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ORIGINAL RESEARCH

Development and Validation of a 7-Day Postoperative Sleep Disturbance Predictive Nomogram in Non-Cardiovascular Surgical Patients: A Prospective Cohort Study of 3851 Adults

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Purpose: This prospective study developed and validated a nomogram to assess the likelihood of early postoperative sleep disturbance (PSD occurring within 7 days after surgery) following non-cardiovascular surgical procedures.

Participants and Study Protocol: The study enrolled 3851 patients receiving non-cardiac procedures recruited in the First Affiliated Hospital of USTC from April 2024 to December 2024. These 3851 patients were randomly allocated into training cohort (n=2682, 70%) and validation cohorts (n=1169, 30%). Variable selection was performed using least absolute shrinkage and selection operator (LASSO) regression, followed by logistic regression analyses (univariate and multivariate) to identify independent risk factors. Based on these identified factors, a prognostic nomogram was developed and underwent comprehensive validation, including receiver operating characteristic (ROC) curve assessment, calibration plotting, and decision curve analysis (DCA) to evaluate its discriminative performance and clinical applicability.

Results: About 37.7% of patients developed PSD within the first 7 postoperative days, with 12.1% persisting at 1 month after surgery. The analysis revealed ten independent PSD risk factors (all $p < 0.05$): female, higher ASA class (III), moderate-to-severe anemia, dissatisfaction with ward environment, anxiety, non-use of dexmedetomidine, older age, extended anesthesia time, lower sufentanil doses and higher postoperative NRS score. The nomogram incorporating these ten predictors demonstrated excellent discriminative performance, with AUC values of 0.826 (95% CI: 0.810–0.843) in the training cohort and 0.822 (95% CI: 0.797–0.847) in the validation cohort, complemented by optimal calibration.

Conclusion: The prediction model incorporating ten routinely available clinical variables demonstrated excellent predictive accuracy and good calibration, highlighting its clinical utility in identifying short-term high-risk PSD patients (within 7 days postoperatively). This tool facilitates timely interventions to reduce PSD incidence and improve recovery outcomes.

Keywords: risk factors, machine learning, dexmedetomidine, anesthesia, nomograms

Introduction

Postoperative sleep disturbances (PSD) represent a prevalent complication characterized by dysregulated sleep-wake patterns in surgical patients, manifesting through functional cerebral disturbances and autonomic hyperactivity that collectively impair sleep quality. This condition typically presents with prolonged sleep latency, sleep fragmentation, and impaired sleep quality.[1]

Several previous investigations have reported the incidence of PSD ranging from 30% to 80%,[2–4] and more than 10% of patients continue to experience these symptoms for at least 6 months with potential for longer duration.[5] Postoperative sleep quality are not routinely assessed, and even when sleep disturbances occur, they are often dismissed as part of normal recovery.

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PSD often coexists with pain, depression, or delirium, complicating clinical recognition. Consequently, PSD remains overlooked by patients, families, and medical staff. However, persistent sleep deprivation triggers multiple adverse consequences: increased stress responses, hyperalgesia, cognitive decline, and cardiovascular instability – all significantly impairing recovery.[6–10] Moreover, PSD shows strong associations with chronic post-surgical pain development while elevating fall risk and potentially reducing bone density.[11]

The etiology of PSD is multifactorial, encompassing advanced age, surgical trauma, anesthetic agents, inflammatory responses, psychological factors, postoperative pain, environmental disturbances such as noise, and nursing interventions.[12–14] Typically, PSD results from complex interactions among these contributing elements. Current management of PSD incorporates a multimodal approach, including pharmacotherapy (dexmedetomidine, zolpidem, melatonin, and esketamine), ward environment enhancement and adoption of Cognitive Behavioral Therapy for Insomnia (CBT-I).[15–18]

While some predictive models for PSD have been investigated, current studies remain constrained by small sample sizes and procedure-specific designs like spinal surgeries,[19,20] requiring further validation through larger-scale studies. This study aimed to develop and validate a predictive model for PSD in non-cardiovascular surgical patients, with the purpose of enabling early identification of high-risk individuals and guiding timely, targeted interventions to optimize sleep quality and postoperative recovery.

Material and Study Protocol

This prospective cohort study received ethical approval from the First Affiliated Hospital of USTC (Hefei, Anhui province, China) on 10 March, 2024 (No.2024-KY096). Prospective registration of this study was completed in the Chinese Clinical Trial Registry (ChiCTR 2400081957). It enrolled adult patients who underwent surgery with general anesthesia in the First Affiliated Hospital of USTC between April and December 2024. The study complied with the ethical principles of the Declaration of Helsinki, and written informed consent was acquired from all participants.

The study enrolled subjects according to these inclusion criteria: adult patients undergoing non-cardiovascular surgical procedures with general anesthesia, who were mentally competent to provide written informed consent.

Exclusion criteria included: (1) with pre-existing poor sleep quality as determined by Pittsburgh Sleep Quality Index (PSQI, authorized use licensed for this study) score ≥7; (2) duration of anesthesia less than 1 hour or exceeding 8 hours. (3) Regular use of sleep aids during perioperative period; (4) postoperatively transferred to the intensive care unit (ICU); (5) received brain surgery; Participants were consecutively enrolled without randomization.

Clinical Characteristics of All Patients

Thirty potential variables were analyzed in the study, categorized as:

Preoperative Factors

Baseline characteristics: Sex, age, education attainment, body mass index (BMI), preoperative night's sleep quality and history of cigarette use; Medical history: Hypertension, diabetes mellitus, cardiac disease, obstructive sleep apnea–hypopnea syndrome (OSAHS), anemia, history of tumor, surgical history, depression and anxiety; Clinical metrics: ASA physical status, ward environment satisfaction, type of surgery.

Intraoperative Factors

Anesthesia duration and induction timing (morning/afternoon); Total opioid administration (sufentanil and remifentanil); Use of dexmedetomidine and sevoflurane.

Postoperative Factors

Time to extubation, patient-controlled intravenous analgesia (PCIA) utilization, postoperative nausea and vomiting (PONV), numeric rating scale (NRS) pain scores, length of hospital stay, and blood transfusion requirements.

Clinical parameters were prospectively recorded during hospitalization, with targeted assessment of PONV and NRS pain scores specifically performed on postoperative day 3. All follow-up data, including assessments conducted at

postoperative day 3, week 1, and month 1, were collected through face-to-face interviews or telephone. All predictive variables and their measurement time points are detailed in Supplementary Table S1.

Assessment of Sleep Disruption

Postoperative sleep quality was measured using the validated PSQI score.[21] It assesses seven components (scored 0–3 each): sleep onset latency, total sleep time, sleep maintenance efficiency, nocturnal awakenings, diurnal impairment, sedative medication use, and self-reported sleep quality.

In the study, PSD was assessed twice (at 7 days and 1 month postoperatively) via face-to-face interviews or telephone follow-ups using the PSQI. A PSQI score ≥7 was operationally defined as PSD. The nomogram was developed based solely on the 7-day postoperative PSD data.

Development and Assessment of the Nomogram

Potential predictors of PSD were initially identified using LASSO regression in the training cohort. Variables with non-zero coefficients selected by LASSO were first evaluated via univariate logistic regression, and those demonstrating significant associations ($p < 0.05$) were subsequently advanced to multivariable logistic regression. To enhance model interpretability and mitigate multicollinearity-though variance inflation factors (VIFs) were not explicitly calculated-LASSO regularization inherently reduced multicollinearity. The final model retained only a limited number of robust predictors, balancing parsimony and predictive performance.

The final predictors were then incorporated into a PSD risk prediction nomogram, developed using the rms package in R software (version 4.3.1). To enhance its clinical utilization, an online dynamic nomogram was created using ShinyApps. The predictive model underwent comprehensive internal validation through the bootstrap resampling method with 1000 iterations.

We evaluated the model's predictive performance through three complementary approaches: (1) predictive discrimination evaluated using the receiver operating characteristic (ROC) curve's area under the curve (AUC); (2) calibration accuracy examined through observed-versus-predicted analyses in both training and validation cohorts; and (3) clinical applicability evaluated using decision curve analysis (DCA) across standardized threshold probabilities. All assessments were implemented separately in the training and validation cohorts to ensure robust evaluation.

Sample Size Considerations

The final model incorporated 30 predictors (continuous, binary, and categorical), totaling 38 candidate predictor parameters. Using the conservative 20 events-per-parameter standard, we required ≥760 PSD events. Given the published PSD incidence rates (30–80%), the minimum sample size was 2534.

Statistical Analysis

Continuous variables following normal distribution were presented as mean ± standard deviation (SD) and analyzed via independent samples *t*-test, while median (interquartile range [IQR]) for non-normally distributed data and assessed using the Mann–Whitney test. Categorical variables were expressed as frequencies (percentages) and compared using the Chi-square test. A two-sided *p*-value threshold of 0.05 was established for determining statistical significance.

Results

The study initially enrolled a total of 4400 patients. A total of 549 patients were excluded from the study based on the following criteria: surgery cancellation (n=7), change in anesthesia mode (n=17), inappropriate anesthesia duration (less than 1 hour or exceeding 8 hours, n=97), unplanned ICU transfer (n=69), reoperation during hospitalization (n=37), and incomplete postoperative follow-up (n=322). Finally, data from 3851 patients were analyzed (Figure 1).

Baseline Clinical Characteristics

Among the 3851 enrolled patients, the median age was 56 years (IQR 46–66), with gender distribution showing 2447 (63.5%) females and 1404 (36.5%) males. These subjects were allocated to a training cohort (n=2682) and a validation

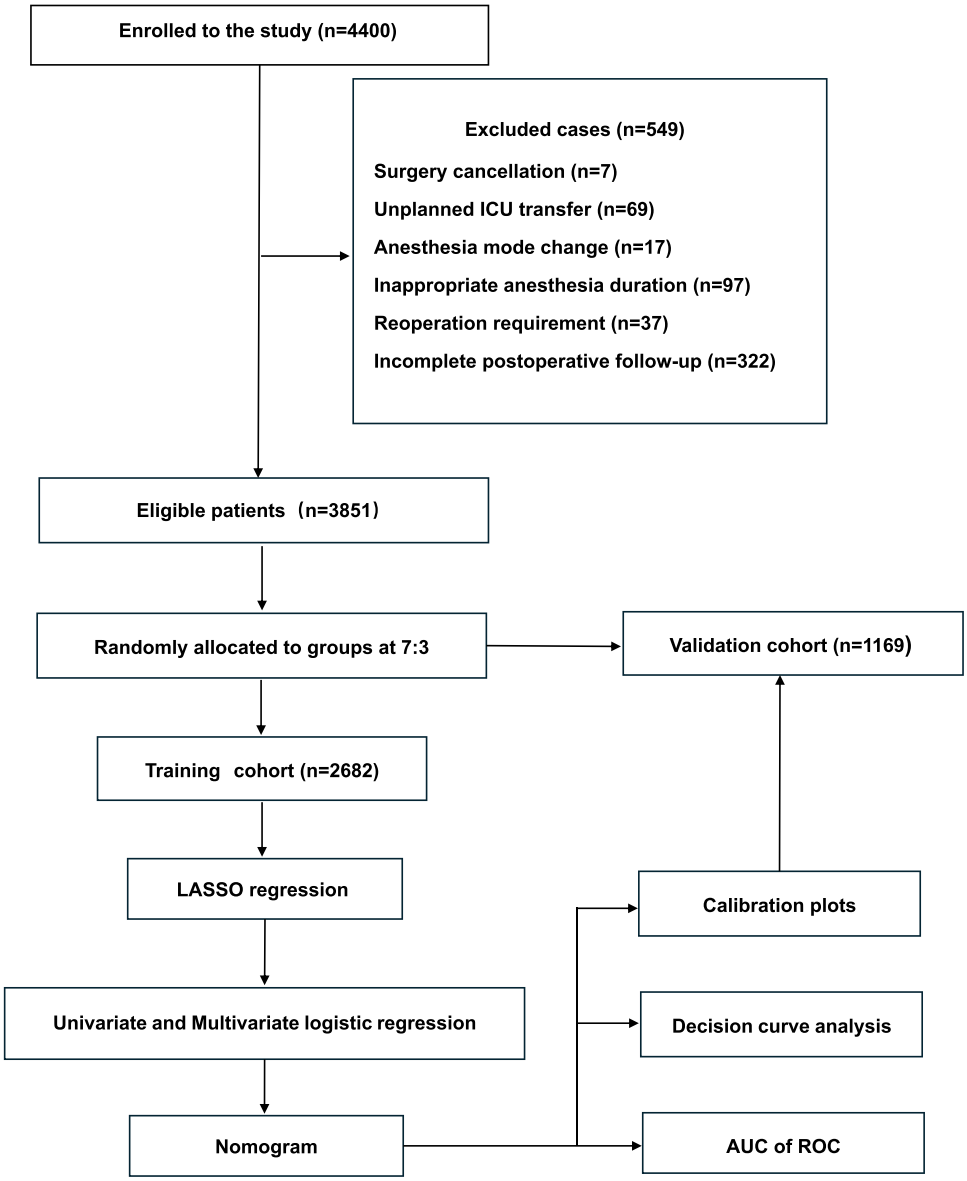

Figure 1 Flow chart of the study.
Abbreviations: ICU, intensive care unit; AUC, area under the curve; ROC, receiver operating characteristic curve; LASSO, Least Absolute Shrinkage and Selection Operator.

cohort (n=1169). About 37.7% of patients reported PSD within the first week, persisting in 12.1% at 1 month after surgery.

In the training cohort, 992 patients (37.0%) were diagnosed with PSD based on PSQI questionnaire, compared to 459 patients (39.3%) in the validation cohort. Table 1 summarizes the baseline characteristics. Baseline characteristics were well balanced between the training and validation cohorts, with no statistically significant differences observed (all $p>0.05$), except for procedure type distribution ($p=0.040$).

Screening for Predictive Factors

LASSO regression selected sixteen predictors with non-zero coefficients from the initial thirty candidate variables (Table 2 and Figure 2). Univariate logistic regression analysis of these predictors initially identified twelve perioperative factors showing significant associations with PSD. Ten predictors remained independently associated with PSD in the multivariate analysis, per the following results: Male ($p<0.001$, odds ratio [OR] 0.53, 95% confidence interval [CI] 0.43–0.66), ASA III ($p=0.021$, OR

Table 1 Participant Characteristics of the Training Cohort and the Validation Cohort

	Total (n=3851)	Training (n=2682)	Validation (n=1169)	P-Value
PSD				
No	2400 (62.3)	1690 (63.0)	710 (60.7)	0.180
Yes	1451 (37.7)	992 (37.0)	459 (39.3)	
Age (years)	56 (46, 66)	56 (46, 66)	56 (46, 66)	0.744
BMI (kg/m^2)	23.0 (22.0,25.0)	23.2 (22.0,25.0)	23.3 (22.1,25.1)	0.348
Length of Stay (d)	5 (5,6)	5 (5,6)	5 (5,6)	0.327
Duration of anesthesia (min)	114 (89,159)	114 (88,158)	116 (90,160)	0.097
Time to tracheal extubation (min)	17 (12,21)	17 (12,21)	17 (12,21)	0.746
Sufentanil (ug)	30 (26,32)	30 (26,32)	30 (26,32)	0.170
Remifentanil (mg)	1.0 (0.9,1.4)	1.0 (0.9,1.4)	1.0 (0.9,1.4)	0.768
NRS score	2 (1,4)	2 (1,4)	2 (1,4)	0.057
Gender				
Female	2447 (63.5)	1713 (63.9)	734 (62.8)	0.521
Male	1404 (36.5)	969 (36.1)	435 (37.2)	
Education				
Lower education	2823 (73.3)	1964 (73.2)	859 (73.5)	0.871
Advanced education	1028 (26.7)	718 (26.8)	310 (26.5)	
ASA				
I	1322 (34.3)	935 (34.9)	387 (33.1)	0.421
II	1261 (32.7)	862 (32.1)	399 (34.1)	
III	1268 (32.9)	885 (33.0)	383 (32.8)	
Smoking				
No	3121 (81.0)	2173 (81.0)	948 (81.1)	0.957
Yes	730 (19.0)	509 (19.0)	221 (18.9)	
Anemia				
No	2467 (64.1)	1703 (63.5)	764 (65.4)	0.534
Light	1081 (28.0)	766 (28.6)	315 (26.9)	
Moderate to Severe	303 (7.9)	213 (7.9)	90 (7.7)	
Surgical history				
No	2617 (68.0)	1841 (68.6)	776 (66.4)	0.167
Yes	1234 (32.0)	841 (31.4)	393 (33.6)	
History of tumor				
No	2101 (54.6)	1482 (55.3)	619 (52.9)	0.186
Yes	1750 (45.4)	1200 (44.7)	550 (47.1)	
Type of surgery*				
Abdominal	552 (14.3)	364 (13.6)	188 (16.1)	
Thoracic	603 (15.7)	419 (15.6)	184 (15.7)	
Head and Neck	560 (14.5)	405 (15.2)	155 (13.3)	
Breast	300 (7.8)	205 (7.6)	95 (8.1)	0.040
Gynaecological	786 (20.4)	556 (20.7)	230 (19.6)	
Urological	441 (11.5)	328 (12.2)	113 (9.7)	
Arthroplasty	419 (10.9)	284 (10.6)	135 (11.6)	
Other Specified	190 (4.9)	121 (4.5)	69 (5.9)	
Sleep disturbance preoperative night				
No	2218 (57.6)	1553 (57.9)	665 (56.9)	0.557
Yes	1633 (42.4)	1129 (42.1)	504 (43.1)	
Satisfaction of ward environment				
No	865 (22.5)	606 (22.6)	259 (22.2)	0.764
Yes	2986 (77.5)	2076(77.4)	910(77.8)	

(*Continued*)

Table 1 (Continued).

	Total (n=3851)	Training (n=2682)	Validation (n=1169)	P-Value
Hypertension				
No	2750 (71.4)	1914 (71.4)	836 (71.5)	0.925
Yes	1101 (28.6)	768 (28.6)	333 (28.5)	
Diabetes				
No	3240 (84.1)	2266 (84.5)	974 (83.3)	0.361
Yes	611 (15.9)	416 (15.5)	195 (16.7)	
Cardiac disease				
No	3361 (87.3)	2337 (87.1)	974 (83.3)	0.694
Yes	490 (12.7)	345 (12.9)	195 (16.7)	
OSAHS				
No	3736 (97.0)	2600 (96.9)	1136 (97.2)	0.694
Yes	115 (3.0)	82 (3.1)	33 (2.8)	
Anxiety				
No	3311 (86.0)	2313 (86.2)	998 (85.4)	0.475
Yes	540 (14.0)	369 (13.8)	171 (14.6)	
Depression				
No	3566 (92.6)	2490 (92.8)	1076 (92.0)	0.385
Yes	285 (7.4)	192 (7.2)	93 (8.0)	
Blood transfusion				0.385
No	3601 (93.5)	2514 (93.7)	1087 (93.0)	
Yes	250 (6.5)	168 (6.3)	82 (7.0)	
Anesthesia induction time				0.408
AM	1887 (49.0)	1326 (49.4)	561 (48.0)	
PM	1964 (51.0)	1356 (50.6)	608 (52.0)	
PCIA				0.893
No	1772 (46.0)	1236 (46.1)	536 (45.9)	
Yes	2079 (54.0)	1446 (53.9)	633 (54.1)	
PONV				0.366
No	3069 (79.7)	2127 (79.3)	942 (80.6)	
Yes	782 (20.3)	555 (20.7)	227 (19.4)	
Dexmedetomidine				0.210
No	2556 (66.4)	1797 (67.0)	759 (64.9)	
Yes	1295 (33.6)	885 (33.0)	410 (35.1)	
TIVA				
No	2580 (67.0)	1821 (67.9)	759 (64.9)	0.072
Yes	1271 (33.0)	861 (32.1)	410 (35.1)	

Notes: Categorical variables were analyzed using chi-square tests, continuous variables with non-normal distributions are presented as median (interquartile range) and were analyzed using Mann–Whitney *U*-tests, with*p<0.05 considered statistically significant.

Abbreviations: PSD, postoperative sleep disturbance; BMI, body mass index; NRS score, numeric rating score for pain; ASA, American Society of Anesthesiologists physical status classification; OSAHS, obstructive sleep apnea hypopnea syndrome; PCIA, patient controlled intravenous analgesia; PONV, postoperative nausea and vomiting; TIVA, total intravenous anesthesia.

1.37, 95% CI 1.05–1.80), Moderate-to-severe anemia (p<0.001, OR 2.00, 95% CI 1.36–2.92), Satisfaction of ward environment (p<0.001, OR 0.55, 95% CI 0.44–0.69), Anxiety (p<0.001, OR 1.75, 95% CI 1.34–2.28), Dexmedetomidine (p<0.001, OR 0.43, 95% CI 0.35–0.53), Age (p<0.001, OR 1.02, 95% CI 1.01–1.03), Anesthesia time (p<0.001, OR 1.00, 95% CI 1.00–1.01), Sufentanil (p<0.001, OR 0.93, 95% CI 0.90–0.95) and NRS score (p<0.001, OR 1.65, 95% CI 1.54–1.77) (Figure 3).

Table 2 Coefficients and Lambda. 1se Value of the LASSO Regression

Factors	Coefficients
Gender	0.403
ASA	−0.027
Anemia	−0.175
History of tumor	−0.064
Satisfaction of ward environment	0.427
Anxiety	−0.398
Blood transfusion	−0.171
PCIA	0.483
PONV	0.085
Dexmedetomidine	0.476
Age (years)	0.018
Length of Stay (d)	−0.093
Duration of anesthesia (min)	0.006
Time to tracheal extubation (min)	−0.036
Sufentanil (ug)	−0.033
NRS score	0.521

Notes: Variables with non-zero coefficients were selected for the final model, while those shrunk to zero were excluded. The optimal lambda (λ) value (lambda.1se) was determined through 10-fold cross-validation to achieve parsimony while maintaining predictive accuracy.

Abbreviations: ASA, American Society of Anesthesiologists physical status classification; PCIA, patient controlled intravenous analgesia; PONV, postoperative nausea and vomiting; NRS score, numeric rating score for pain; 1se, 1 standard error.

Construction of the Nomogram

These identified predictors were incorporated into a predictive model for PSD (Figure 4). Within the nomogram, each predictor was weighted according to its association with PSD risk factors. These weighted components were integrated into a composite risk score to quantify PSD probability.

The nomogram demonstrated significant predictive accuracy in the study, with AUC values of 0.826 (95% CI: 0.810–0.843) in the training cohort (Figure 5A) and 0.822 (95% CI: 0.797–0.847) in the validation cohort (Figure 5B).

Calibration plots assess nomogram prediction accuracy against actual results. In the study, the calibration plots for both training (Figure 6A) and validation (Figure 6B) cohorts showed strong agreement between the nomogram's predicted probabilities and actual observed outcomes of PSD.

DCA evaluated the nomogram's clinical utility across probability thresholds. Compared to the treat-all and treat-none approaches, our model showed significantly better net benefits in both training and validation cohorts (Figure 7).

We subsequently created an interactive online nomogram (available at: https://flower123.shinyapps.io/DynNomapp2/) incorporating the ten identified predictors using the ShinyApps platform. The incidence of PSD [0.655 95% CI: (0.587–0.718)] in a virtual patient can be calculated by entering relevant clinical information on this online nomogram (Supplementary Figure S1).

Discussion

Sleep serves as an essential biological imperative in humans. Adequate sleep duration and quality provide significant physiological benefits, including enhanced immune competence, improved neurocognitive development and memory consolidation, as well as better metabolic regulation.[22]

The PSQI was selected in this study for its comprehensive seven distinct dimensions (including sleep latency, efficiency, and daytime dysfunction), which better captures the nature of postoperative sleep disturbances. Although

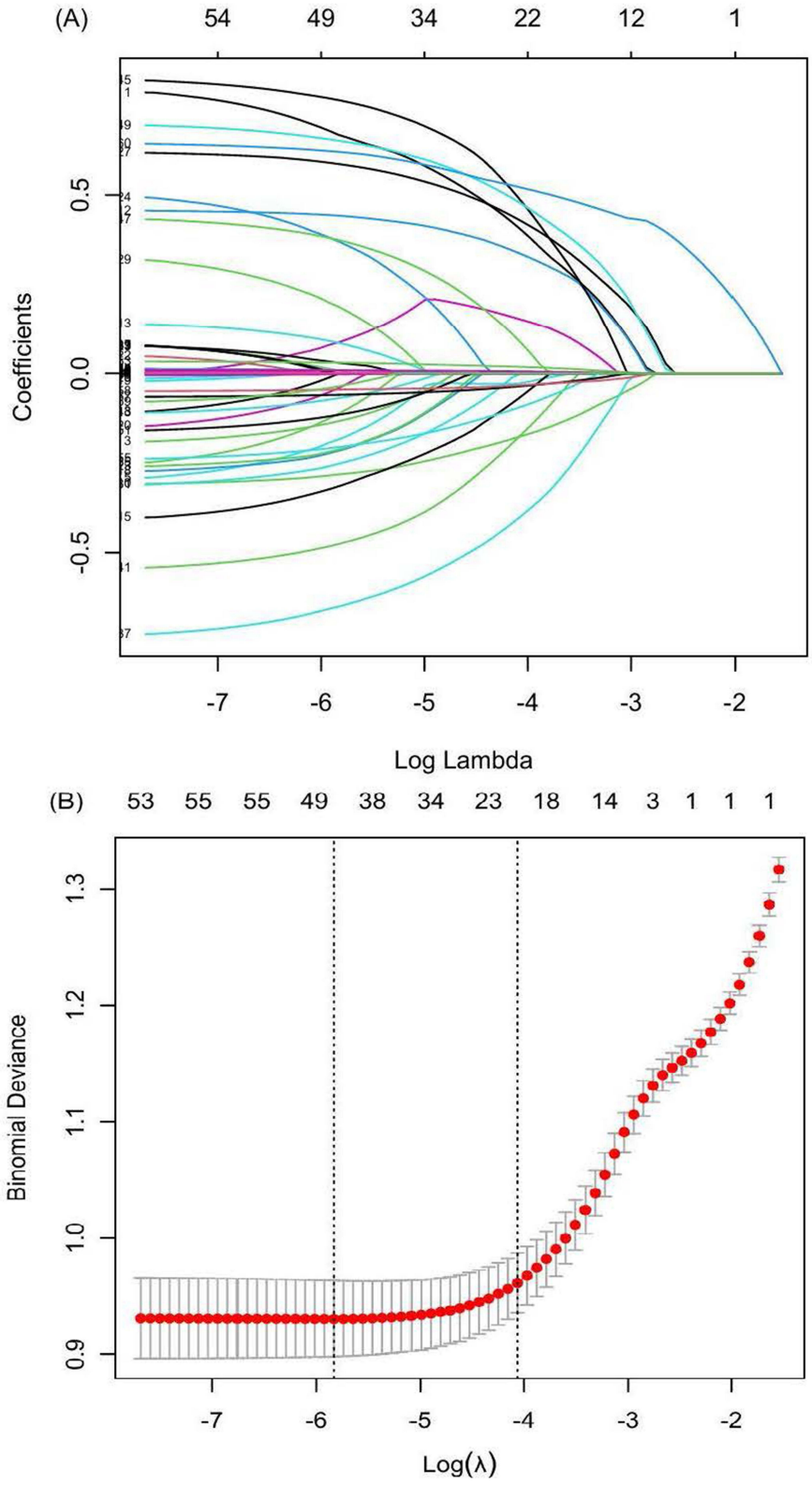

Figure 2 Selection of demographic and clinical features using the Least Absolute Shrinkage and Selection Operator (LASSO) regression. (**A**) Lasso coefficient profile plot. (**B**) The result of 10-fold Cross-Validation. Dotted vertical lines on the left: the minimum values; Dotted vertical lines on the right: the optimal values.

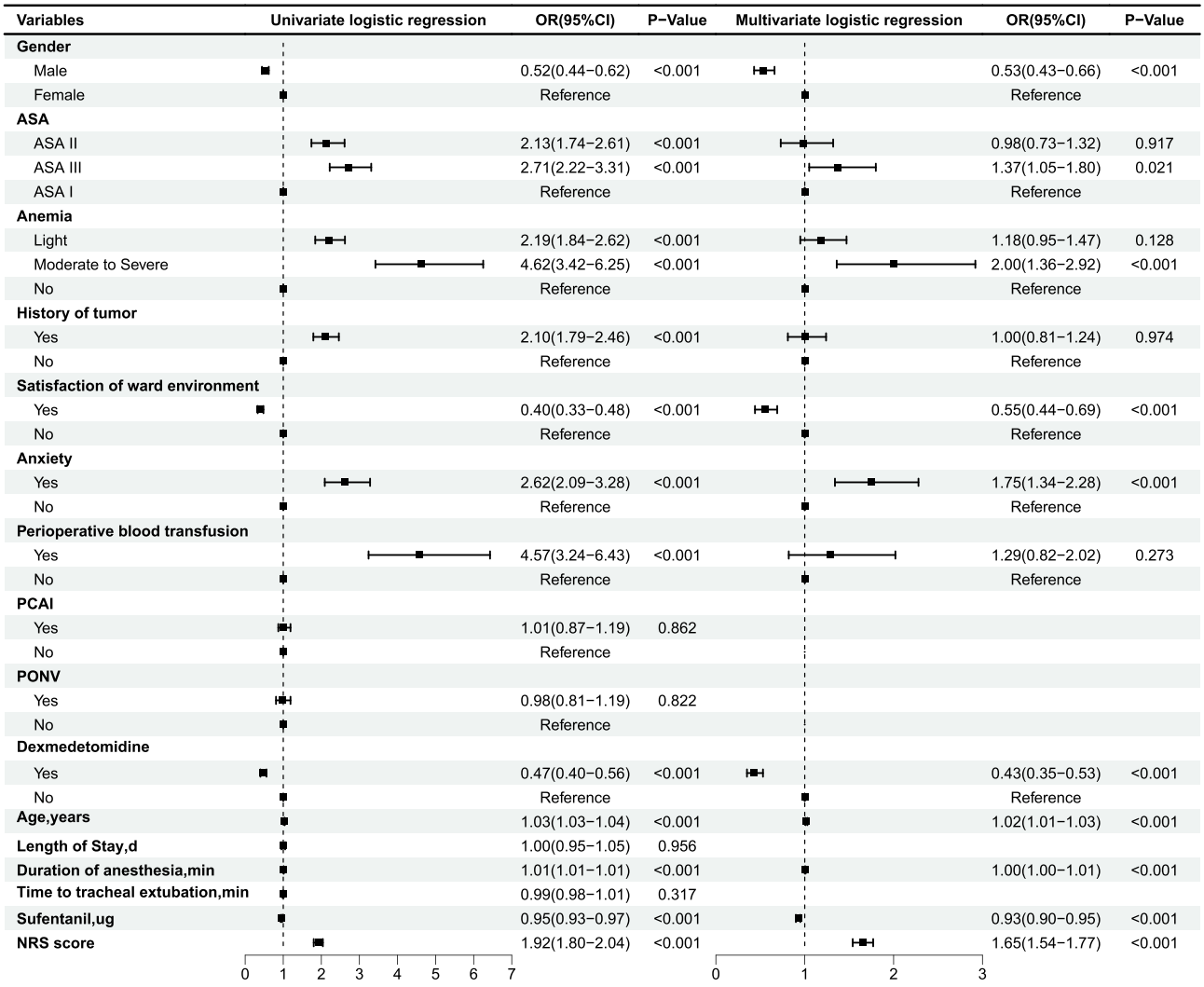

Figure 3 Forest plot displaying univariate and multivariate logistic regression results of the 16 variables selected by LASSO regression.
Abbreviations: OR, odds ratio; CI, confidence interval; ASA, American Society of Anesthesiologists physical status classification; PCAI, Patient-controlled intravenous analgesia; PONV, Postoperative nausea and vomiting; NRS score, numeric rating score for pain.

designed with a 1-month recall period, the PSQI has demonstrated validity for shorter-term assessment (3, 7, and 28 days).[23] Thus, the PSQI was used to evaluate postoperative sleep quality at 1-week and 1-month follow-ups.

The observed prevalence of PSD in our study was moderate (37.7%), potentially attributable to the duration of postoperative follow-up. In our study, we specifically documented patients with persistent sleep disturbances at 1 week postoperatively. Notably, a substantial proportion of patients who developed early postoperative sleep dysfunction (days1-3) demonstrated progressive improvement over time. Consequently, while 37.7% of patients still exhibited sleep-related problems at 1 week postoperatively, the prevalence declined markedly to 12.1% by the 1-month follow-up. Continued sleep deprivation can cause negative emotions, hemodynamic instability, chronic pain, impaired respiratory function, postoperative delirium and early postoperative fatigue, all of which may detrimentally affect postoperative outcome.[24–26]

Previous studies have established that female sex, anxiety, pain, and environmental dissatisfaction are significant contributors to sleep disruption,[27–30] this study further confirms their additional role in predicting PSD among non-cardiac surgery patients. Female patients exhibit increased vulnerability to PSD due to interrelated psychosocial and biological factors. Psychosocial contributors include heightened concern for familial and social relationships, which may predispose to anxiety and depressive symptoms. Concurrently, biological factors such as hormonal fluctuations directly

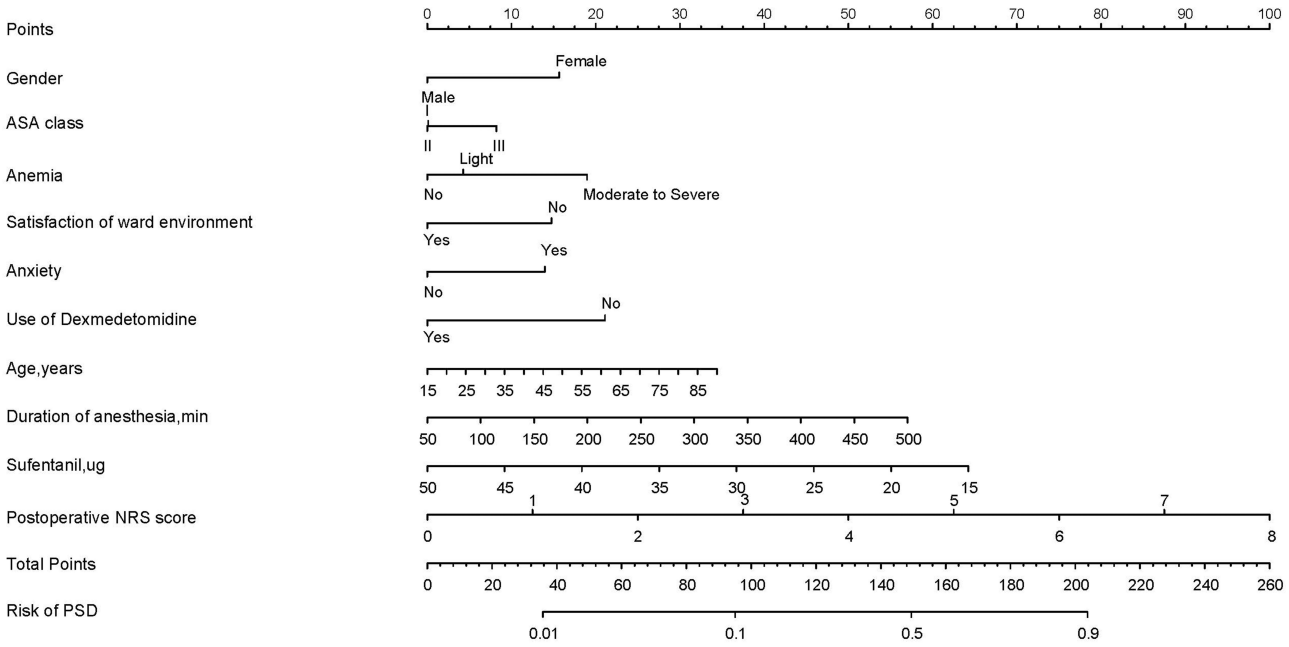

Figure 4 Nomogram to predict the probability of PSD in non-cardiac surgery. Place a vertical line at the level of each variable. Add up the points for all variables and place a vertical line downwards at the corresponding total to obtain the predicted probability of PSD. Example Calculation: For a 58-year-old female patient with: Gender: Female (→ 15 points); ASA class: II (→ 0 points); Anemia: No (→ 0 points); Satisfaction of ward environment: Yes (→ 0 points); Anxiety: Yes (→ 15 points); Use of Dexmedetomidine: No (→ 20 points);Age: 58 years (→ 20 points); Duration of anesthesia: 100 min (→ 5 points); Sufentanil: 30 ug (→ 36 points); NRS pain score: 3 (→ 38 points) 1. Locate each parameter on corresponding axes 2. Sum all points: 149 points 3. Align 149 points on "Total Points" axis → 50% PSD risk.

influence sleep-wake regulation mechanisms.[31,32] Multiple studies have consistently identified anxiety as a significant predictor of sleep disorder prevalence across diverse populations.[33] Clinical evidence indicates patient anxiety primarily originates from biopsychosocial factors, particularly disease-related hypervigilance and treatment-associated financial strain within family. Advanced neuroimaging modalities have delineated overlapping neural substrates underlying the comorbidity of sleep and anxiety disorders, characterized by maladaptive crosstalk among dopaminergic (D2), serotonergic (5-HT1A), and adenosinergic (A2A) receptor systems that collectively perpetuate a pathophysiological cycle of sleep fragmentation and hyperarousal.[34,35] Pain is recognized as the fifth vital sign. Postoperative pain typically peaks within 24–72 hours after surgery and persists for 4–6 days, potentially disrupting sleep through multiple pathways: surgical trauma-induced nociceptive stimuli directly impair sleep continuity; inflammatory mediators trigger peripheral sensitization and central transmission via neural, humoral and cellular routes across the blood–brain barrier, dysregulating key neurotransmitter systems (particularly norepinephrine and dopamine) and altering sleep architecture.[36,37] Furthermore, pain-related sympathetic hyperactivity and metabolic changes may additionally contribute to postoperative sleep impairment.[16]

This study revealed increasing age was also one of the risk factors for PSD. Sleep duration exhibits a progressive decline with advancing age in humans. Age-related sleep alterations include progressively shortened duration, reduced arousal thresholds, increased nocturnal awakenings with prolonged wake-after-sleep onset, and daytime sleepiness. Notably, elderly patients showed significantly decreased urinary 6-sulfatoxy melatonin levels versus younger, suggesting impaired melatonin-mediated circadian regulation contributes to PSD. Therefore, elderly women constitute a high-risk population for PSD.

Anesthetic agents have a significant impact on patients' postoperative sleep architecture. Dexmedetomidine, a highly selective α2-adrenergic receptor agonist, demonstrates potent sedative, analgesic, and anxiolytic effects. Furthermore, this agent enhances sleep quality by reducing fragmentation, shifting N1 to N2 stage, and restoring circadian rhythm, thereby promoting physiological sleep.[38,39] Thus, dexmedetomidin reduces the incidence of PSD and improves postoperative sleep quality.[40] It can be effectively administered via intravenous infusion, nasal drip or nasal spray, with varying concentrations available.[41,42] In our study, intraoperative infusion of dexmedetomidine *(0.2 $\mu g \cdot kg^{-1} \cdot h^{-1}$)* was

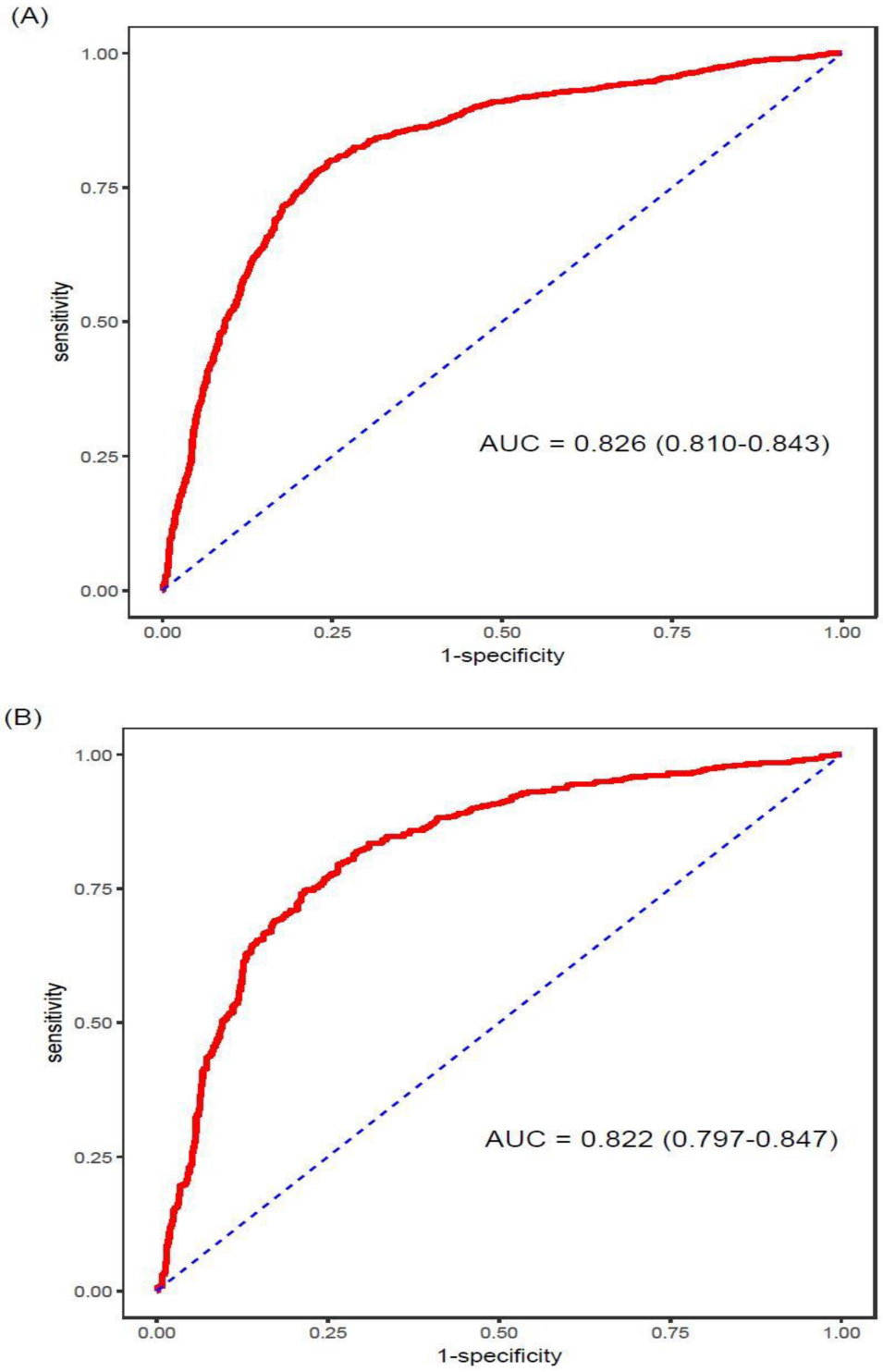

Figure 5 ROC curves of the nomogram for predicting the probability of PSD. (**A**) the training cohort; (**B**) the validation cohort. The area under the curve (AUC) of training cohort and validation cohort were 0.826 and 0.822, respectively.

identified as a protective factor against PSD. The finding confirms that low-dose (compared to higher-dose) intravenous dexmedetomidine effectively improves postoperative sleep quality in patients, consistent with previous reports.[43,44] In the study, the utilization rate of total intravenous anesthesia (TIVA) was 33.0%. Although volatile anesthetics (especially sevoflurane and isoflurane) have been shown to disrupt sleep and increase fragmentation,[45,46] this study found TIVA was

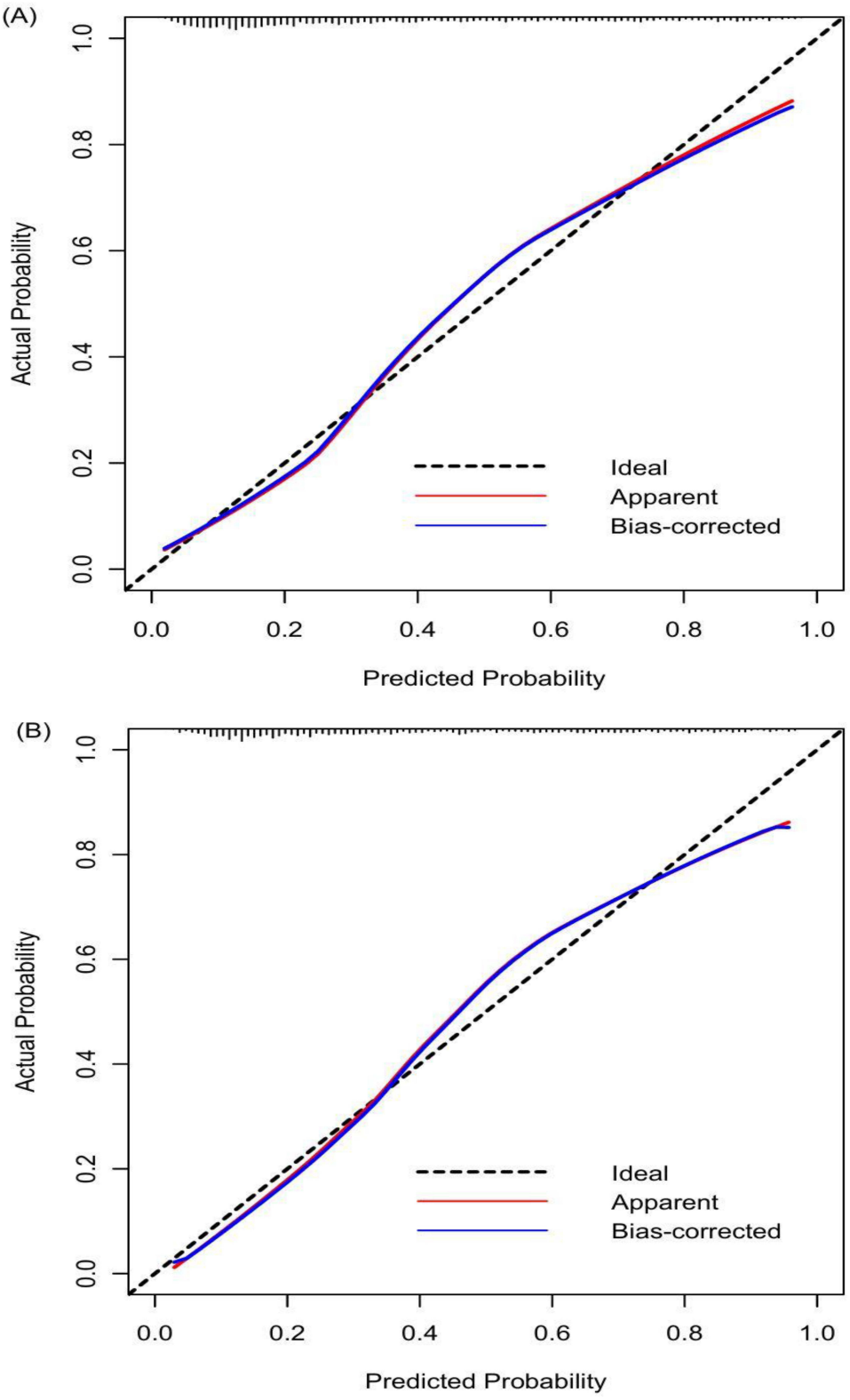

Figure 6 Calibration plots of the nomogram. (**A**) Training cohort; (**B**) Validation cohort.

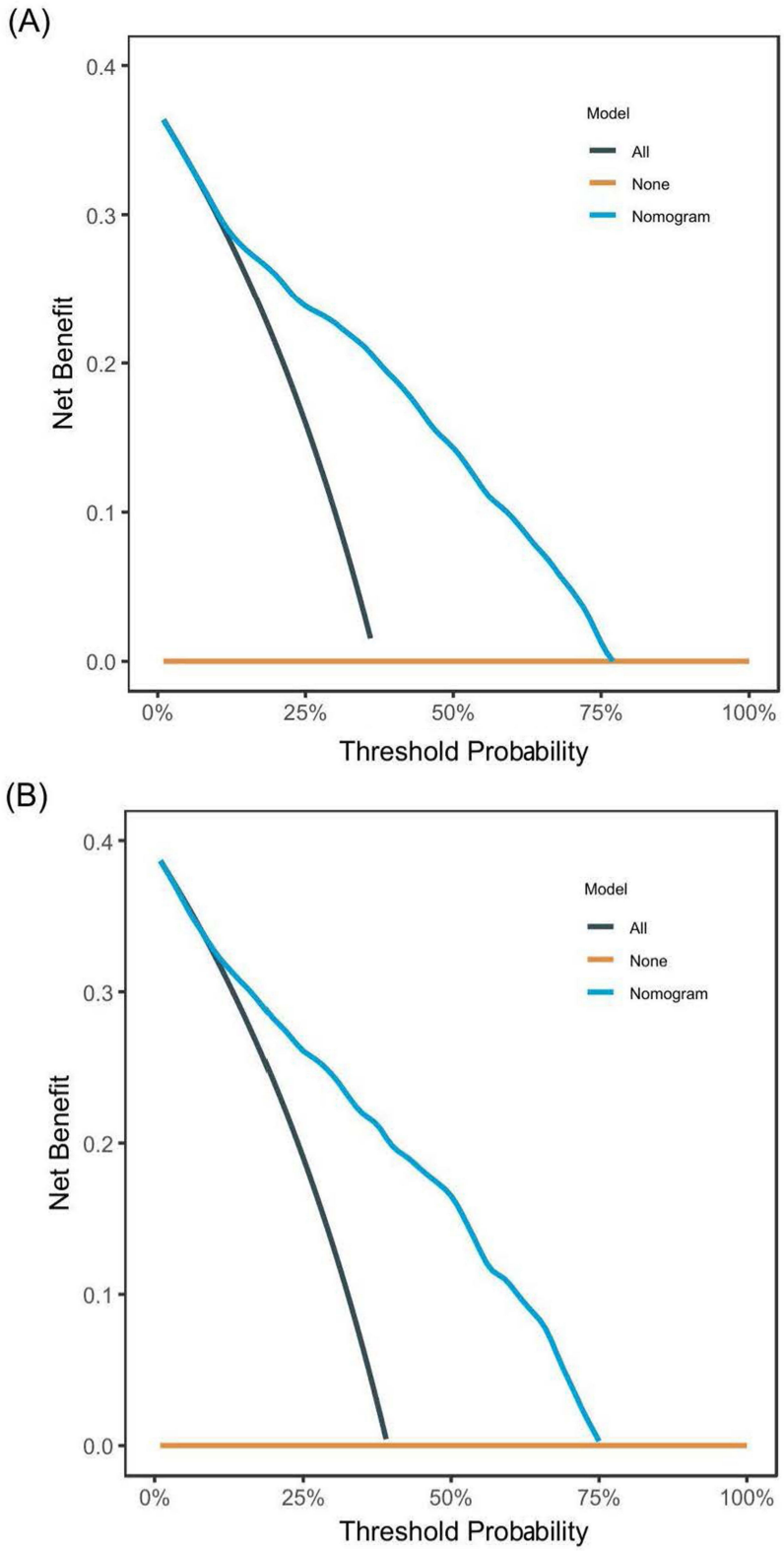

Figure 7 Decision curve analysis of the nomogram. (**A**) Training cohort. (**B**) Validation cohort. The dark green line (All-line) represents the assumption that intervention is performed on all patients. The Orange line (None-line) represents the assumption that intervention is performed on no patients. The blue line represents the nomogram.

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not significantly better than balanced inhalation anesthesia for maintaining postoperative sleep quality. This may be attributed to the transient disruption of sleep architecture and circadian rhythms by inhalation anesthetics, which typically resolves within 24–72 hours postoperatively.[47] The long-term effects of inhaled anesthetics on sleep require further investigation.

Therefore, we recommend a comprehensive intervention strategy for high-risk populations, particularly patients with anxiety and elderly women. This approach encompasses: routine preoperative psychological screening followed by psychosocial or pharmacological intervention when clinically warranted; intraoperative administration of dexmedetomidine; strict implementation of perioperative multimodal analgesia protocols; and judicious melatonin supplementation for elderly patients with objectively confirmed circadian rhythm disturbances. Collectively, these measures aim to significantly mitigate the risk of PSD.

Currently, a limited number of studies have focused on developing PSD predictive models for general anesthesia patients. Du et al established an 8-predictor model exclusively for spinal surgery patients,[20] whereas Yang et al constructed a 9-variable nomogram model based on 881 non-cardiac surgery patients, demonstrating AUC values of 0.82 and 0.80 in the training and validation cohorts, respectively.[19] All the studies employed LASSO regression for variable selection followed by logistic regression. Our predictive model incorporated ten clinically accessible perioperative variables, including female sex, anxiety status, ward environment dissatisfaction, lower intraoperative sufentanil dosage, non-use of dexmedetomidine, and higher NRS pain scores, aligning with those two previous studies. Distinctively, this study incorporated perioperative anemia and ASA physical status classification into the final nomogram. The ASA classification system assesses a patient's preoperative physical status. Multiple studies have demonstrated that patients with higher ASA classification grades exhibit significantly increased perioperative mortality rates.[48,49] Patients with ASA class III typically present with severe chronic comorbidities, particularly cardiovascular and respiratory diseases. These conditions contribute to both sleep architecture disruption with fragmentation and sustained systemic inflammatory activation. Through blood–brain barrier penetration, proinflammatory mediators may further impair circadian rhythm regulation by modulating hypothalamic suprachiasmatic nucleus (SCN) activity.

Furthermore, these patients typically demonstrate prolonged postoperative recovery periods and frequently require multidisciplinary care coordination. Consequently, patients with ASA class III status exhibit significantly higher incidence rates of PSD compared to ASA class I–II counterparts.

Perioperative anemia is a common clinical concern, with an Incidence of 35.9% in our study cohort. Multiple large-scale retrospective cohort studies have established anemia as a significant predictor of 30-day postoperative mortality.[50,51] Furthermore, anaemia is strongly associated with the development of sleep disorders in adults.[52,53] Neuroimaging evidence demonstrates that reduced cerebral blood flow in the frontotemporal region correlates with lower hemoglobin levels, while cortical thinning in this area is linked to shorter sleep duration.[54,55] Furthermore, chronic anemia may contribute to psychological distress, including anxiety, which can exacerbate sleep disturbances.

While prior studies have established a significant association between poor sleep quality and OSAHS,[56] our study did not confirm this association. Only 3% of our cohort had comorbid OSAHS. This low prevalence may result from preoperative diagnostic limitations, which consequently excluded it from consideration as a PSD risk factor. Future investigations employing standardized OSAHS diagnostic criteria are needed to definitively establish its association with PSD.

Nomograms serve as user-friendly visual prediction tools. Our study developed a nomogram based on 3851 patients (notably larger than previous studies), achieving the C-index values of 0.826 in the training cohort and 0.822 in the validation cohort, indicating robust discriminative performance. All incorporated variables are both clinically routine and readily obtainable in practice. Nevertheless, the current study has certain limitations. First, as a single-center study developing this prediction model exclusively in patients without pre-existing sleep disorders, our findings may have limited generalizability. The model's performance may differ in patients with pre-existing sleep disturbances, those undergoing alternative anesthesia techniques (eg, regional anesthesia), or in different clinical settings. Second, the study focused on early PSD prediction (1-week postoperatively). While this provides timely clinical guidance, the short follow-up precludes assessment of persistent sleep disturbances. Future studies should extend the follow-up to 6–12 months to identify chronic predictors and develop corresponding long-term prediction models. Third, although the PSQI is

a validated assessment tool, its reliance on subjective self-reporting may compromise measurement accuracy, particularly among older adults and individuals with limited education. Future investigations should incorporate objective measures such as polysomnography to complement self-reported data.

Conclusion

This study developed and validated a clinically applicable nomogram for predicting early PSD within 7 days after non-cardiovascular surgery. By integrating 10 perioperative predictors using rigorous prospective data from 3851 patients, the model demonstrates high predictive accuracy and optimal calibration, offering clinicians a comprehensive risk assessment tool. For those identified as high-risk, targeted interventions – including preoperative psychological support, environmental modifications, anemia correction, and judicious intraoperative anesthetic management may effectively reduce PSD incidence and improve recovery outcomes. The nomogram requires multicenter validation with objective polysomnographic measures to confirm its generalizability beyond the current single-center study design.

Data Sharing Statement

All data supporting the findings of this study are available upon reasonable request from the corresponding author. The authors are willing to provide relevant data when appropriate while adhering to ethical and privacy protection requirements.

Author Contributions

Jia-Li Mao (First Author): Conceptualization, Data curation, Formal analysis, Investigation, Software, Methodology, Writing-original draft, Writing – review & editing

Shu-Hua Shu (Corresponding Author): Conceptualization, Methodology, Project administration, Resources, Supervision, Writing – review & editing

Ling Hu: Methodology, Data curation, Investigation, Writing – review & editing

Xue-Feng Wang: Conceptualization, Investigation, Data curation, Writing – review & editing

Sheng Wang: Conceptualization, Project administration, Writing – review & editing

Xiao-Qing Fan: Investigation, Data curation, Writing – review & editing

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