of the IAs. The reasons for the lack of a second treatment was that the majority of IAs were unruptured, occlusion of the IA could occur in the medium to long term, and in most cases the only additional treatment available would be another FDS which would increase the risks associated with this device.

The statistical model chosen was a genetic algorithm for the selection of variables. Genetic algorithms do not guarantee to obtain the global maximum accuracy but represent a trade-off between greedy algorithms like stepwise ascent or descent, and extreme time-consuming exploration of all available predictor variable combinations. Mimicking aspects of Darwinian processes for machine learning was already hypothesized as a fruitful branch to explore by Alan Turing in 1950, and progressively came to use in the 1970s and 1980s. Genetic algorithms usually outperform stepwise ascent or descent in variable selection for model creation [15,16]. Recently, machine learning analysis has been used in the field of interventional neuroradiology [34,35].

We acknowledge potential limitations of our study, including the need for an external validation of the score with patients from different centers and larger cohorts. We recognize the relative complexity of the score given the variance of the weighting, but it includes only six variables that can be easily and routinely assessed from the clinic and imaging data. In addition, the possibility of very late appearance of complete thrombosis in an initially RROC=B/C IA cannot be ruled out. Also, we have chosen to include ten patients treated with two FDSs as this variable was not retained during the statistical selection step and furthermore, this factor is not usually used in predictive studies. Finally, the IA thrombosis is a complex spatio-temporal process mediated by several mechanisms such as vascular morphology, biochemical factors produced by the IA wall, blood flow patterns and biomechanical factors of the FDS including endothelialization of the device's struts, and should thus not be limited to clinico-angiographic data. Our score was developed for its ability to predict the occlusion of an IA treated with FDS; it does not take into account other important outcomes in the choice of treatment such as the occurrence of a complication (e.g. ischemic stroke).

This opens the field of a more personalized patient management because of an IA-specific complete thrombosis threshold [21]. Despite these limitations, improved standardization of pre-treatment assessment with the use of the DIANES score is intended to provide a radioclinical tool to predict success after FDS implantation in routine clinical care. This score may provide a predictive stratification of FDS success for assessment of new treatments in therapeutic trials.

Conclusions

The DIANES score presented herein, which includes pre-treatment clinical factors and imaging morphological features of both the IA and the parent artery, showed an association with the final occlusion status. This clinico-radiological grading scale, built on components easily assessed routinely, needs to be tested in a larger separate validation cohort and could be used for the selection of therapeutic alternatives for exclusion treatment in patients with IAs.

Disclosures

Pr Frédéric Clarençon reports conflict of interest with Medtronic, Guerbet, Balt Extrusion (payment for readings), Codman Neurovascular (core lab). Dr Nader Sourour is consultant for Medtronic, Balt Extrusion, Microvention, Stock/Stock Options: Medina. The other authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper. The manuscript is not supported by industry.

Competing Interests

None.

Contributorship Statement

Conception and design: AG, CT, FC; Acquisition of data: AG, ES, NS, FC; Analysis and interpretation of data: AG, CT, FC; Drafting the article: AG, CT, FC; Critically revising the article: ES, JG, BM, KP, SL, VD; Reviewed submitted version of manuscript: AG, CT, FC; Approved the final version of the manuscript on behalf of all authors: FC.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Research Ethics Approval

Approval of the institutional review board was obtained (CPP-Ile-de-France VI, Groupe Hospitalier Pitié-Salpêtrière, Pr Nathalie BRION, June 14th 2019); without patient informed consent required.

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Figure 1 Legends:

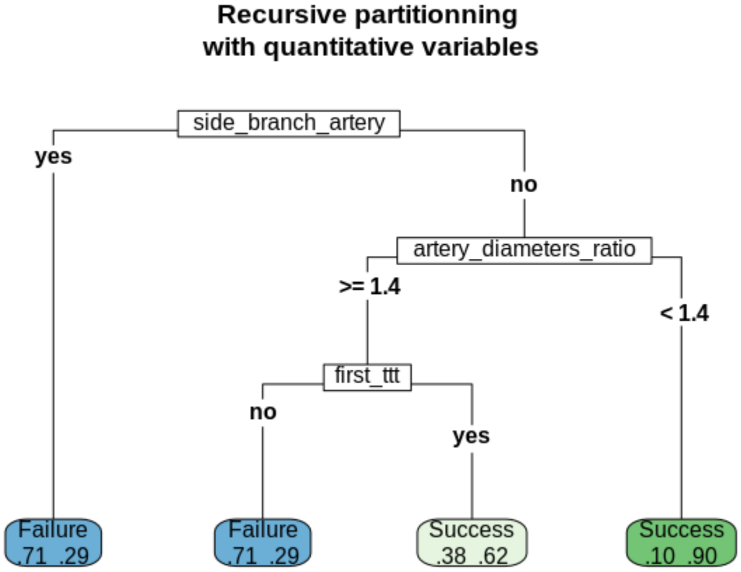
Above: Graphs showing receiver operating characteristic (ROC) curves with area under the curve (AUC) and 95% confidence intervals (CIs) for occlusion prediction in the training sample (A), in the test sample (B), and in the whole cohort (C).

Below: Dot plot displaying patients' distribution from either side of the threshold value of the DIANES score (two points) in both success (RROC=A) and failure (RROC=B/C) groups at last follow-up in the whole cohort.

DIANES score = diameter, indication, artery, neck, exit, sex score, RROC = Raymond-Roy occlusion classification.

Supplemental material:

<u>Recursive partitioning CART tree from the quantitative variables:</u>



CART tree	Accuracy	Sensitivity	Specificity	Positive Predictive Value (PPV)	Negative Predictive Value (NPV)	Balanced Accuracy
Training sample	0.8137 95% CI : (0.7245, 0.884)	0.8500	0.6818	0.9067	0.5556	0.7659
Test sample	0.7692 95% CI : (0.6316, 0.8747)	0.8649	0.5333	0.8205	0.6154	0.6991

Penalized logistic regression LASSO from qualitatively rendered variables:

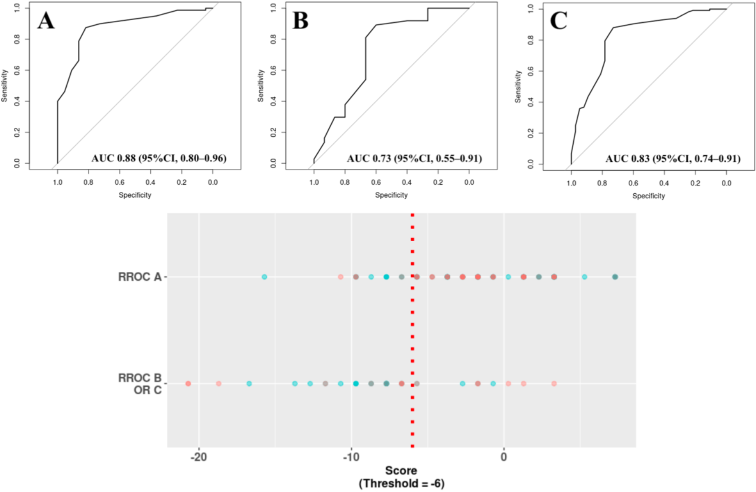
Component	Score
Sex: Male	0.8
Indication: Recanalization	-1
Side-branch artery: Yes	-1.1
Aneurysm's diameter (mm): > 8.9	-1.1
Parent artery diameters ratio (PDR): > 1.3	-0.8
Neck ratio (NR): > 1.1 ; 1.8 ≤	-0.4
Neck ratio (NR): > 1.8	0.2
Convexity of the parent artery	-0.2
Threshold (under = predictive of failure)	0.75

LASSO	Accuracy	Sensitivity	Specificity	Positive Predictive Value (PPV)	Negative Predictive Value (NPV)	Balanced Accuracy
Training sample	0.8725 95% CI : (0.7919, 0.9304)	0.8875	0.8182	0.9467	0.6667	0.8528
Test sample	0.7885 95% CI : (0.653, 0.8894)	0.9189	0.4667	0.8095	0.7000	0.6928

Simplified version of the DIANES score:

Component	Score
1. Sex	
Male	2
Female	-2
2. Indication	
First treatment	2
Recanalization	-2
3. Side-branch artery	
No	3
Yes	-3
4. Aneurysm's diameter (mm)	
≤ 8.9	2
> 8.9	-2
5. Neck ratio (NR)	
≤ 1.1	1
> 1.1 ; 1.8 ≤	-1
> 1.8	1
6. Parent artery diameters ratio (PDR)	
≤ 1.3	2
> 1.3	-2
Threshold (under = predictive of failure)	-1

Simplified DIANES score	Accuracy	Sensitivity	Specificity	Positive Predictive Value (PPV)	Negative Predictive Value (NPV)	AUC
Training sample	0.87 (0.80 - 0.94)	0.91 (0.84 - 0.96) [73 / 80]	0.72 (0.52 - 0.91) [16 / 22]	0.92 (0.86 - 0.98) [73 / 79]	0.69 (0.5 - 0.88) [16 / 23]	0.88 (0.80 - 0.97)
Test sample	0.77 (0.65 - 0.89)	0.92 (0.82 - 1) [34 / 37]	0.40 (0.59 - 0.66) [6 / 15]	0.79 (0.66 - 0.91) [34 / 43]	0.67 (0.33 - 1) [6 / 9]	0.70 (0.52 - 0.89)
Whole cohort	0.84 (0.77 - 0.90)	0.91 (0.86 - 0.67) [107 / 117]	0.60 (0.41 - 0.75) [22 / 37]	0.88 (0.81 - 0.94) [107 / 122]	0.69 (0.52 - 0.85) [22 / 32]	0.82 (0.73 - 0.91)



A
AUC 0.88 (95%CI, 0.80–0.96)
B
AUC 0.73 (95%CI, 0.55–0.91)
C
AUC 0.83 (95%CI, 0.74–0.91)
Sensitivity
Specificity
RROC A
RROC B OR C
Score
(Threshold = -6)