



Machine Learning with SHAP-Driven Interpretability Enhances Decision-Making in Coronary Bifurcation Percutaneous Coronary Intervention: A Prospective Study

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Abstract

Background: This prospective registry-based cross-sectional study of 500 percutaneous coronary intervention (PCI) patients assessed lesion morphology, clinical and procedural determinants of coronary bifurcation complexity, and the utility of machine learning (ML) for lesion stratification.

Objectives: Characterize bifurcation lesion classes (0: No bifurcation; 1: Simple; 2: Complex), identify key demographic, anatomical, and procedural predictors of complexity, and evaluate interpretable ML models for accurate classification.

Methods: We analyzed patient demographics, comorbidities, angiographic features (e.g., side-branch stenosis, bifurcation angle, calcification), and procedural outcomes, selecting ten critical complexity drivers. Four ML approaches – k-nearest neighbors (KNN), support vector machines (SVM), ensemble trees, and probabilistic classifiers – were optimized via hyperparameter tuning and feature-selection methods, with SHapley Additive exPlanations (SHAP) values quantifying feature importance.

Results: The SHAP analysis identified side-branch stenosis, heavy calcification, and dual-stent technique as top predictors. Weighted KNN and medium-scale SVM achieved 89 - 92% accuracy, while ensemble models peaked at 97.8% using 10 - 15 features. Complex lesions (class 2) required dual-stent deployment more often (35% vs. 10%) and had lower post-PCI TIMI 3 flow (85% vs. 92%). Wrapper-based feature selection outperformed filter and embedded methods, reaching 96.8% accuracy.

Conclusions: Integrating anatomical metrics, patient risk factors, and interpretable ML significantly improves PCI decision-making for bifurcation lesions, outperforming traditional systems and enabling personalized interventional strategies to optimize outcomes and resource allocation.

Keywords: Coronary Bifurcation, Machine Learning, SHAP Analysis, Percutaneous Coronary Intervention, Lesion Complexity, Procedural Outcomes

1. Background

Coronary artery disease (CAD) remains a leading cause of global morbidity and mortality, and percutaneous coronary intervention (PCI) is the primary revascularization modality for both acute coronary

syndromes and stable CAD by restoring myocardial perfusion in a minimally invasive manner (1). Coronary bifurcation lesions (CBLs) account for 15 - 20% of all PCIs (2-10) and, despite advances in stent technology, adjunctive pharmacotherapy, and operator expertise, are associated with higher procedural complexity and

less favorable short- and long-term outcomes than non-bifurcation lesions (2, 3, 6-8, 10).

Contemporary strategies comprise provisional stenting – initial main-vessel stenting with side-branch intervention only if compromised – which reduces metal burden and repeat revascularization (3, 4, 6-13), and planned two-stent techniques (double-kissing crush, culotte, T-stenting, TAP) reserved for anatomically complex bifurcations but requiring longer procedure times and greater contrast use (2, 7, 13). Lesion anatomy is standardized by the Medina classification of $\geq 50\%$ stenosis in the proximal main vessel, distal main vessel, and side branch (2, 14-20), while intracoronary imaging (IVUS, OCT) provides detailed plaque and apposition assessment but remains underutilized due to cost and training barriers (10, 21-23).

Key challenges include optimal strategy selection for large side branches supplying significant myocardium – where upfront two-stent approaches may be advantageous (3, 6, 7, 9, 11, 13, 24-29) – and prediction of side-branch occlusion from plaque shift or carina displacement, addressed by angiographic scores such as V-RESOLVE (15, 21, 30, 31). Heavy calcification and anatomical variations (bifurcation angle, vessel diameter, and segment length) further complicate stenting (1, 10, 15, 20, 32).

In response, this study investigates the relationships between patient demographics, Medina classification, lesion complexity, bifurcation angle, vessel size, calcification severity, stenting technique, and adjunctive therapies in a large bifurcation PCI cohort, correlating these variables with major adverse cardiac events (MACE), target lesion revascularization (TLR), stent thrombosis, and mortality over extended follow-up. Advanced statistical and machine-learning techniques will identify independent predictors of adverse outcomes and develop refined risk stratification models, with the goal of optimizing patient selection, procedural planning, and long-term results in this challenging CAD subset.

2. Objectives

In response, this study investigates the relationships between patient demographics, Medina classification, lesion complexity, bifurcation angle, vessel size, calcification severity, stenting technique, and adjunctive therapies in a large bifurcation PCI cohort, correlating these variables with MACE, TLR, stent thrombosis, and mortality over extended follow-up. Advanced statistical and machine-learning techniques will identify independent predictors of adverse outcomes and develop refined risk stratification models, with the goal

of optimizing patient selection, procedural planning, and long-term results in this challenging CAD subset.

3. Methods

3.1. Study Design

This prospective, registry-based cross-sectional study was conducted at Chamran Heart Hospital and Askariyeh Hospital from March 21, 2023, to January 19, 2025. The study aimed to evaluate predictors of coronary bifurcation lesion complexity and associated procedural outcomes in patients undergoing PCI.

3.2. Participants

A total of 500 consecutive patients who underwent coronary bifurcation angioplasty were enrolled. Inclusion criteria encompassed adults aged 40 – 90 years undergoing PCI for bifurcation lesions. Exclusion criteria included records with more than 15% missing or corrupted data fields. Demographic, clinical, angiographic, and procedural data were prospectively captured in an electronic catheterization laboratory database.

3.3. Scales

Lesion complexity was operationalized using a three-tier angiographic classification system: class 0 (no true bifurcation), class 1 (simple bifurcation defined by side-branch diameter ≥ 2 mm or bifurcation angle $> 70^\circ$ with flow limitation), and class 2 (complex bifurcation). Quantitative stenosis severity was measured on a continuous scale from 0% to 100% using edge-detection software. Additional morphologic features—tortuosity, eccentricity, severe calcification, myocardial bridging, aneurysm, and spontaneous dissection—were coded as dichotomous (present/absent) variables. Clinical outcomes included procedural success, contrast-induced nephropathy, peri-procedural myocardial infarction, vascular access complications, and 30-day MACE. Left ventricular ejection fraction and TIMI flow grade (pre- and post-PCI) served as functional scales of cardiac performance (Figure 1).

3.4. Data Collection

Trained research coordinators administered a structured questionnaire at hospital admission to collect demographic (age, sex, nationality), socioeconomic (insurance status, education level), and anthropometric data (height, weight measured with calibrated stadiometers and scales). Cardiovascular risk

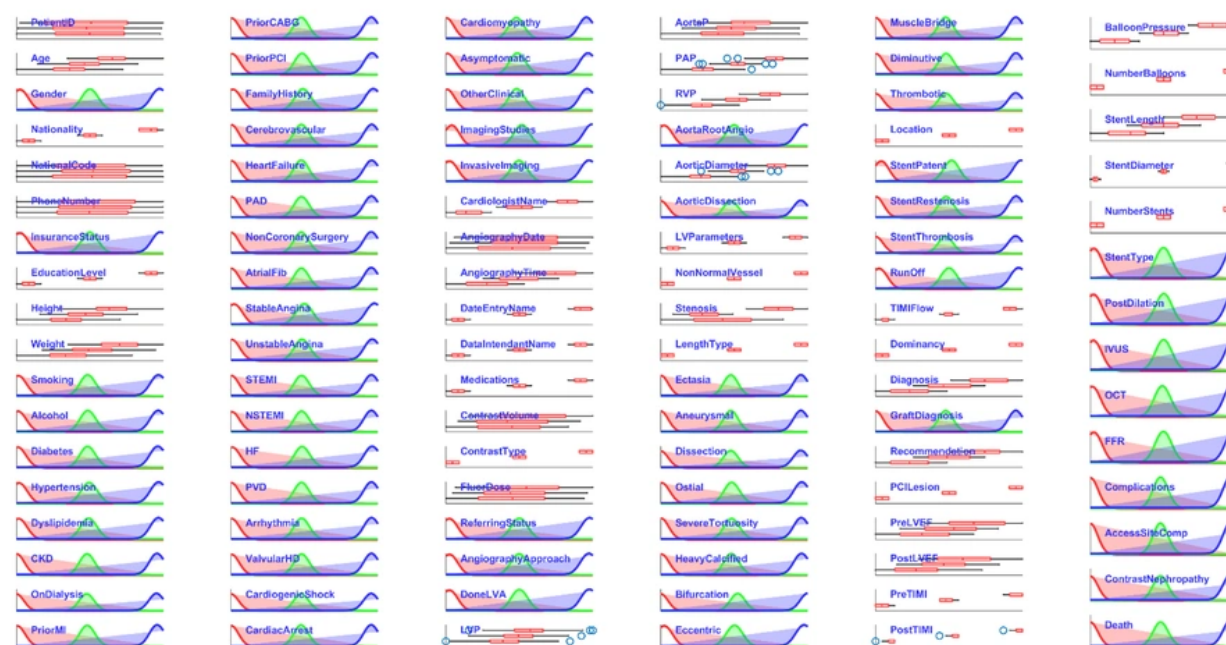


Figure 1. Three-class coronary bifurcation lesion map with quantitative angiographic parameters, illustrating the interplay between lesion morphology, patient risk factors, and procedural outcomes.

factors, prior coronary events (coded per ICD-10), comorbidities (heart failure, atrial fibrillation, peripheral and cerebrovascular disease), and family history of premature coronary disease ($\approx 30\%$ prevalence) were systematically documented. During angiography, procedural metadata—including date, start time, contrast volume (50–150 mL), fluoroscopy dose ($100 - 400 \text{ cGy}\cdot\text{cm}^2$), vascular access route, and urgency status—were extracted from DICOM files. Hemodynamic pressures were recorded via fluid-filled catheters. Angiographic assessments were independently verified by two operators. Stent-related parameters (length: 10–30 mm; diameter: 2.5–4.0 mm; type: Bare-metal vs. drug-eluting; dual-stent use) and adjunctive techniques (IVUS, OCT, FFR) were also recorded.

3.5. Data Analysis

Continuous variables are presented as mean $\pm$ standard deviation or median (interquartile range), and categorical variables as counts and percentages. Comparisons across bifurcation classes for procedural outcomes and complications were performed using chi-square tests for categorical variables and independent t -

tests or Mann–Whitney U tests for continuous variables, as appropriate. Multivariable logistic regression models, adjusted for age, sex, comorbidities, and vascular access route, were used to identify independent predictors of adverse outcomes, with interaction terms included to test whether stent strategy effects varied by lesion complexity. A unified machine learning framework was deployed to predict lesion complexity, evaluating k-nearest neighbors (KNN), support vector machines (SVM), tree-based ensembles (random forests, gradient boosting, RUSBoost), and probabilistic classifiers (Naive Bayes, discriminant analysis). Feature selection combined filter methods (Pearson correlation, neighborhood component analysis), embedded regularizers (Lasso, Elastic Net), and SVM-based wrapper approaches. Model interpretability was ensured using SHapley Additive exPlanations (SHAP) analysis. All analyses were conducted in Python 3.9, with statistical significance defined as two-sided $P < 0.05$. 3-6-Ethical Consideration The study was approved by the Ethics Committee of Isfahan University of Medical Sciences ([IR.MUI.MED.REC.1403.439](https://doi.org/10.30479/IR.MUI.MED.REC.1403.439)) and conducted in accordance with the ethical principles of the Declaration of Helsinki (1975, revised 1983). Written

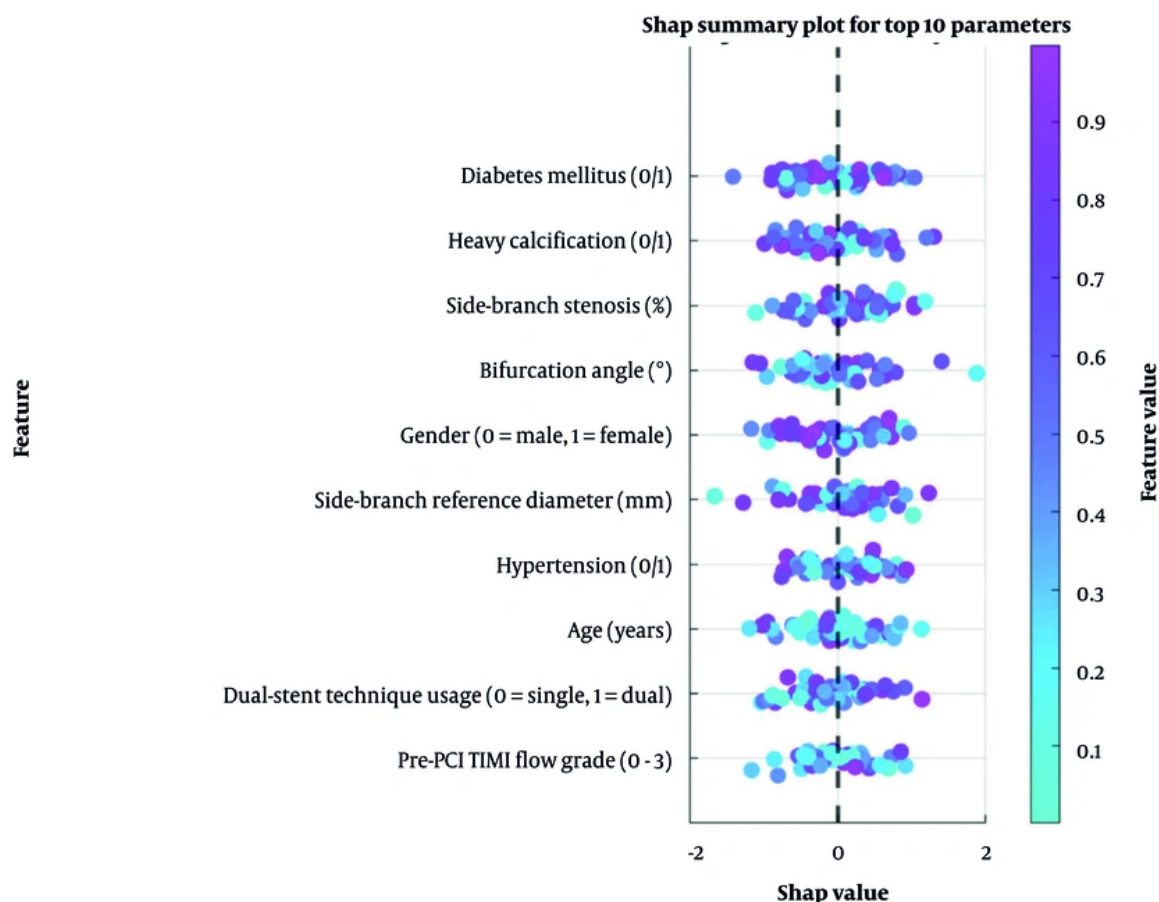


Figure 2. SHapley Additive exPlanations (SHAP) summary plot of ten key clinical and procedural features in bifurcation angioplasty. The x-axis shows each feature's additive impact (SHAP value) on model output, while the color gradient reflects raw feature values across 500 patients – enabling detailed analysis of feature interactions for personalized intervention strategies.

informed consent was obtained from all participants prior to enrollment.

4. Results

The cohort's mean age was 65 ± 10 years (gender coded male = 0, female = 1). Smoking and alcohol use each affected approximately 30% of the cohort, while diabetes mellitus, hypertension, dyslipidemia, and chronic kidney disease (30% of whom were on dialysis) were present in 25%, 40%, 35%, and 10% of patients, respectively. Prior myocardial infarction, PCI, and CABG occurred in 15%, 20%, and 10% of cases; heart failure, atrial fibrillation, peripheral arterial disease, and

cerebrovascular disease each affected 5 - 15% of the cohort.

In class 1 lesions, mean side-branch stenosis was $35 \pm 10\%$, compared to $65 \pm 12\%$ stenosis and $75 \pm 8^\circ$ bifurcation angles in class 2 lesions. Post-PCI TIMI grade 3 flow was achieved in 92% of class 1 and 85% of class 2 lesions. Dual-stent techniques were used in 10% of class 1 lesions versus 35% of class 2 lesions, and adjunctive IVUS/OCT and FFR were employed in 50% and 30% of all cases, respectively.

The present investigation assessed bifurcation angioplasty complexity using ten patient- and lesion-specific parameters – demographics (age, sex, hypertension, diabetes), anatomic characteristics (side-branch stenosis, bifurcation angle, side-branch

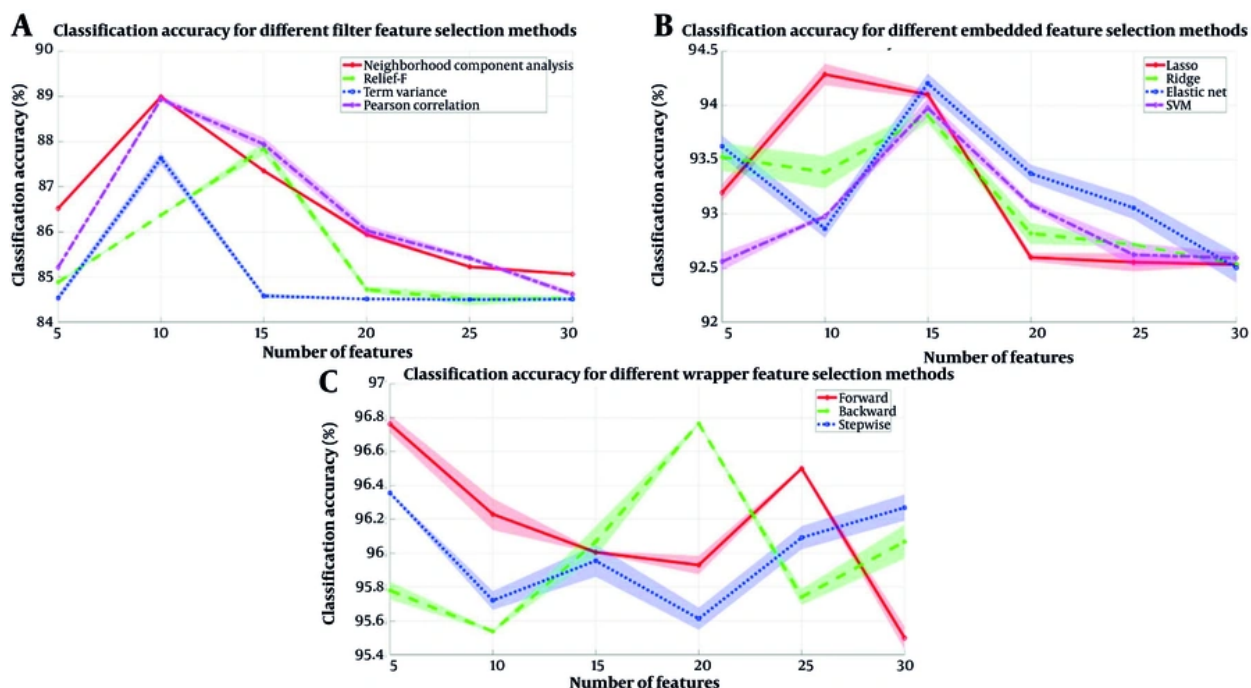


Figure 3. Classification accuracy of the support vector machines (SVM) classifier using three categories of feature selection methods: A, filter methods; B, embedded methods; and C, wrapper methods. The horizontal axis indicates the number of selected features, and the vertical axis represents classification accuracy (%). NCA and Pearson correlation (filter methods) achieved ~88.9% accuracy with 10 features. Lasso and elastic net (embedded methods) achieved 94.2% and 94.1% accuracy with 10 and 15 features, respectively. Forward and backward selection (wrapper methods) reached the highest accuracies of 96.5% and 96.8% with 25 and 20 features, respectively.

diameter, heavy calcification, pre-PCI TIMI flow), and stenting strategy (single vs. dual). Advanced age, female sex, hypertension, and diabetes predispose individuals to diffuse, calcified disease in smaller vessels, thereby increasing procedural risk and guiding device selection. Lesion severity – defined by stenosis $\geq 50\%$, wide bifurcation angles, larger diameters, pronounced calcification, and impaired TIMI flow – and the choice of a dual-stent approach further amplify technical challenges.

The SHAP were applied to the SVM model to decompose its predictions into feature-level contributions. In Figure 2, each of the 500 patient samples is represented as a point along the horizontal axis corresponding to its SHAP value, with color denoting the raw feature magnitude. Side-branch stenosis, heavy calcification, and dual-stent utilization emerged as the most influential predictors. This high-resolution SHAP summary plot elucidates both individual and interactive feature effects, thereby underpinning transparent, patient-tailored interventional strategies.

The performance of the SVM classifier was evaluated across three distinct feature-selection paradigms – filter, embedded, and wrapper – by examining classification accuracy as a function of the number of selected features (Figure 3).

Filter-based techniques, illustrated in the top-left panel of Figure 3, demonstrated rapid, model-agnostic selection. Neighborhood component analysis and Pearson correlation each achieved a maximum accuracy of 88.9% when restricted to ten features, indicating their efficacy in identifying informative variables despite computational simplicity.

Embedded methods, depicted in the top-right panel, integrate feature selection within the model training process via regularization. The Lasso method attained an accuracy of 94.2% with ten features, while the elastic net approach reached 94.1% using fifteen features, underscoring the advantage of simultaneous dimensionality reduction and decision-boundary optimization.

Wrapper strategies, presented in the bottom panel, yielded the highest classification performance at the

expense of increased computational cost. Forward selection achieved a peak accuracy of 96.5% with twenty-five features, whereas backward selection attained 96.8% using twenty features, thereby confirming the superior predictive power of exhaustive, model-guided searches.

Collectively, these findings reveal that wrapper methods offer the greatest accuracy, embedded techniques provide a favorable balance between performance and feature parsimony, and filter approaches afford efficient preliminary screening. The integration of multiple selection strategies through hybrid frameworks may further enhance model robustness and applicability in clinical settings.

In this study, we performed a unified evaluation of diverse classifiers on a three-class bifurcation angioplasty dataset — no bifurcation, simple bifurcation, and complex bifurcation — by systematically tuning hyperparameters through cross-validation and varying the number of selected features (5, 9, 13, 17, 22, 28). We assessed KNN variants (weighted, cosine, and Gaussian kernels at fine-, medium-, and coarse-scale granularities), SVM (linear, polynomial degrees 2 - 5, and radial basis function kernels with $\gamma = 0.001 - 10$ and $C = 0.1 - 1,000$), regularized discriminant analyses (LDA and covariance-regularized QDA), decision and regression trees (depths 3 - 20 with impurity-decrease thresholds 0.001 - 0.1 and feature subsampling), ensemble learners (boosted, bagged, subspace discriminant, subspace KNN, and RUSBoost with 50 - 500 estimators, learning rates 0.01 - 0.3, and sampling or under-sampling ratios of 0.8 and 0.5), and naive Bayes models (Gaussian and kernel).

As shown in Figure 4, most classifiers peaked in accuracy with 10 - 15 features: Linear SVM and medium-scale RBF SVM reached approximately 97.2% at 10 features; subspace discriminant and subspace KNN ensembles achieved approximately 97.8%; cosine and weighted KNN variants attained approximately 92.5%; coarse and regression trees peaked at approximately 91.3%; QDA reached approximately 81.3%; and Gaussian naive Bayes approximately 77.3%. These results highlight that careful algorithm selection, targeted feature dimensionality, and rigorous hyperparameter optimization are essential for maximizing predictive performance in complex, multiclass vascular-bifurcation classification tasks.

5. Discussion

This study integrates clinical, angiographic, and machine-learning-derived insights to stratify CBLs into three classes — no (class 0), simple (class 1), and complex (class 2) — and reaffirms that side-branch stenosis $\geq 50\%$,

acute bifurcation angles $> 70^\circ$, and heavy calcification are key drivers of procedural complexity (1, 2). The SHAP analysis further quantifies each feature's impact, identifying stenosis severity, calcific burden, and dual-stent deployment as the most influential predictors, in line with biomechanical constraints on stent apposition and branch preservation (3, 4). Weighted KNN and medium-scale SVM models achieved 89 - 92% accuracy, demonstrating that non-linear approaches capture complex interactions among demographic, anatomical, and procedural variables more effectively than threshold-based scores such as Medina or V-RESOLVE (5, 6).

Our models reveal indirect effects of systemic risk factors — diabetes and hypertension — mediated through diffuse calcification and reduced vessel caliber (2, 7), and confirm that pre-PCI TIMI flow and side-branch diameter are critical determinants of technical success (8, 9). Clinically, class 2 lesions exhibited higher dual-stent adoption (35% vs. 10% in class 1), consistent with guidelines favoring upfront two-stent strategies for high-risk bifurcations, albeit with longer procedure times and increased contrast use (6, 10). Nevertheless, TIMI 3 restoration rates were lower in class 2 (85% vs. 92%), underscoring persistent challenges in optimizing flow dynamics due to plaque shift or stent malapposition (11, 12).

These findings support hybrid workflows that integrate machine learning (ML)-based risk stratification with intracoronary imaging (utilized in 50% of cases) to refine pre-procedural planning in calcified or angulated lesions (13, 24). Limitations include the single-center, retrospective design limiting generalizability; the need for longitudinal studies to confirm causal inferences from SHAP (e.g., dual-stent usage as both predictor and outcome); and the absence of long-term endpoints (MACE, stent thrombosis), necessitating extended follow-up to validate prognostic utility.

5.1. Conclusions

Integrating interpretable machine-learning models with detailed clinical and angiographic data enhances stratification of coronary bifurcation lesion complexity beyond conventional schemes. Key determinants — side-branch stenosis, calcification, patient factors (age, diabetes), and dual-stent deployment — demonstrate the potential for tailored PCI strategies. Prospective, multicenter validation and seamless integration with real-time intravascular imaging will be essential to confirm predictive accuracy and inform intraprocedural decision-making. Adoption of such data-driven

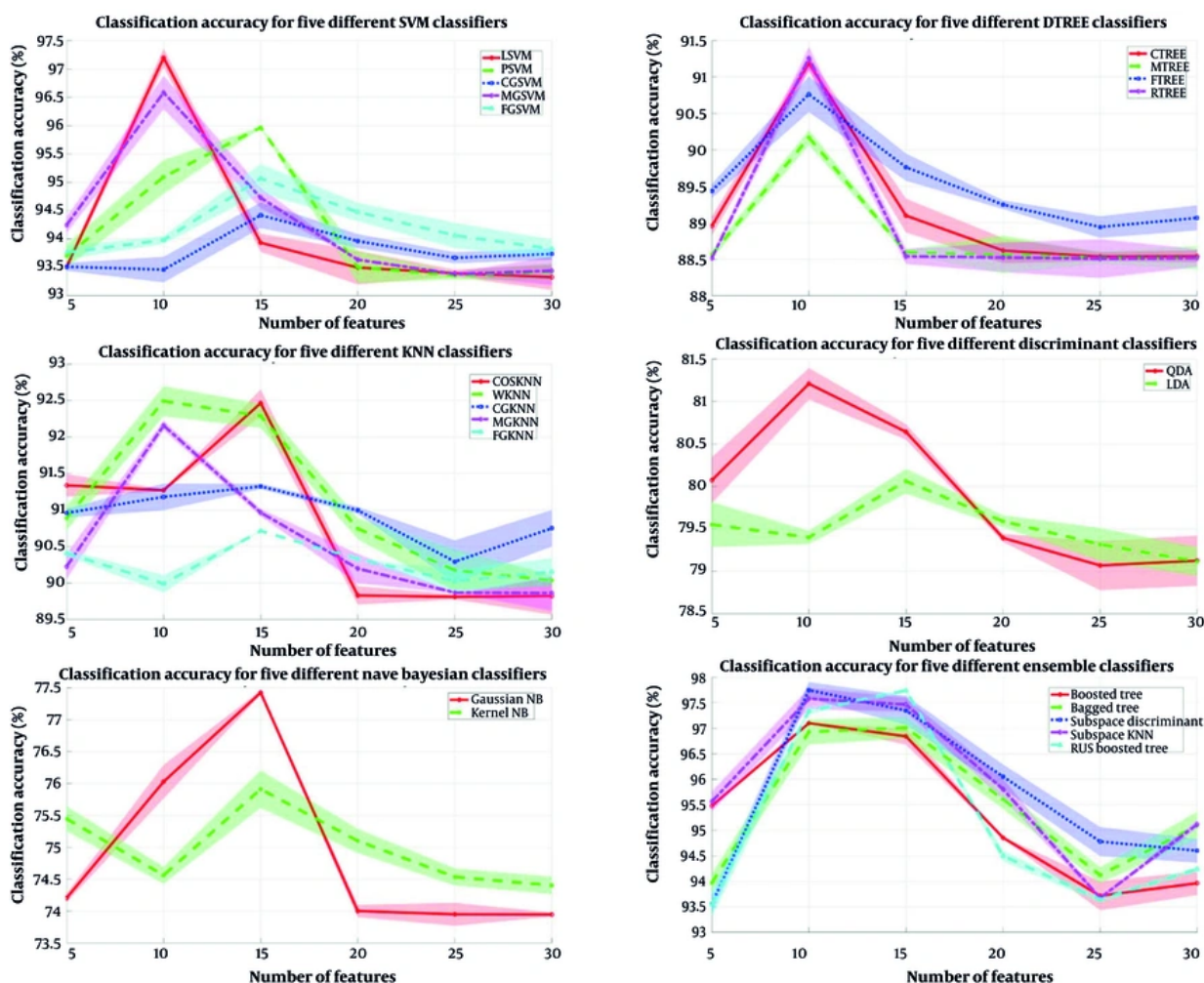


Figure 4. Comparative accuracy of hyperparameter-optimized machine learning (ML) models — including k-nearest neighbors (KNN) variants, support vector machines (SVM) kernels, decision trees, and probabilistic classifiers — in classifying angioplasty lesions as no, simple, or complex bifurcations, demonstrating each model's accuracy and robustness across varying lesion complexities.

frameworks promises to reduce complications, optimize resource utilization, and improve long-term outcomes in high-risk bifurcation interventions.

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Footnotes

Authors' Contribution: Study concept and design: A. Kh. F. and I. Z.; Acquisition of data: I. Z. and E. Sh.; Analysis and interpretation of data: E. Sh. and B. N.; Drafting of the manuscript: B. N. and M. B.; Critical revision of the manuscript for important intellectual content: A. Kh. F. and E. Sh.; Statistical analysis: B. N. and

M. B.; Administrative, technical, and material support: I. Z. and M. B.; Study supervision: A. Kh. F.

Conflict of Interests Statement: The authors declare no conflict of interests.

Data Availability: The dataset presented in the study is available on request from the corresponding author during submission or after publication. The data are not publicly available due to privacy and confidentiality concerns.

Ethical Approval: The present study was approved by the Ethical Committee of Isfahan University of Medical Sciences (IR.MUI.MED.REC.1403.439).

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Informed Consent: Informed consent was obtained from the patients.

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