

# Dynamic carotid Doppler characteristics associated with spinal anesthesia-induced hypotension during cesarean delivery: a two-center prospective exploratory study

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## Research Article

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**Dynamic carotid Doppler characteristics associated with spinal anesthesia-induced hypotension during cesarean delivery: a two-center prospective exploratory study**

**Abstract**

**Background**

Spinal anesthesia-induced hypotension (SAIH) is common during cesarean delivery, but noninvasive methods for assessing maternal hemodynamic vulnerability before anesthesia remain limited. This study explored the relationship between preanesthetic carotid Doppler characteristics, including conventional indices, positional responses, and a waveform-derived dynamic index, and the occurrence of SAIH.

**Methods**

This prospective, two-center exploratory observational study included 101 parturients undergoing elective cesarean delivery under spinal anesthesia. At the first center, 61 participants constituted the primary exploratory cohort and 19 subsequently recruited participants formed a temporal exploratory cohort. A further 21 participants were prospectively recruited at a second center as an independent-center exploratory cohort. Bilateral carotid artery and middle cerebral artery Doppler spectra were obtained before anesthesia in the supine and left lateral positions. Conventional Doppler variables, positional changes, and a waveform-derived carotid blood flow dynamic index (CBDI) were evaluated. L2-regularized logistic regression was additionally used for

exploratory multivariable modeling.

## **Results**

SAIH occurred in 28 of 61 participants (45.9%) in the primary exploratory cohort, 4 of 19 (21.1%) in the temporal exploratory cohort, and 5 of 21 (23.8%) in the independent-center exploratory cohort. Carotid-derived features showed more pronounced between-group differences than middle cerebral artery-derived features. Among the evaluated variables, lateral-position carotid CBDI showed the largest effect size. An exploratory five-feature carotid model yielded area under the receiver operating characteristic curve values of 0.817 and 0.750 in the temporal and independent-center exploratory cohorts, respectively. Given the small number of hypotensive events in these cohorts, these performance estimates should be interpreted as preliminary.

## **Conclusions**

Preanesthetic carotid Doppler characteristics differed between parturients with and without subsequent SAIH, and dynamic and positional carotid measurements may provide complementary information regarding maternal hemodynamic vulnerability. These findings are hypothesis-generating and support further investigation in larger, prospectively designed studies before predictive or clinical application can be considered.

**Keywords:** cesarean delivery; spinal anesthesia-induced hypotension; carotid Doppler ultrasound; maternal hemodynamics; waveform analysis; carotid blood flow dynamic index

## **Background**

Spinal anesthesia-induced hypotension (SAIH) remains common during cesarean delivery despite advances in obstetric anesthesia and the widespread use of prophylactic vasopressor strategies[1, 2]. Maternal hypotension may contribute to nausea, vomiting, dizziness, and reduced uteroplacental perfusion, and severe or prolonged episodes may adversely affect maternal comfort and fetal well-being[1, 3-5]. Identification of patients at increased risk of SAIH before anesthesia could facilitate individualized hemodynamic management and targeted preventive measures[6].

Numerous predictors of SAIH have been investigated, including baseline hemodynamic variables, heart rate variability, ultrasonographic indices of volume status, and invasive waveform-derived parameters[7-11]. However, currently available approaches have several limitations. Some require invasive monitoring that is not routinely justified in elective cesarean delivery, whereas others rely on static physiological measurements that may not adequately reflect maternal compensatory reserve. Reported predictive performance has also been inconsistent, and a practical, noninvasive preanesthetic assessment method has yet to be established[12].

Carotid Doppler ultrasonography has emerged as a promising tool for noninvasive hemodynamic assessment[13, 14]. Previous studies have shown that carotid Doppler variables, including flow time and velocity–time integral, correlate with stroke volume, cardiac output, and fluid responsiveness[14-17]. In late pregnancy, positional changes substantially influence venous return and cardiovascular compensation[18]. Therefore, assessment of carotid hemodynamics in different body positions may provide additional

information regarding maternal circulatory reserve before spinal sympathetic blockade[19-21].

In addition to conventional Doppler variables, dynamic information embedded in the waveform itself may contain physiologically relevant signal that is not fully captured by static velocity- or time-based indices. Data-driven analysis of waveform dynamics has shown promise in other hemodynamic monitoring contexts, but most previous studies have focused on invasive arterial pressure waveforms rather than noninvasive ultrasound-derived flow signals[22]. Whether dynamic carotid waveform features can contribute to preoperative risk stratification for spinal anesthesia-induced hypotension in cesarean delivery remains uncertain.

Accordingly, we conducted a prospective, two-center exploratory observational study to examine the relationship between preanesthetic carotid Doppler characteristics and spinal anesthesia-induced hypotension in parturients undergoing elective cesarean delivery. We evaluated conventional Doppler variables, a waveform-derived carotid blood flow dynamic index, and postural changes between the supine and lateral positions. We also compared carotid-derived characteristics with middle cerebral artery-derived characteristics and performed exploratory multivariable modeling. We hypothesized that carotid Doppler characteristics, particularly those reflecting lateral-position hemodynamics and waveform dynamics, would show more pronounced differences between parturients with and without subsequent hypotension than middle cerebral artery-derived characteristics.

## **2. Methods**

### **2.1 Study design and participants**

This was a prospective, two-center exploratory observational study conducted in two sequential phases. The first phase was conducted at Qilu Hospital of Shandong University between September 2, 2022 and April 5, 2023. The study was approved by the Ethics Committee of Qilu Hospital of Shandong University (KYLL-202205-028-2; September 2, 2022).

At the first center, an initial cohort of 70 participants underwent preanesthetic Doppler assessment. Nine participants were excluded because of missing ultrasound images and/or images of insufficient quality for waveform analysis, leaving 61 participants in the primary exploratory cohort. A subsequent temporal cohort of 19 participants was recruited using the same study protocol, and all 19 were included in the analysis. Thus, a total of 80 participants from the first center were analyzed.

Following completion of the first-center phase and exploratory analysis, a second independent cohort was prospectively recruited at Jinan Maternal and Child Health Hospital between December 3, 2025 and January 20, 2026. This phase was separately approved by the Ethics Committee of Jinan Maternal and Child Health Hospital (KY R-25-051; August 7, 2025). The same eligibility criteria, anesthetic management, ultrasound acquisition protocol, and outcome definitions were applied at both centers. All 21 participants recruited at the second center were included as an independent-center exploratory cohort. This cohort was used to explore the reproducibility and transportability of the findings from the first-center phase rather than as a definitive

external validation cohort.

Eligible participants were aged  $\geq 18$  years, had a singleton pregnancy with a gestational age  $>28$  weeks, and were scheduled for elective cesarean delivery under spinal anesthesia. Exclusion criteria were emergency surgery, coexisting cardiovascular disease, contraindication to spinal anesthesia, American Society of Anesthesiologists physical status III or higher, severe arrhythmia or aortic regurgitation, preoperative infection, and refusal to participate.

Written informed consent was obtained from all participants, and the study was conducted in accordance with the Declaration of Helsinki. As this was an observational study, trial registration was not applicable. Participant flow is shown in Figure 1.

Given the exploratory nature of the study, no formal a priori sample-size calculation was performed. The sample size was determined by the number of eligible participants available during the respective study periods.

## **2.2 Perioperative management and outcome definition**

Routine prophylactic fluid preloading was not performed. Lactated Ringer's solution was administered as co-loading at 10-15 mL/kg/h starting at the induction of spinal anesthesia. Combined spinal-epidural anesthesia was performed in the lateral decubitus position using a midline approach at the L3-L4 or L4-L5 interspace. Intrathecal 0.5% ropivacaine (2.5-3.0 mL) was administered according to maternal height and weight, and an epidural catheter was placed for rescue supplementation if required.

The primary outcome was the occurrence of spinal anesthesia-induced hypotension

(SAIH) after induction of spinal anesthesia and before fetal delivery. This observation window was selected to capture hemodynamic changes temporally related to spinal sympathetic blockade while minimizing potential postpartum influences. Baseline blood pressure was defined as the mean of three consecutive noninvasive blood pressure measurements obtained at 1-min intervals after the participant had rested calmly in the operating room. During the peri-induction period, blood pressure was measured every 1-3 min according to routine clinical monitoring.

SAIH was considered present if any of the following criteria were met: (1) a decrease in systolic blood pressure of  $>30\%$  from baseline; (2) a decrease in mean arterial pressure of  $>20\%$  from baseline; or (3) an absolute systolic blood pressure  $<90$  mmHg and/or mean arterial pressure  $<65$  mmHg. Participants were classified into the hypotension group (HG) or non-hypotension group (NHG) according to the occurrence of the primary outcome.

### **2.3 Ultrasound acquisition**

Standard monitoring, including systolic blood pressure, diastolic blood pressure, mean arterial pressure, and heart rate, was established on arrival in the operating room. Ultrasound examinations were performed using a Mindray TE9 ultrasound system (Mindray, Shenzhen, China). A 4-12 MHz linear-array transducer was used for common carotid artery (CA) assessment, and a 2.5 MHz phased-array transducer was used for middle cerebral artery (MCA) assessment.

Ultrasound examinations were performed by trained operators following a standardized acquisition protocol. Some examinations across the two study phases were performed by the same operator, whereas others were performed by different trained operators at the participating centers. Before data collection, operators were trained to standardize vessel identification, probe positioning, Doppler sampling, and waveform recording procedures.

Bilateral CA and MCA Doppler spectra were obtained before anesthesia in two body positions: the supine position (T0) and the left lateral position (T1). Measurements at T1 were obtained after a 5-min stabilization period in the left lateral position. For waveform analysis, segments containing at least three consecutive cardiac cycles of adequate quality were selected.

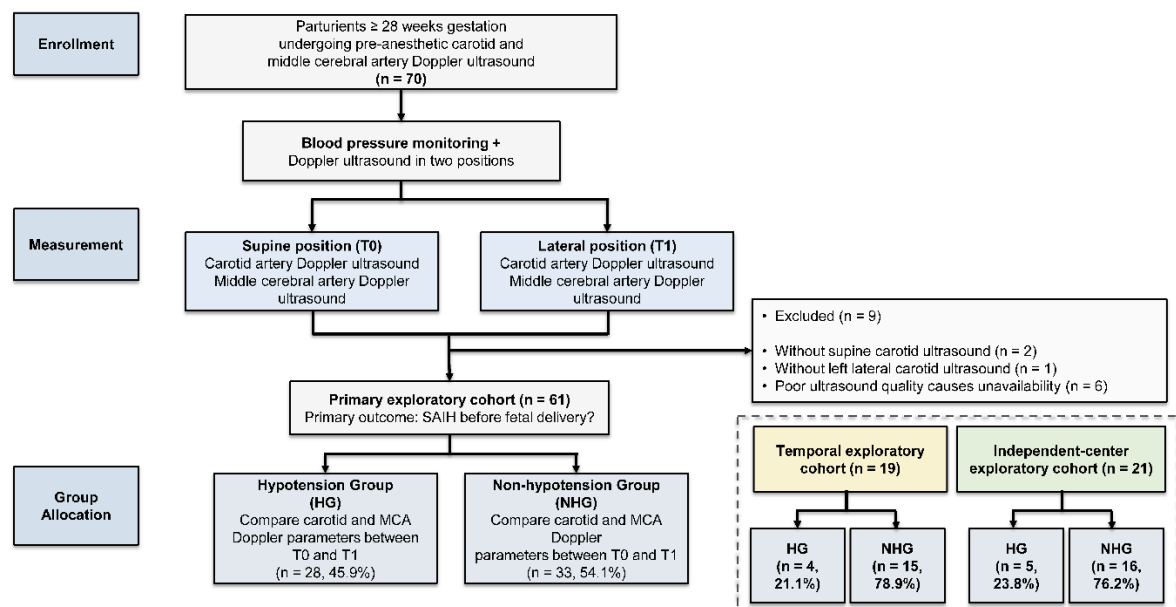


**Fig. 1. Participant flow through the two sequential study phases.** At the first center, 70 participants underwent preanesthetic Doppler assessment in the initial cohort; 9 were excluded because of missing ultrasound images and/or images of insufficient quality for waveform analysis, leaving 61 participants in the primary exploratory cohort. A subsequent temporal cohort of 19 participants was recruited and all were included, resulting in 80 analyzed participants at the first center. At the second center, 21

participants were prospectively recruited and all were included as an independent-center exploratory cohort. A total of 101 participants were included in the final analysis.

## 2.4 Waveform processing and derivation of Doppler features

The ultrasound blood flow data processing workflow is shown in Figure 2. Raw Doppler images were exported in DICOM format and processed using a custom waveform analysis pipeline. Spectral envelopes were extracted by morphological envelope detection, denoised using wavelet filtering, and resampled to 500 Hz by interpolation. Automated key-point detection was then applied to derive conventional Doppler variables, including peak systolic velocity, end-diastolic velocity, peak diastolic velocity, mean velocity, velocity-time integral, flow time, corrected flow time using the Bazett and Wodey formulas, acceleration time, deceleration time, systolic/diastolic ratio, resistive index, and pulsatility index.

To characterize dynamic flow properties beyond conventional static Doppler variables, a hypothesis-generating computational feature called carotid blood flow dynamic index (CBDI) was derived from the carotid waveform. The one-dimensional flow tracing signal was first normalized to the range of  $[-1, 1]$  and then reconstructed into a 3-dimensional phase space  $x(t) = [s(t), s(t + \tau), s(t + 2\tau)]^T$  using a fixed delay parameter  $\tau = 10$  sampling points, where  $s(t)$  denotes the normalized blood flow signal. The reconstructed trajectory was modeled as a nonlinear dynamic system,  $\dot{x} = f(x)$ . For each waveform, a 3-dimensional radial basis function (RBF) neural network was constructed according to deterministic learning theory, using Gaussian basis functions with a neuron spacing of 0.1 and an activation radius of 0.08. After iterative

weight updating to convergence, the network output,  $\hat{f}(x) = W^T S(x)$ , was used to estimate the instantaneous dynamic variation of the reconstructed trajectory. Fourier spectral analysis was then applied separately to the 3 dynamic components, their amplitude spectra were averaged, and an exponential function was fitted to the mean amplitude spectrum. The fitted exponential coefficient  $b$  was defined as CBDI. CBDI was treated as an exploratory waveform-derived feature.

## 2.5 Feature construction and exploratory modeling

Candidate features included conventional Doppler variables and CBDI from the carotid artery and middle cerebral artery at T0 and T1, postural percentage changes from T0 to T1, and demographic variables including age and body mass index. Postural change was calculated as:

$$\Delta\% = \frac{T1-T0}{T0} \times 100\%$$

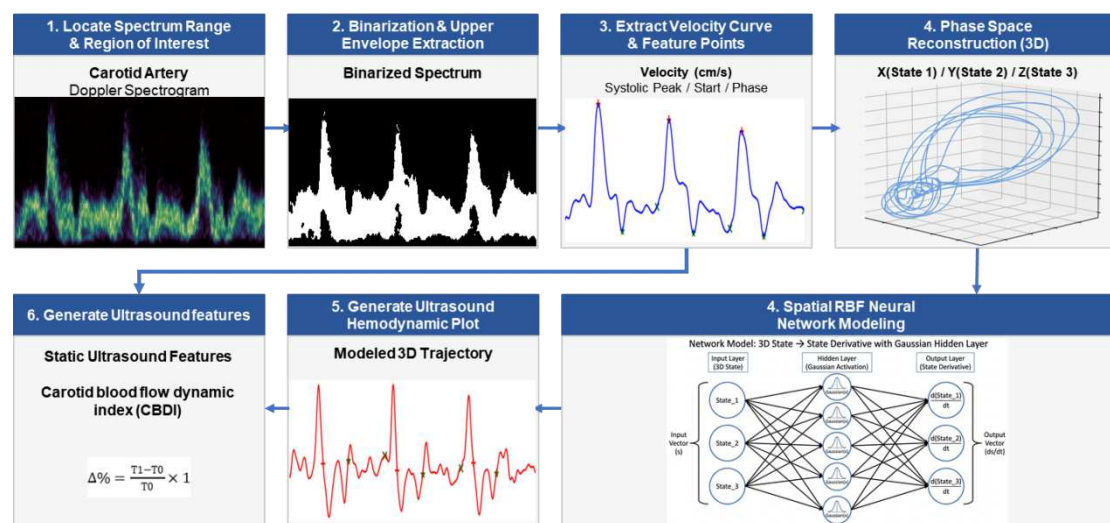


Fig.2 Doppler image of carotid artery blood flow spectrograms, flow waveforms, and key points.

Continuous variables were standardized using z-score transformation. Given the limited sample size and risk of overfitting, logistic regression with L2 regularization was selected as the primary modeling approach. Tree-based models were evaluated for exploratory comparison only (Details are provided in Supplementary Table S1). Feature selection and hyperparameter tuning were restricted to the primary exploratory cohort and included univariate filtering, vascular territory restriction, and correlation-based redundancy removal. To avoid information leakage, feature selection was performed within each cross-validation fold (nested cross-validation). Specifically, for each of the 5 outer folds, univariate filtering and correlation-based redundancy removal were conducted using only the training folds, and the selected features were then applied to the held-out fold.

## **2.6 Statistical analysis and exploratory model assessment**

Continuous variables are presented as mean  $\pm$  standard deviation or median (interquartile range), as appropriate, and were compared using the independent-samples t test or Mann-Whitney U test. Categorical variables are presented as number (percentage) and were compared using the chi-square test or Fisher exact test, as appropriate. The Benjamini-Hochberg false discovery rate procedure was applied as a supplementary control for multiple comparisons in univariate feature screening.

Model discrimination was assessed using the area under the receiver operating characteristic curve, with 95% confidence intervals estimated by 1000 bootstrap resamples. Calibration was described using the Brier score and calibration plots.

Threshold-based classification metrics were also calculated to explore potential operating characteristics of the five-feature logistic regression model; these analyses were considered exploratory because of the limited number of outcome events in the temporal and independent-center exploratory cohorts. All analyses were performed using Python 3.9, and a 2-sided  $p < .05$  was considered statistically significant.

During manuscript preparation, the authors used ChatGPT (OpenAI) for English-language editing and organizational suggestions. All AI-assisted content was reviewed and revised by the authors, who take full responsibility for the final manuscript.

### **3. Results**

#### **3.1 Study Population**

A total of 101 parturients were included in the study. At Qilu Hospital of Shandong University, 61 participants constituted the primary exploratory cohort and 19 subsequently recruited participants constituted the temporal exploratory cohort. An additional 21 participants recruited at Jinan Maternal and Child Health Hospital constituted the independent-center exploratory cohort. Spinal anesthesia-induced hypotension occurred in 28 of 61 participants (45.9%) in the primary exploratory cohort, 4 of 19 (21.1%) in the temporal exploratory cohort, and 5 of 21 (23.8%) in the independent-center exploratory cohort.

Baseline maternal and obstetric characteristics are summarized in Table 1 and Supplementary Tables S2 and S3. Most baseline variables were comparable across

cohorts and between the hypotension and nonhypotension groups, although some inter-cohort differences were present in body weight, height, and neonatal head circumference. Given the limited cohort sizes, these comparisons were interpreted descriptively.

Table 1. Baseline characteristics of the three study cohorts

| Characteristic                  | Primary<br>exploratory<br>cohort<br>(n=61) | Temporal<br>exploratory<br>cohort<br>(n=19) | Independent-<br>center<br>exploratory<br>cohort<br>(n=21) | Statistical<br>Test | P-value |
|---------------------------------|--------------------------------------------|---------------------------------------------|-----------------------------------------------------------|---------------------|---------|
| Gestational age<br>(days)       | 270.5<br>(266.75-<br>277.25)               | 270.0<br>(264.50-<br>276.00)                | 272.0 (266.00-<br>275.00)                                 | Kruskal-<br>Wallis  | 0.818   |
| Height(cm)                      | 161.0 ± 5.9                                | 164.4 ± 6.5                                 | 159.8 ± 4.2                                               | ANOVA               | 0.033*  |
| Weight(kg)                      | 70.0 (66.50-<br>78.00)                     | 79.0 (74.50-<br>86.75)                      | 75.0 (70.00-<br>79.50)                                    | Kruskal-<br>Wallis  | 0.048*  |
| BMI (kg/m <sup>2</sup> )        | 27.5 (25.21-<br>30.74)                     | 30.1 (26.95-<br>31.22)                      | 29.0 (27.34-<br>31.52)                                    | Kruskal-<br>Wallis  | 0.194   |
| Gestational<br>weight gain (kg) | 12.5 (10.00-<br>15.00)                     | 13.0 (10.00-<br>15.00)                      | 15.0 (15.00-<br>17.00)                                    | Kruskal-<br>Wallis  | 0.072   |
| Neonatal birth                  | 3376.7 ±                                   | 3370.0 ±                                    | 3311.9 ± 337.5                                            | ANOVA               | 0.811   |

|               |                     |                     |                     |                |           |
|---------------|---------------------|---------------------|---------------------|----------------|-----------|
| weight (g)    | 359.4               | 553.0               |                     |                |           |
| Neonatal head |                     |                     |                     |                |           |
| circumference | 35.0 (34.00-36.00)  | 35.0 (34.00-36.00)  | 34.0 (32.00-34.00)  | Kruskal-Wallis | <0.001*** |
| (cm)          |                     |                     |                     |                |           |
| SBP (mmHg)    | 118.0 (111.0-127.0) | 120.0 (118.0-121.0) | 120.0 (112.0-125.0) | Kruskal-Wallis | 0.619     |
| DBP (mmHg)    | 76.1 ± 9.5          | 79.8 ± 9.5          | 75.6 ± 8.0          | ANOVA          | 0.262     |
| MAP (mmHg)    | 90.4 ± 8.8          | 93.9 ± 8.9          | 90.1 ± 7.7          | ANOVA          | 0.260     |
| HR (bpm)      | 90.0 (78.0-96.0)    | 90.0 (81.0-102.5)   | 85.0 (81.0-95.0)    | Kruskal-Wallis | 0.791     |

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*Note: Data are presented as mean ± standard deviation for normally distributed variables, or median (interquartile range) for non-normally distributed variables. Normality was assessed using the Shapiro-Wilk test. For three-group comparisons, ANOVA was used when all groups were normally distributed and homoscedastic (Levene test); otherwise, the Kruskal-Wallis test was used. \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ .*

### 3.2 Univariate Analysis of Doppler-derived features

Statistical analysis of the 92 candidate features in the primary exploratory cohort (shown in Supplementary Figure 1) revealed that feature signals derived from the carotid artery exhibited greater statistical significance than those from the middle cerebral artery.

In the primary exploratory cohort, 5 carotid features showed significant between-group differences on univariate analysis: lateral carotid CBDI, supine carotid peak diastolic velocity, supine carotid corrected flow time by the Bazett formula, supine carotid

corrected flow time by the Wodey formula, and supine carotid velocity-time integral, as shown in Table 2. Among these, lateral carotid CBDI showed the largest separation between groups and the largest effect size. By contrast, no middle cerebral artery-derived feature showed a significant between-group difference.

Although some postural change features showed directional trends, none showed a consistently robust association with SAIH in univariate analysis. These findings supported prioritizing carotid-derived features in subsequent exploratory modeling.

MCA-related features showed similar postural changes in both the hypotension and non-hypotension groups, whereas CA-related features exhibited different directions of change between the two groups (Table 2 and Supplementary Table S4). However, although these features showed directional trends, none showed a consistently robust association with SAIH in univariable analysis. These findings support prioritizing carotid-derived features in subsequent exploratory modeling.

Table 2. Selected Doppler-derived features associated with hypotension in the primary exploratory cohort

| Feature              | <i>p</i> -value | Hypotension        | Non-hypotension | Cohen's <i>d</i> | Location   |
|----------------------|-----------------|--------------------|-----------------|------------------|------------|
|                      |                 | group<br>(Mean±SD) | group (Mean±SD) |                  |            |
| CA_Lateral_cbdi      | 0.0056*         | 50.15±13.53        | 60.30±14.98     | −0.71            | Lateral CA |
| CA_Supine_D_peak     | 0.0097*         | 30.65±5.56         | 34.68±6.42      | −0.67            | Supine CA  |
| CA_Supine_FTc_Bazett | 0.0189*         | 0.30±0.09          | 0.33±0.06       | −0.39            | Supine CA  |
| CA_Supine_FTc_Wodey  | 0.0301*         | 0.31±0.10          | 0.34±0.07       | −0.35            | Supine CA  |

|               |         |                |              |         |           |
|---------------|---------|----------------|--------------|---------|-----------|
| CA_Supine_VTI | 0.0481* | 15.85±6.05     | 18.71±4.88   | -0.52   | Supine CA |
| CA_Δcbdi      | 0.1187  | -1.1 ± 24.8    | 13.5 ± 37.2  | -0.4531 | CA prcf   |
| MCA_ΔDT       | 0.5598  | -166.2 ± 809.0 | 58.7 ± 212.8 | -0.4009 | MCA prcf  |
| CA_ΔPSV       | 0.2781  | 5.5 ± 21.4     | -2.1 ± 22.3  | +0.3482 | CA prcf   |
| CA_ΔD_peak    | 0.4223  | 9.3 ± 46.1     | -2.2 ± 27.4  | +0.3108 | CA prcf   |
| CA_ΔMV        | 0.2013  | 5.7 ± 17.4     | -0.6 ± 22.7  | +0.3070 | CA prcf   |

*Note: MWU, Mann–Whitney U test; CA, carotid artery; MCA, middle cerebral artery; SD, standard deviation.*

*CA PRCF: the abbreviation for CA positional relative change feature, which describes the relative variation characteristics of CA measured in lateral position compared with supine position.*

*MCA PRCF: the abbreviation for MCA positional relative change feature, which describes the relative variation characteristics of MCA measured in lateral position compared with supine position.*

### 3.3 Exploratory multivariable modelling

Given the limited sample size and the risk of overfitting, logistic regression was used as the primary exploratory multivariable modeling approach. Tree-based models were evaluated for exploratory comparison.

Among the carotid-focused models, a parsimonious 5-feature logistic regression model incorporating supine carotid peak diastolic velocity, supine carotid corrected flow time by the Bazett formula, supine carotid corrected flow time by the Wodey formula, supine carotid velocity-time integral, and lateral carotid CBDI was selected for exploratory assessment. This model yielded a cross-validation AUC of 0.765 in the primary exploratory cohort, an AUC of 0.817 in the temporal exploratory cohort, and an AUC of 0.750 in the independent-center exploratory cohort (as shown in Supplementary Table S5). All features retained in the model had negative standardized coefficients,

indicating that higher values corresponded to a lower estimated probability of SAIH, as shown in Figure 3.

A broader 11-feature carotid logistic regression model (detailed features were provided in Supplementary Table S6 and Supplementary Figure S2) was also evaluated as a sensitivity analysis and showed similar overall discrimination, with a cross-validation AUC of 0.786, an AUC of 0.783 in the temporal exploratory cohort and an AUC of 0.800 in the independent-center exploratory cohort. Because both models were derived and evaluated in small cohorts, these estimates should be interpreted as preliminary.

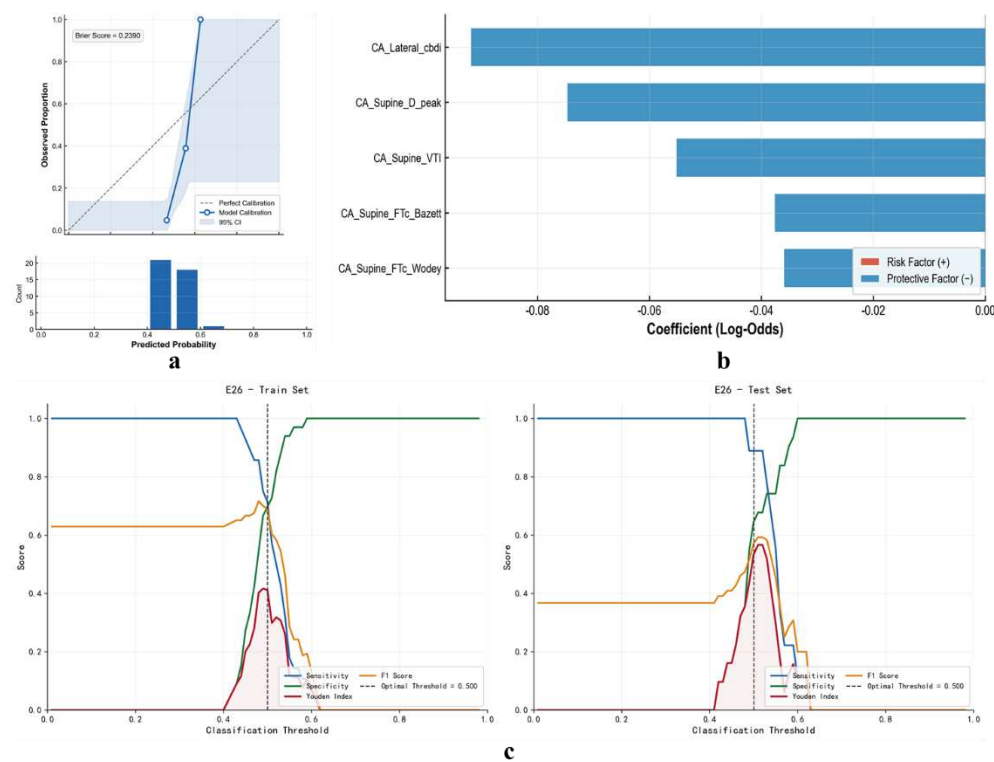


**Fig.3.** Calibration (a), standardized feature coefficients (b), and threshold analysis (c) of the five-feature logistic regression model in the temporal and independent-center exploratory cohorts. All five features exhibit negative standardized coefficients, indicating a uniform physiological rationale: lower feature values consistently correspond to a higher risk of hypotension.

### 3.4 Comparison of modeling approaches

Exploratory comparisons were performed among logistic regression, random forest, gradient boosting machine, and XGBoost using the carotid feature set, as detailed in Table 3. Tree-based models achieved very high apparent performance in the primary exploratory cohort but showed lower performance in the exploratory evaluation cohorts, consistent with overfitting in this small-sample setting. In contrast, logistic regression showed more consistent discrimination across cross-validation and the two exploratory evaluation cohorts and was therefore retained for exploratory interpretation.

Table 3. Exploratory comparison of modeling approaches using carotid-derived features

| Model               | CV AUC | Train AUC | Temporal<br>AUC | Independent-center<br>exploratory cohort AUC |
|---------------------|--------|-----------|-----------------|----------------------------------------------|
| Logistic Regression | 0.786  | 0.817     | 0.783           | 0.800                                        |
| Random Forest       | 0.743  | 0.995     | 0.700           | 0.750                                        |
| Gradient Boosting   | 0.642  | 0.999     | 0.567           | 0.750                                        |
| XGBoost             | 0.639  | 1.000     | 0.600           | 0.750                                        |

### 3.5 Calibration and exploratory threshold analysis

As shown in Figure 3, calibration was assessed descriptively using the calibration plots. Given the limited number of events in the temporal and independent-center exploratory cohorts, calibration estimates were considered preliminary.

Exploratory threshold-based analyses showed that classification performance varied substantially across probability cutoffs and between the two exploratory cohorts (as

shown in Figure 3 and Supplementary Table S7). In general, lower thresholds increased sensitivity at the cost of very low specificity, whereas higher thresholds improved specificity but markedly reduced sensitivity. A probability threshold of 0.50 provided a relatively more balanced operating point in the exploratory analyses, but threshold-specific performance remained unstable because the temporal and independent-center exploratory cohorts contained only 4 and 5 hypotensive events, respectively. Accordingly, no clinically actionable threshold can be recommended on the basis of the present data.

Across ablation analyses (Supplementary Table S8), carotid-based models consistently outperformed middle cerebral artery-only models. The middle cerebral artery-only model showed poor discrimination, with performance in the exploratory evaluation cohorts near or below chance level. Models combining supine and lateral carotid features generally performed better than single-timepoint models, supporting the complementary contribution of baseline and postural-response information.

## **Discussion**

In this two-center prospective exploratory observational study, preoperative carotid Doppler-derived features were associated with spinal anesthesia-induced hypotension in parturients undergoing elective cesarean delivery. Across exploratory analyses, carotid-derived variables provided better discrimination than middle cerebral artery-derived variables, and models incorporating both supine and lateral measurements

generally showed higher discrimination than single-position models. Among the exploratory variables, lateral carotid CBDI exhibited the largest effect size, suggesting that waveform dynamics may contain information beyond conventional Doppler parameters.

Spinal anesthesia-induced hypotension remains common during cesarean delivery despite contemporary preventive strategies. Accurate preoperative risk stratification remains challenging, and currently available approaches often rely on static physiological measurements or invasive monitoring. In this context, carotid Doppler assessment is attractive because it is noninvasive, rapidly obtainable, and may provide a closer surrogate of central hemodynamics than peripheral vascular measurements. An important observation was the relatively better discrimination provided by carotid-derived variables compared with middle cerebral artery-derived variables. Several mechanisms may explain this finding. Cerebral blood flow is influenced by autoregulatory processes that may buffer changes in systemic hemodynamics, whereas carotid flow patterns may more directly reflect preload reserve and circulatory compensation. Preservation of cerebral autoregulation during anesthesia has been demonstrated in previous studies and may partly explain the limited discrimination observed with middle cerebral artery-derived variables[23, 24]. CBDI was introduced as an exploratory feature intended to summarize waveform dynamics beyond conventional Doppler variables. In the primary exploratory cohort, lateral carotid CBDI exhibited the largest effect size among candidate variables.

Although this observation does not establish CBDI as a validated biomarker, it suggests that dynamic characteristics embedded in carotid waveforms may contain information not fully captured by conventional velocity- or time-based indices.

Additional studies are required to evaluate the reproducibility, standardization, and robustness of this feature across operators, devices, and acquisition conditions, as measurement variability and device-related differences remain important challenges in hemodynamic monitoring[25, 26].

From a modeling perspective, logistic regression provided more stable performance estimates than tree-based approaches. More complex models achieved high apparent performance in the primary exploratory cohort but showed lower performance in the exploratory evaluation cohorts, suggesting overfitting in this small-sample setting.

Similar concerns regarding optimism and instability of prediction models, particularly those based on machine learning approaches, have been emphasized in recent methodological studies[27-30].

Several limitations merit emphasis. First, this exploratory study included a modest sample size, and the temporal and independent-center exploratory cohorts contained only four and five outcome events, respectively. The small number of outcome events in these cohorts limits the precision and stability of model performance estimates.

Second, feature selection and model development were exploratory and data-driven, increasing the possibility of optimistic bias. Third, blood pressure was measured intermittently rather than continuously, which may have resulted in underdetection of transient hypotensive episodes. Fourth, potentially relevant perioperative variables,

including sensory block height and vasopressor exposure, were not incorporated.

Finally, interobserver reproducibility and test–retest repeatability of CDBI were not assessed and require dedicated investigation. The generalisability of the findings may also be limited by the modest sample size, recruitment from two centers within the same region, and potential operator- and device-related variability.

Accordingly, the present findings do not support the use of the proposed model to guide vasopressor administration or alter routine clinical management. Rather, they provide preliminary evidence that dynamic carotid Doppler characteristics may contain useful information for future preanesthetic risk stratification. Larger prespecified multicenter studies are required to confirm these observations, establish reproducible measurement procedures, evaluate model calibration more rigorously, and determine whether clinically meaningful decision thresholds exist. Updated reporting recommendations for prediction models may facilitate future development and validation efforts.

## **Conclusions**

In this two-center prospective exploratory observational study, preoperative carotid Doppler-derived features, including a dynamic waveform-based index, were associated with spinal anesthesia-induced hypotension during elective cesarean delivery. Carotid-derived features provided better discrimination than middle cerebral artery-derived features in exploratory analyses, and combined supine and lateral assessments appeared to provide complementary information. These findings support further investigation of

dynamic carotid Doppler analysis as a noninvasive approach to preanesthetic risk stratification; however, they are insufficient to support clinical implementation at this stage.

### **List of abbreviations**

AUC: Area under the receiver operating characteristic curve

CA: Carotid artery

CBDI: Carotid blood flow dynamic index

CV: Cross-validation

DBP: Diastolic blood pressure

DICOM: Digital Imaging and Communications in Medicine

FTc: Corrected flow time

HG: Hypotension group

HR: Heart rate

MAP: Mean arterial pressure

MCA: Middle cerebral artery

NHG: Non-hypotension group

RBF: Radial basis function

SAIH: Spinal anesthesia-induced hypotension

SBP: Systolic blood pressure

VTI: Velocity-time integral

## **Declarations**

### **Ethics approval and consent to participate**

The first-center phase of the study was approved by the Ethics Committee of Qilu Hospital of Shandong University (KYLL-202205-028-2; September 2, 2022). The second-center phase was approved by the Ethics Committee of Jinan Maternal and Child Health Hospital (KY R-25-051; August 7, 2025). Written informed consent was obtained from all participants before enrollment. The study was conducted in accordance with the Declaration of Helsinki.

### **Consent for publication**

Not applicable.

### **Availability of data and materials**

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

### **Competing interests**

The authors declare that they have no competing interests.

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### **Authors' contributions**

CLW, CW, WLL, QHS, PD, BY, CQZ, NY, DW, and GHC contributed to the conceptualization of the study. CLW, WLL, PD, BY, DW, and GHC contributed to data curation and investigation. CW, QHS, CQZ, and NY performed the formal analysis. CLW, CW, WLL, QHS, and NY contributed to methodology. CLW was responsible for project administration, resources, and supervision. CW and QHS contributed to software development. CLW, CW, QHS, and NY contributed to validation, and QHS and WLL contributed to visualization. WLL, QHS, PD, BY, NY, and GHC drafted the original manuscript. CLW, CW, WLL, QHS, CQZ, and DW reviewed and edited the manuscript. All authors read and approved the final manuscript.

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