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RESEARCH

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TCD-Guided management in carotid endarterectomy: a retrospective study

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Abstract

Background: Stroke, primarily resulting from ischemic conditions, is the foremost cause of mortality and long-term impairment and is frequently associated with narrowing of the carotid arteries. Although carotid endarterectomy (CEA) is the treatment of choice, it carries the risk of cerebral ischemia and reduced blood flow. Transcranial Doppler (TCD) ultrasound offers a nonintrusive method to assess cerebral blood circulation during CEA, potentially enhancing surgical outcomes. The objective of this study was to assess the clinical utility and safety of TCD monitoring during CEA and to identify factors influencing postoperative complications.

Methods This retrospective analysis included 158 CEA patients (from January 2021–August 2023) who underwent TCD monitoring and whose data were compared to historical standard care data. The primary outcomes were operation duration and artery occlusion time. Secondary outcomes included carotid shunt usage, seven-day postoperative complications, and six-month carotid artery patency. Logistic regression identified factors linked to adverse reactions, and a predictive model was evaluated with a receiver operating characteristic (ROC) curve.

Results: Comparative analysis indicated significant reductions in both the duration of surgery (113.26 ± 7.29 min) and artery occlusion time (21.85 ± 2.92 min) for patients monitored with TCD ($P < 0.001$) and an increase in carotid shunt implementation (25% as opposed to traditional care). The observed postoperative complications were minor, with a nonsignificant trend that favored the use of TCD-monitored procedures (1% vs. historical rates). Factors such as patient age and plaque echogenicity were found to be predictive of postoperative issues, with plaque echogenicity emerging as a significant predictive factor (OR = 10.70, 95% CI: 2.14–202, $P = 0.02$) upon multivariate analysis. The predictive model exhibited high precision (AUC = 0.93).

Conclusion This retrospective evaluation suggested that TCD monitoring in the CEA may reduce procedural time and potentially decrease postoperative complications, supporting its use for personalized surgical planning.

Keywords Carotid endarterectomy, Transcranial doppler, Cerebral ischemia, Postoperative complications

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Introduction

Stroke is a leading cause of mortality and disability, predominantly manifesting as an ischemic event [1, 2]. Carotid artery stenosis plays a crucial role in this process. Ischemic stroke accounts for approximately 80% of all stroke cases, with carotid artery stenosis being a major contributing factor [3]. Carotid endarterectomy (CEA), recognized as the gold standard for managing carotid artery stenosis [4], serves as a preventive measure against stroke. However, the risk of cerebral ischemia and hypoperfusion during CEA presents significant challenges to patient safety and outcomes [4–6].

Transcranial Doppler (TCD) is an advanced, noninvasive diagnostic tool that enables real-time assessment of both intracranial and extracranial vascular circulation and hemodynamics [7, 8]. TCD facilitates real-time monitoring of cerebral blood flow, aiding in blood pressure management and decision-making regarding the diversion of blood flow during CEA, thereby minimizing intraoperative complications [9].

This study aimed to evaluate the clinical utility and safety of TCD monitoring during CEA. The primary outcome was the reduction in operation duration and artery occlusion time. Secondary outcomes included the rate of carotid shunt usage, seven-day postoperative complications, and six-month carotid artery patency. By comparing surgical outcomes between the TCD and control groups, we sought to enhance the scientific rationale for CEA procedures, optimize surgical strategies, and improve patient outcomes by minimizing postoperative complications.

Materials and methods

Study participants

This study presents a retrospective analysis of the utility of transcranial Doppler (TCD) monitoring during carotid endarterectomy (CEA) procedures. A total of 158 patients who underwent CEA between January 2021 and August 2023 were included in this study. The cohort comprised 107 males and 51 females, aged between 48 and 82 years, with an average age of 65.22 ± 10.94 years. The inclusion criteria included age between 40 and 85 years, confirmed carotid artery stenosis ≥ 70% determined by ultrasonography or computed tomography angiography (CTA), and the absence of absolute surgical contraindications. The exclusion criteria were severe heart disease, coagulopathy, a history of cerebral hemorrhage, or inability to complete postoperative follow-up.

Study methods

In this retrospective study, the medical records of patients who underwent CEA were analyzed. Participants were categorized into the TCD group or control group based on the monitoring techniques used during surgery. Group allocation rather than randomization was determined by standard practice at the time of surgery. All CEA procedures were performed under general anesthesia, adhering to the standard of care.

Experienced surgeons, defined as those who have performed at least 50 CEA procedures in the past five years, conducted all operations. This definition ensures a high level of proficiency and expertise in performing CEA. In the TCD group, real-time TCD monitoring was conducted using a 2-2.5 MHz probe through various acoustic windows, including temporal and orbital approaches, to monitor the middle cerebral artery (MCA) and other major intracranial arteries. This monitoring guided intraoperative blood pressure regulation and flow diversion decisions during critical surgical steps, such as clamping and unclamping of the carotid artery. Carotid shunting was based on predefined criteria, including clinical assessment and ultrasound parameters. A shunt was placed if the mean flow velocity dropped below 40 cm/s or if significant reductions in cerebral perfusion were observed.

In the control group, conventional monitoring practices included the use of surface electroencephalography (EEG), stump pressure measurement, and near-infrared spectroscopy (NIRS) to monitor cerebral perfusion during surgery. These methods provide indirect assessments of cerebral blood flow and are commonly used in the absence of TCD monitoring. The outcome measures included intraoperative blood pressure regulation, flow diversion, early postoperative complications within seven days, and carotid artery patency at the six-month postoperative follow-up.

Data collection

Data, including patient demographics, surgical notes, intraoperative monitoring data, postoperative complication records, and postoperative vascular ultrasonography results, were extracted from medical records. Clinical variables potentially affecting postoperative outcomes, such as age, sex, history of hypertension and diabetes, preoperative stenosis rate, intraoperative blood pressure changes, and flow diversion status during surgery, were reviewed and documented.

Statistical analysis

Continuous variables are presented as the mean ± standard deviation and were compared using t tests. Univariate analysis was performed with chi-square or Fisher's exact tests to evaluate associations between variables and postoperative adverse reactions. A P value of less than 0.05 indicated statistical significance. Significant variables from the univariate analysis were included in a logistic regression model to identify independent factors. The model's predictive accuracy was assessed using a

Table 1 Baseline characteristics

Variables	Total (*n* = 158)	TCD (*n* = 87)	Control group (*n* = 71)	*P*
Age	65.22 ± 10.94	65.22 ± 11.34	65.35 ± 10.59	0.940
Gender				0.396
Female	50	30	20	
Male	108	57	51	
Hypertension				0.062
No	57	37	20	
Yes	101	51	50	
Diabetes				0.533
No	78	41	37	
Yes	80	46	34	
Stenosis ratio	85.01 ± 8.31	85.70 ± 8.27	84.15 ± 8.34	0.668
Plaque echogenicity				
Soft	54	27	27	0.503
Mix	61	37	24	
Hard	43	23	20	

Table 2 Comparative analysis of CEA levels intraoperatively and postoperatively

Variables	Total (*n* = 158)	TCD (*n* = 87)	Control group (*n* = 71)	*P*
Operation duration	115.58 ± 7.32	113.26 ± 7.29	117.56 ± 5.44	0.001
Occlusion time	23.10 ± 3.46	21.85 ± 2.92	24.80 ± 3.06	<0.001
Carotid shunt				0.047
No	127	62	65	
Yes	31	22	9	
Complications (Within 7 days after operation)				0.027
No	151	86	65	
Yes	7	1	6	
Review results (6 months after operation)				0.267
No Stenosis	157	87	70	
Restenosis	1	0	1	

receiver operating characteristic (ROC) curve. Statistical analysis was performed using R software, with the rms package for constructing the forest plot and the ggplot2 package for graphical representation.

Ethical considerations

This study was conducted in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The study protocol was approved by the Institutional Review Board (IRB) of Jinan People's Hospital, with the ethical protocol number 2024-LW-106. The study followed the STROBE guidelines for reporting observational studies.

Results

Comparison of baseline characteristics

This study included 158 patients, 87 of whom were in the TCD group and 71 of whom were in the control group. A comparative analysis of the baseline characteristics indicated no significant differences between the groups in terms of age, sex, hypertension history, diabetes history, or carotid artery stenosis rate. The statistical equivalence at the onset of the study confirmed the comparability of the cohorts. For detailed information, refer to Table 1.

Intraoperative and postoperative CEA indicator analysis

A comparative analysis of key intraoperative and postoperative indicators after CEA in the TCD and control groups revealed significant differences in several areas. The TCD group exhibited a significantly shorter operation duration, averaging 113.26±7.29 min, compared to 117.56±5.44 min in the control group ($P<0.001$). Similarly, the occlusion time was notably reduced in the TCD group, averaging 21.85±2.92 min, compared to 24.80±3.06 min in the control group ($P<0.001$). The rate of carotid shunt utilization was significantly greater in the TCD group (25%) than in the control group (13%) ($P=0.047$). Postoperative complications within the first week were low in both groups, but the control group had a slightly greater incidence (9% vs. 1% in the TCD group), which was statistically significant ($P=0.027$). A six-month postoperative review revealed no significant difference in restenosis rates between the groups, with one case reported in each group. For further details, please refer to Table 2; Figs. 1 and 2 for graphical representations.

Univariate analysis of factors influencing post-CEA complications

This study examined the influence of various factors on the occurrence of complications after CEA. The mean age of the patients in the cohort was 65.28±10.97 years. Patients who experienced complications had a significantly greater mean age (73.29±12.92 years) than did those without complications (64.91±10.78 years) ($P=0.048$). Sex was not a significant predictor of post-CEA complications ($P=0.514$), nor was the presence of hypertension ($P=0.219$) or diabetes ($P=0.260$) significantly related to the rate of complications. The degree of stenosis was not a significant factor influencing complication rates ($P=0.577$). However, longer operation durations were associated with an increased risk of complications ($P=0.018$), whereas carotid shunt usage did not significantly impact complication rates ($P=0.138$). The postoperative stroke incidence was 1% in the TCD group and 9% in the control group ($P=0.027$). The mortality

Table 3 Univariate analysis of factors influencing post-CEA complications

Variables	Total ($n=158$)	Complications ($n=7$)	No-Complications ($n=151$)	*P*
Age	65.28 ± 10.97	73.29 ± 12.92	64.91 ± 10.78	0.048
Gender				0.514
Female	50	3	47	
Male	108	4	104	
Hypertension				0.219
No	57	1	56	
Yes	101	6	95	
Diabetes				0.260
No	78	2	76	
Yes	80	5	75	
Stenosis ratio	85.01 ± 8.31	83.29 ± 5.62	85.09 ± 8.42	0.577
Plaque echogenicity				0.002
Soft	43	6	37	
Mix	61	1	60	
Hard	54	0	54	
Operation duration	115.20 ± 6.85	121.14 ± 4.45	114.92 ± 6.83	0.018
Occlusion time	23.18 ± 3.32	25.00 ± 3.42	23.09 ± 3.42	0.208
Carotid shunt				0.138
No	127	6	121	
Yes	31	1	30	
TCD				0.027
No	71	6	65	
Yes	87	1	86	

rates were 0% for both groups. The detailed postoperative complications included stroke, acute myocardial infarction, death, and nerve injury, as specified in Table 3.

Multivariate analysis of factors influencing post-CEA complications

Although hypertension was not statistically significant in the univariate analysis ($P=0.219$), it was included in the multivariate analysis based on clinical experience, as six of the seven patients with complications had hypertension. Multivariate analysis identified independent predictors of post-CEA complications. Age was not a significant independent predictor, with an odds ratio (OR) of 1.06 (95% CI: 0.97–1.18, $P=0.24$), and hypertension indicated a nonsignificant trend toward an increased risk, with an OR of 4.49 (95% CI: 0.59–96.05, $P=0.21$). Plaque echogenicity was significantly associated with post-CEA complications, with an OR of 10.70 (95% CI: 2.14–202, $P=0.02$). Neither a longer operation duration (OR: 1.13, 95% CI: 0.95–1.38, $P=0.19$) nor TCD monitoring (OR: 0.13, 95% CI: 0.01-98, $P=0.09$) were found to be significant factors influencing post-CEA complications. Figure 3 shows a graphical representation of these findings.

Prediction model evaluation

The predictive efficacy of our model was assessed using a receiver operating characteristic (ROC) curve, illustrating the trade-off between sensitivity and specificity across various classification thresholds. The ROC curve,

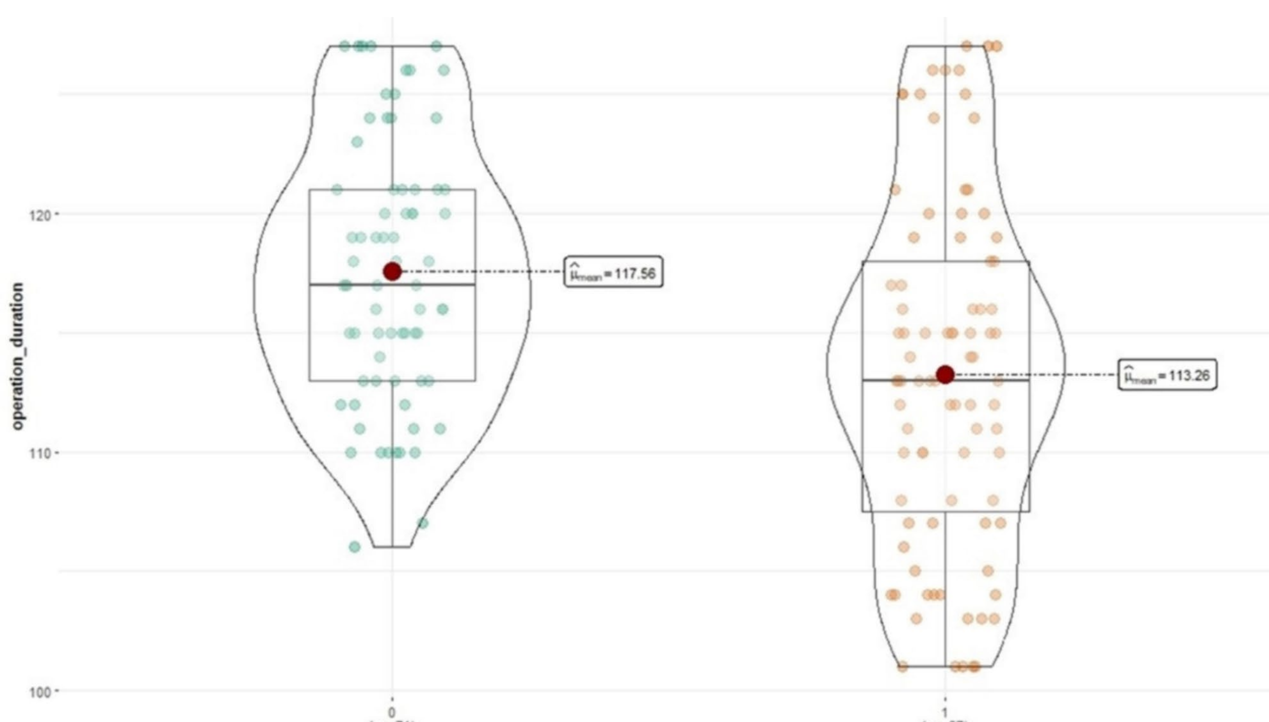

Fig. 1 Comparison of CEA surgery duration between TCD and control group

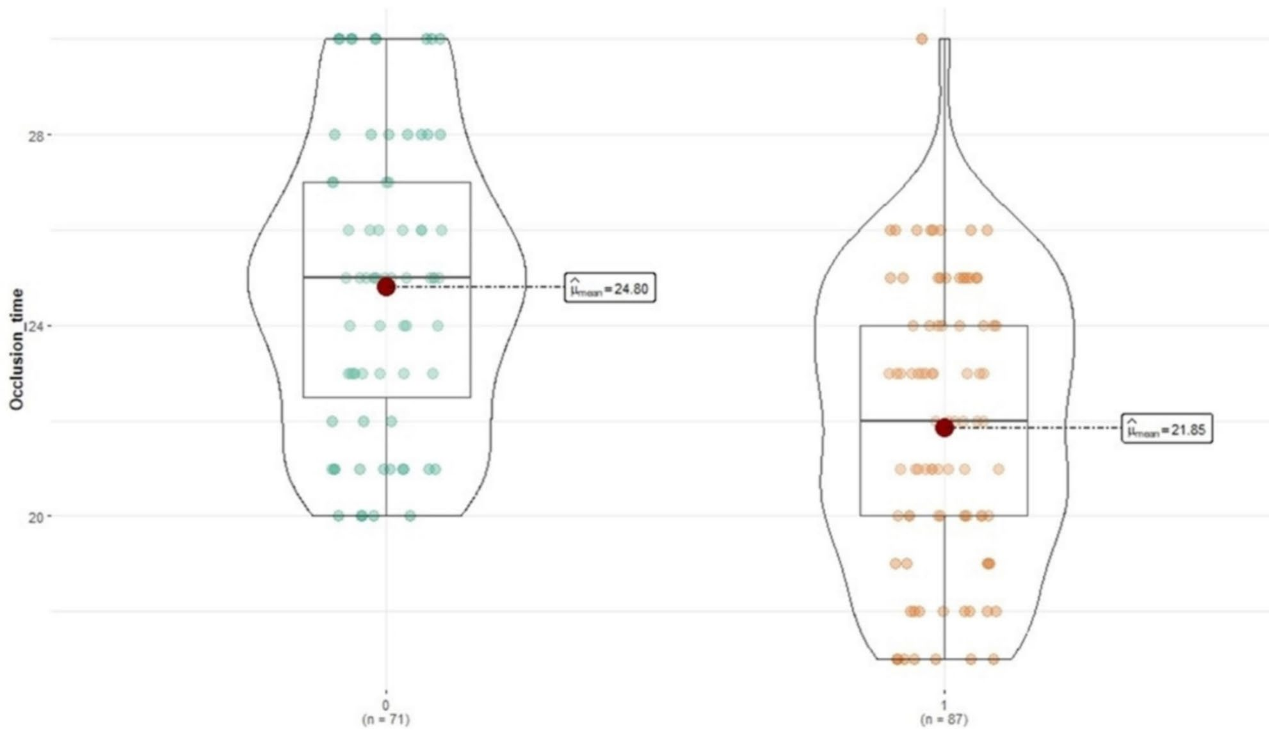

Fig. 2 Comparison of occlusion times during CEA surgery between TCD and control groups

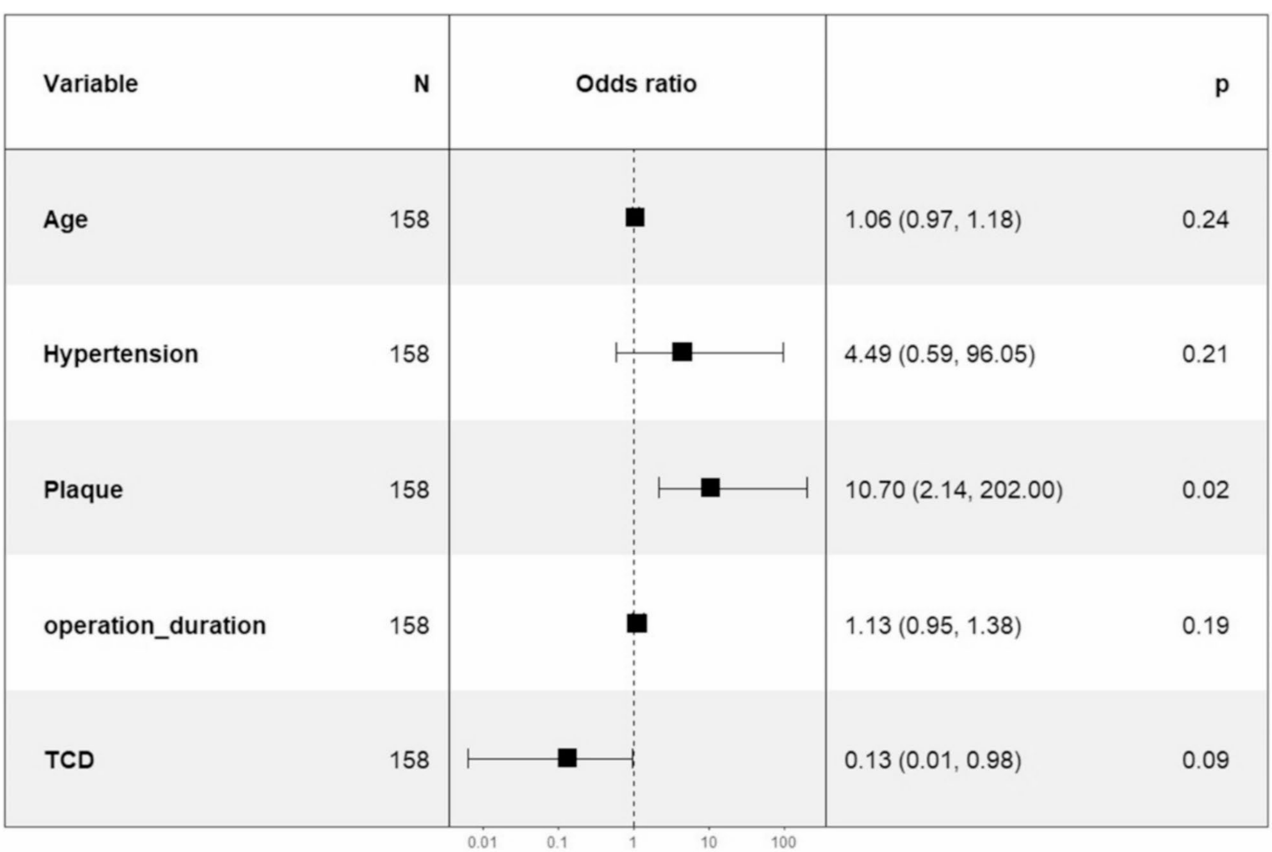

Fig. 3 Multivariate regression analysis for factors influencing post-CEA complications

with an area under the curve (AUC) of 0.93 (Fig. 4), demonstrated excellent discriminatory power, distinguishing between positive and negative outcomes with high confidence. This high AUC indicates that the model has strong accuracy and reliability in predicting post-CEA complications and is thus a valuable tool for preoperative risk assessment.

Discussion

The findings of this retrospective study underscore the substantial utility of TCD monitoring in determining the duration of CEA surgical procedures. The observed reduction in both operation and occlusion times within the TCD group aligns with the literature, suggesting the need for the integration of TCD to guide surgical interventions and prevent cerebral ischemia [10–12]. TCD provides real-time assessment of cerebral blood flow, which enhances the precision of surgical decision-making and can potentially decrease patient risk and associated morbidity [13–15]. The real-time feedback from TCD monitoring allows for more precise and timely surgical interventions, reducing the overall procedure duration and minimizing carotid artery occlusion time. This efficiency likely contributes to better patient outcomes by decreasing the risk of ischemic complications.

The increased rate of carotid shunt utilization in the TCD group, despite the reduction in operation and occlusion times, highlights the utility of TCD in real-time monitoring of cerebral blood flow. TCD enables the immediate detection of cerebral hypoperfusion, prompting timely intervention with shunt placement to maintain adequate cerebral perfusion. This proactive approach likely contributed to the higher shunt rate observed in the TCD group. The overall reduction in surgical and occlusion times suggests that TCD monitoring facilitates more efficient surgical management, allowing for quicker decision-making and adjustments during the procedure [16, 17].

Our retrospective analysis indicated a trend toward lower postoperative complication rates among patients in the TCD group, although this difference was not statistically significant. This finding may be attributed to the overall low complication rate in both groups, reflecting the exemplary surgical care provided to the study population. However, the reduced incidence of complications in the TCD group suggested a possible protective role of TCD, consistent with its established function in intraoperative hemodynamic regulation [18, 19].

Preoperative evaluation of cerebral circulation is crucial in the context of CEA. In our study, preoperative

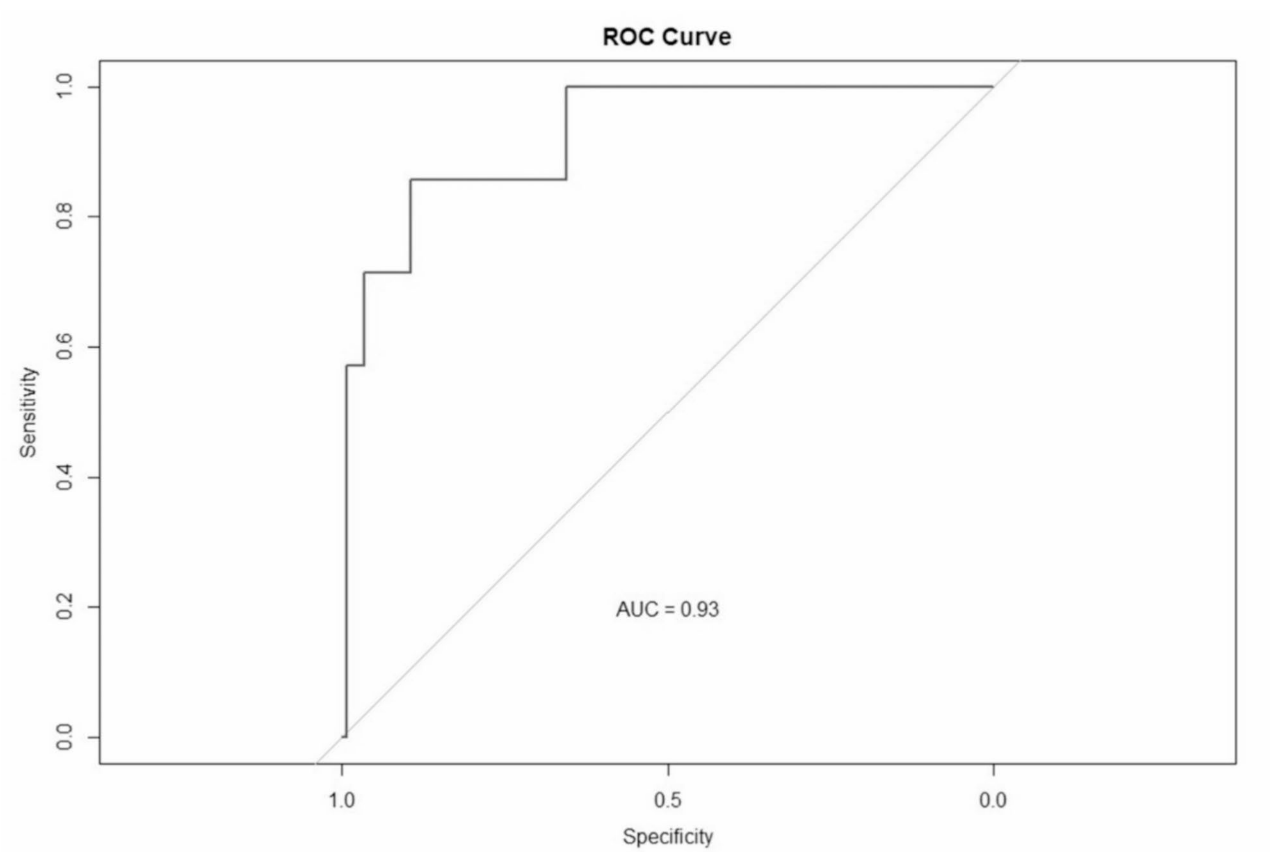

Fig. 4 Receiver operating characteristic curve analysis for logistic regression model

cerebral circulation was assessed using carotid ultrasound and computed tomography angiography (CTA) to determine the degree of stenosis and identify any unfavorable plaque characteristics. This evaluation helps in planning the surgical approach and anticipating potential complications. The real-time monitoring of embolic signals and hemodynamic changes allows for immediate corrective actions, which may contribute to reduced complications such as stroke, myocardial infarction, and nerve injury postoperatively. Despite the lack of statistical significance, the trend observed in our study supports existing evidence on the protective role of TCD in preventing perioperative strokes and other complications during CEA [8, 20].

The univariate analysis identified age and plaque echogenicity as notable predictors of postoperative complications, supporting the literature that highlights the influence of patient-specific traits on surgical outcomes [21, 22]. Multivariate analysis confirmed plaque echogenicity as an independent risk factor, underscoring the importance of tailored surgical strategies, especially for patients with unique plaque features [23–25]. Echogenic plaques are often associated with a greater risk of embolization and perioperative complications, emphasizing the need for meticulous intraoperative monitoring and individualized patient management [26, 27].

The predictive model for postoperative complications, marked by a high area under the curve (AUC=0.93), demonstrated robust risk stratification for CEA patients. By incorporating TCD monitoring with clinical variables, this model serves as a valuable tool for clinicians, aiding in preoperative assessment and facilitating the creation of personalized treatment plans. This integration of predictive analytics and real-time monitoring can enhance patient care by enabling more precise risk assessment and tailored surgical interventions [28–30].

Limitations and future research directions

A critical review of our study revealed several limitations. The modest sample size may have affected the broader applicability of our findings. Future research should aim to replicate these results in a larger, multicenter cohort to bolster the generalizability of our conclusions. Moreover, the limited follow-up period constrained the evaluation of long-term outcomes post-CEA. Studies with extended follow-up durations are essential to gauge the enduring benefits of TCD monitoring.

Conclusion

This retrospective analysis demonstrates that TCD monitoring in carotid endarterectomy offers significant benefits, including reduced operation and occlusion times, as well as a lower rate of postoperative complications. These findings strongly support the integration of TCD monitoring as a standard practice in CEA, especially for patients with high-risk profiles. Adopting TCD monitoring could represent a significant advancement in personalized surgical planning, ensuring optimal cerebral perfusion and minimizing the risk of ischemic complications.

Author contributions

Na Yang and Changjiang Zhou conceived of and designed the study. Na Yang, Zhen Song and Bai Zhang collected the data. Qinghong Wang and Hongmei Qi analyzed the data. Zhen Song, and Na Yang drafted the manuscript. All authors have reviewed and approved the final version of the manuscript before submission.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethical approval

The retrospective nature of this study was reviewed and approved by the Ethics Committee of Jinan People's Hospital (Approval No. 2024-LW-106). The approval was granted with consideration of the ethical standards pertaining to the use of existing data.

Competing interests

The authors declare no competing interests.

Consent to participate

As this study is retrospective and involves the analysis of existing data, consent to participate was not applicable. However, the study was conducted in compliance with the principles of the Declaration of Helsinki, and any necessary waivers were obtained from the Ethics Committee.

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