Journal of Pain Research

Dovepress
Taylor & Francis Group

ORIGINAL RESEARCH

Preoperative Beta and Gamma EEG Spectral Power as Independent Predictors of Acute Postoperative Pain in Spinal Surgery: A Prospective Observational Cohort Study

Hui Wu[1–4,*], Meiyan Zhou[2,*], Songtao Liu[2,*], Yu Qi[2], Fan Zhou[1–4], Liwei Wang[1,2], Conghai Fan[1,3,4]

[1]College of Anesthesiology, Xuzhou Medical University, Xuzhou, Jiangsu, People's Republic of China; [2]Department of Anesthesiology, Xuzhou Central Hospital, Xuzhou, Jiangsu, People's Republic of China; [3]Jiangsu Province Key Laboratory of Anesthesioloy and Brain Science, Xuzhou Medical University, Xuzhou, Jiangsu, People's Republic of China; [4]Jiangsu Province Key Laboratory of Anesthesiology, Xuzhou Medical University, Xuzhou, Jiangsu, People's Republic of China

*These authors contributed equally to this work

Correspondence: Liwei Wang, College of Anesthesiology, Xuzhou Medical University, No. 199 Jiefang South Road Quanshan District, Xuzhou, Jiangsu, 221009, People's Republic of China, Tel +8618952170255, Email doctorlww@sina.com; Conghai Fan, College of Anesthesiology, Xuzhou Medical University, No. 209 Tongshan Road, Yunlong District, Xuzhou, Jiangsu, 221004, People's Republic of China, Tel +8613013983238, Email FGYXhao@163.com

---

Purpose: The purpose of this paper was to explore the relationship between preoperative EEG frequency band characteristics and postoperative acute pain in patients undergoing spinal surgery, in order to provide a scientific basis for personalized pain management.

Methods: The study included 78 patients undergoing spinal surgery under general anesthesia. Two hours before surgery, the resting EEG of the patients was collected for 10 minutes with eyes closed and relaxed, and the power spectrum characteristics of different frequency bands were extracted by time-frequency analysis. Collected pain scores, anxiety and sleep scales of all patients before and after surgery. Combined with statistical analysis methods for data processing, the correlation between preoperative EEG frequency band power and postoperative pain was explored.

Results: Our study revealed that preoperative beta and gamma power in patients undergoing spinal surgery were negatively correlated with postoperative pain and demonstrated significant predictive value for pain outcomes (β: $\rho = -0.84$, $P<0.001$; γ: $\rho = -0.85$, $P<0.001$). Notably, γ-band due to their specific association with the temporal-insular network, exhibited the most robust predictive efficacy. Furthermore, preoperative β-band and γ-band were also negatively correlated with postoperative anxiety and sleep quality.

Conclusion: Preoperative β and γ oscillations represent promising neurophysiological correlates of acute pain susceptibility following spine surgery. Our findings suggest that these EEG metrics could serve as one of the components in a future multi-factorial predictive model for personalized pain management. However, given the multifactorial nature of pain and the lack of validated clinical thresholds, further research is required to establish their practical utility in guiding perioperative analgesic strategies. Future studies should focus on integrating these EEG biomarkers with psychological and clinical assessments to develop robust prediction tools.

Keywords: electroencephalogram, acute pain, spinal surgery, pain prediction

---

Introduction

Spine surgery ranks among the top surgical procedures in terms of the incidence and intensity of moderate-to-severe acute postoperative pain, making it one of the most pressing clinical scenarios for postoperative pain prediction and management.[1] However, the objective prediction of acute postoperative pain remains a major challenge in both clinical and research settings. A German prospective cohort study comparing postoperative pain intensity across 179 surgical procedures reported that the incidence of numeric rating scale (NRS) scores ≥ 6 on the first postoperative day reached

https://doi.org/10.2147/JPR.S593873
Received: 14 January 2026
Accepted: 24 April 2026
Published: 30 April 2026

72.7% after spine surgery, ranking second among all surgical types.[2] Notably, the study further indicates that even within spinal surgery, pain levels vary across different surgical procedures, such as spinal fusion versus decompression. The subjects of this study were patients undergoing spinal decompression surgery. Although this procedure is less invasive than fusion surgery, the incidence and intensity of acute postoperative pain remain among the highest across various surgical types, posing a significant challenge for pain prediction and management.

Pain occurrence and perception constitute a complex psychophysiological process influenced by factors such as gender, age, emotional state, and surgical trauma. Current clinical pain management still largely relies on surgical type and patient self-report, lacking individualized predictive tools.[3] Research indicates that pain perception is closely associated with neural oscillations involving brain regions such as the sensory cortex, anterior cingulate cortex, and insula, which play key roles in pain transmission and modulation.[4,5] As a non-invasive and convenient technique for monitoring neural activity, electroencephalography (EEG) can capture electrophysiological changes in these brain regions and holds particular value in assessing the function of the anterior cingulate cortex.[6–8] In recent years, significant progress has been made in pain prediction research using EEG time-frequency features. In experimental pain models, thermal stimulation can lead to decreased α band power in occipital-parietal regions, which correlates with pain intensity, while increased β and γ band activity in the prefrontal cortex is also associated with enhanced pain perception.[9–11] Clinical observations have further shown that procedural pain (eg., venous puncture, skin incision) can induce EEG alterations such as increased δ activity or decreased α activity.[12,13] Extensive research has demonstrated that long-term nociception can induce structural and functional cortical reorganization, including alterations in gray matter volume in key brain regions such as the insula and anterior cingulate cortex, as well as abnormal functional connectivity in resting-state networks.[14,15] Such neuroplastic changes driven by chronic pain may directly influence the composition of preoperative resting-state EEG signals, thereby potentially confounding EEG-based biomarkers for postoperative pain prediction.[16] Therefore, when investigating the predictive value of EEG, it is essential to carefully assess whether the observed oscillatory activity represents a stable neural trait shaped by prior pain experience or merely reflects a transient state influenced by current baseline pain burden. By rigorously controlling enrollment criteria during the study design and adjusting for preoperative pain scores in the statistical analysis, it becomes possible to identify biomarkers that maintain stable predictive performance. Together, this evidence demonstrates a stable association between EEG spectral activity and pain perception, laying an important foundation for its application in predicting acute postoperative pain.

Although previous studies have confirmed the feasibility of using preoperative EEG to predict pain in thoracoscopic surgery, its predictive value in spinal surgery, a procedure associated with a high pain burden and a patient population often suffering from preoperative chronic pain, remains underexplored.[2,14] Extensive research has demonstrated that long-term nociception can induce structural and functional cortical reorganization, including alterations in gray matter volume in key brain regions such as the insula and anterior cingulate cortex, as well as abnormal functional connectivity in resting-state networks.[15,16] Such neuroplastic changes driven by chronic pain may directly influence the composition of preoperative resting-state EEG signals, thereby potentially confounding EEG-based biomarkers for postoperative pain prediction.[17] Therefore, when investigating the predictive value of EEG, it is essential to carefully assess whether the observed oscillatory activity represents a stable neural trait shaped by prior pain experience or merely reflects a transient state influenced by current baseline pain burden. By rigorously controlling enrollment criteria during the study design and adjusting for preoperative pain scores in the statistical analysis, it becomes possible to identify biomarkers that maintain stable predictive performance.

Therefore, the aim of this study is not to identify an idealized biomarker that reflects “pure” pain susceptibility under controlled conditions, but rather to discover a practical neurophysiological marker capable of effectively predicting an individual’s pain response to new surgical trauma in real-world, complex clinical scenarios. This study not only evaluates the predictive capacity of beta and gamma oscillations in spinal surgery but also rigorously controls for preoperative pain levels and intraoperative opioid use to isolate the genuine predictive signal of EEG. This research direction is more aligned with practical clinical application and may enable the preoperative screening of high-risk patients and the optimization of analgesic strategies, thereby improving pain management outcomes, reducing the risk of substance abuse, and enhancing the quality of postoperative recovery.

Materials and Methods

This clinical study was conducted in the Department of Anesthesiology, Xuzhou Central Hospital. The study protocol was approved by the Medical Ethics Committee of Xuzhou Central Hospital. Written informed consent was obtained from all participants. The study was registered on the Clinical Trial Registry (https://www.chictr.org.cn/bin/userProject) with the registration number ChiCTR2500101616.

Subjects

From May 2025 to December 2025, a total of 100 patients scheduled to undergo lumbar laminectomy decompression or cervical spinal canal decompression at Xuzhou Central Hospital were enrolled in the study. The inclusion criteria were (1) Patients aged ≥ 18 years and ≤ 60 years; (2) Clear consciousness, can carry on the normal communication; (3) ASA grade I–II; (4) The diagnosis was confirmed by imaging and was not combined with other bone diseases; (5) Sign informed consent; (6) Patients choose to use Patient-Controlled Intravenous Analgesia (PCIA) for postoperative analgesia. Exclusion criteria were (1) Patients with spinal trauma; (2) Patients with craniocerebral diseases and craniocerebral surgery; (3) Patients with nervous system diseases or mental illness; (4) Patients with confirmed chronic pain syndromes (such as fibromyalgia, complex regional pain syndrome, etc.) or those who have been regularly using analgesics for an extended period (over 3 months); (5) Preoperative radiotherapy or chemotherapy. Detailed demographic information is summarized in the Table 1.

Experimental Design

One day before surgery, patients were instructed to abstain from smoking, alcohol, fasting, and drinking, as well as to avoid consuming coffee or caffeine-containing beverages, and to sign the informed consent form. Prior to EEG recording, the NRS was used to assess the patient's current resting preoperative pain intensity, and anxiety and sleep

Table 1 The Demographic and Clinical Characteristics

Variables	**Group H (n = 39)**	**Group L (n = 39)**	***P***
Age	46.77 ± 7.99	46.59 ± 8.40	0.923
Preoperative NRS score	2.49 ± 1.76	2.31 ± 1.54	0.633
Preoperative AIS score	2.10 ± 0.94	1.97 ± 0.84	0.528
Preoperative SAS score	48.85 ± 10.71	45.08 ± 21.58	0.229
Sex, n (%)			0.821
Male	21 (53.85)	20 (51.28)	
Female	18 (46.15)	19 (48.72)	
Operation type, n (%)			0.791
Cervical spinal canal decompression	12 (30.77)	14 (35.90)	
Lumbar vertebral plate decompression	27 (69.23)	25 (64.10)	
Smoking, n (%)	9 (23.08)	10 (25.64)	0.792
Drinking, n (%)	6 (15.38)	7 (17.95)	0.761
Hypertension, n (%)	10 (25.64)	8 (20.51)	0.591
Diabetes, n (%)	7 (17.95)	4 (10.26)	0.329
ASA Physical Status, n (%)			0.475
I	27 (69.23)	24 (61.54)	
II	12 (30.77)	15 (38.46)	
Ibuprofen, n (%)*	2 (5.13)	1 (2.56)	1.000
Paracetamol, n (%)*	1 (2.56)	1 (2.56)	1.000
Flurbiprofen axetil, n (%)*	4 (10.26)	3 (7.69)	1.000

Notes: *Preoperative medications (ibuprofen, paracetamol, flurbiprofen axetil) were administered as single acute doses within 24 hours before surgery for pre-existing pain.

Abbreviations: NRS, numerical rating scale; AIS, Athens Insomnia Scale; SAS, Self–Rating Anxiety Scale; ASA, American Society of Anesthesiologists Physical Status Classification System.

scales were completed. This preoperative NRS score was included as a key covariate in subsequent analyses to control for potential confounding effects of baseline pain load on the EEG predictive model. Two hours before surgery, 10 minutes of 64-channel EEG (Brain Vision) data were acquired from patients in a closed-eye, relaxed state.

All patients received standardized general anesthesia. Anesthesia was induced with midazolam (0.02–0.05 mg/kg), propofol (1–2 mg/kg), sufentanil (0.3–0.6 μg/kg), and cisatracurium (0.15 mg/kg), followed by tracheal intubation. Maintenance was achieved with propofol (4–12 mg/kg/h) and remifentanil (0.1–0.3 μg/kg/min), with supplemental sufentanil and cisatracurium as needed. To minimize the confounding effect of opioid-induced hyperalgesia, a standardized intraoperative opioid administration protocol was strictly followed. The infusion rate of remifentanil was titrated to maintain heart rate and blood pressure within 20% of baseline values, with the explicit aim of avoiding an infusion rate ≥ 0.2 μg/kg/min. The cumulative dose of sufentanil throughout the procedure was limited to a maximum of 0.6μg/kg. Postoperatively, PCIA was initiated with a solution of hydromorphone 10 mg, flurbiprofen axetil 250 mg, and metoclopramide 30 mg diluted to 100 mL with 0.9% sodium chloride, set at a background infusion rate of 2 mL/h, self–controlled dose 0.5 mL, and a lockout interval of 15 min. All intraoperative medications were administered according to a weight-based protocol to minimize variability in anesthesia management, thereby ensuring that observed differences in postoperative pain were not attributable to anesthetic factors.

Postoperative pain management followed a standardized stepwise protocol, with PCIA serving as the primary measure. Rescue analgesia with flurbiprofen axetil (50 mg per dose, maximum daily dose of 200 mg) was administered when NRS scores ≥ 4. Resting NRS pain scores were assessed on postoperative days 1, 2, and 3 prior to any rescue analgesia, and the Self-Rating Anxiety Scale (SAS) and Athens Insomnia Scale (AIS) were completed on the first postoperative day. Based on the NRS scores on the first postoperative day, patients were classified into a high-pain group (NRS ≥ 4) and a low-pain group (NRS < 4). The threshold of NRS ≥ 4 was chosen according to the American Society of Regional Anesthesia and Pain Medicine (ASRA) guidelines and previous literature, as it is widely accepted as the cutoff for moderate-to-severe pain that warrants clinical intervention.[18]

EEG Recordings

In a quiet, temperature-controlled room, the patient assumed a supine or seated position on a bed. A 64-channel EEG cap was placed on the head to record EEG data, with electrode placement following the International 10–20 System. Conductive gel was applied to each electrode, and all electrode impedances were maintained below 10 kΩ. The amplifier was set to a sampling rate of 1000 Hz, using the fronto-central electrode (FCz) as the online reference and the anterior frontal midline electrode (AFz) as the ground. Electrode positions were measured and localized based on cranial landmarks (nasion, inion, and left/right pre-auricular points) to ensure accurate and reproducible placement. During EEG data acquisition, all subjects were instructed to remain awake, relaxed, and with their eyes closed, as resting-state EEG data exhibit greater stability under eyes-closed conditions compared to eyes-open conditions.[19]

EEG Data Preprocessing

EEG data were processed using MATLAB2022b toolbox EEGLAB. The data was band–pass filtered between 1–45 Hz and notch filtered between 48–52 Hz, and the sampling rate of continuous EEG was reduced to 500 Hz. In order to remove artifacts, a 2s time window was used to segment continuous EEG data. EEG data were visually inspected, with bad channels interpolated and bad segments removed. Artifactual components related to ocular, muscular, or cardiac activities were identified and removed using independent component analysis (ICA), based on topographical maps, time-series patterns, and a probability threshold set to >0.8. Following ICA and additional baseline correction, the data were re-referenced to the average reference by subtracting the mean of all electrodes from each individual channel's signal.

EEG Spectrum Analysis

In MATLAB, all the data after preprocessing were established into a STUDY file for statistical analysis. Under the same conditions, they were divided into two groups: low pain group (L group) and high pain group (H group). The data after statistical analysis were visualized to present different results. The power spectral density (PSD) of the index was calculated by fast fourier transform through MATLAB script. The data were sampled at 500 Hz. For each 2-second epoch

(1000 data points), a 1024-point Fast Fourier Transform (FFT) was applied with no overlap between epochs. This was followed by a logarithmic transformation (calculated as 10*log10, resulting in PSD) and subsequent averaging across epochs. Finally, the mean value of all frequency points within each frequency band was calculated to represent the power spectral density for that band.

In order to evaluate the inter-group difference of EEG spectrum, the power values of each electrode in each frequency band were statistically analyzed. The statistical method was independent sample *t*-test. The p value of each electrode was corrected by multiple comparison, and the false discovery rate (FDR) program was used to correct the significance level, and the p value was set to be less than 0.05.

EEG Source Localization Analysis

Source localization was performed using the sLORETA algorithm, which provides a weighted minimum norm inverse solution. The LORETA-KEY software was employed to conduct standardized low-resolution brain electromagnetic tomography on artifact-free EEG data to determine the sources of neural activity. The solution space of sLORETA was constrained to the cortical gray matter using the MNI152 template, discretized into 6239 voxels at a spatial resolution of 5 mm. The power of each EEG rhythm was computed for each voxel per participant. For each frequency band, an independent samples *t*-test was conducted on the power values across all 6239 voxels between groups. The resulting p-values for each frequency band were then corrected for multiple comparisons using the False Discovery Rate (FDR) procedure.

Statistical Analysis

Statistical analyses of patients' demographic information were performed using SPSS 23.0. Categorical variables (ie., sex, ASA physical status, surgical type) were compared using the Chi-square test, while continuous variables (ie., age) were compared using the independent samples *t*-test. To ascertain the independent predictive value of preoperative EEG activity, hierarchical regression models were constructed. In Step 1 (Model 1), the preoperative NRS score was entered as the predictor. In Step 2 (Model 2), preoperative β or γ band power was added while retaining the preoperative NRS score. By comparing the change in R^2 (ΔR^2) between Model 1 and Model 2, the additional predictive power contributed by the EEG metrics, after accounting for the variance explained by preoperative pain, was evaluated.Furthermore, a multiple regression analysis incorporating demographic characteristics, preoperative anxiety/sleep scores, preoperative pain, and EEG power was conducted to identify independent predictors of postoperative pain. The Variance Inflation Factor (VIF) was calculated to test for multicollinearity, ensuring that preoperative pain and EEG indicators were not highly collinear. Relationships between variables were examined using Spearman correlation analysis.The predictive efficacy of preoperative EEG activity for postoperative pain was assessed using Receiver Operating Characteristic (ROC) curve analysis. Sensitivity and specificity for identifying patients with postoperative pain were reported, and the Area Under the Curve (AUC) along with its 95% confidence interval (95% CI) were calculated.

Sample Size Estimation

The sample size for this study was estimated using G*Power software (version 3.1). Based on a similar study that used preoperative EEG power to predict postoperative pain, a medium effect size of Cohen's d ≈ 0.7 was assumed.[14] The parameters were set as follows: α error probability = 0.05 (two-tailed), statistical power (1-β) = 0.8. Using an independent samples *t*-test model for calculation, the results indicated that 34 subjects were required per group, resulting in a total sample size of 68. This calculation was based on the standardized sample size formula: *n = 2 * [(Z_{1-α/2} + Z_{1-β}) / d]^2*. After accounting for an estimated 15% attrition rate, we planned to recruit 80 patients. Ultimately, a total of 78 patients completed the study, and the effective sample size exceeded the minimum requirement calculated.

Results

We screened 93 patients who underwent spinal surgery, as shown in Figure 1. 4 patients were excluded according to the exclusion criteria, 7 patients refused to participate, 2 patients withdrew from surgery, and 1 patient changing to local anesthesia. 80 patients participated in the trial. According to the NRS results on the first day after surgery, 39 patients

https://doi.org/10.2147/JPR.S593873

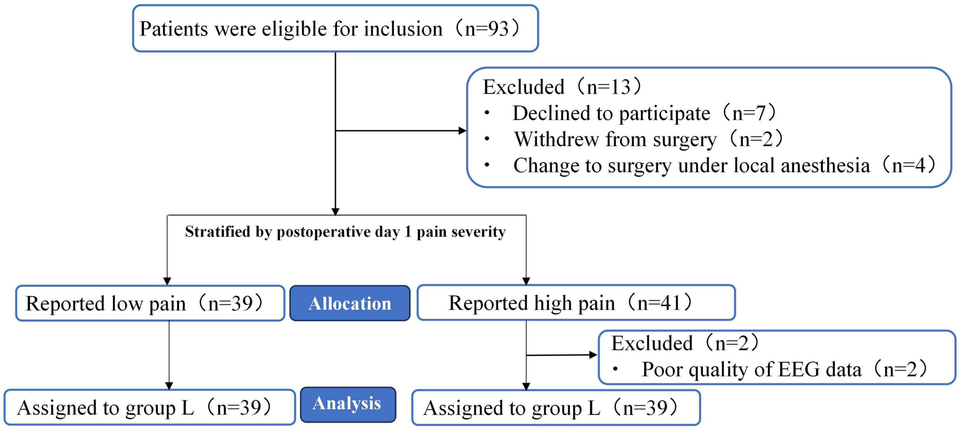

Figure 1 Flow diagram.

reported mild pain (NRS < 4) and 41 patients reported severe pain (NRS ≥4). Among these, 2 patients with NRS ≥4 were excluded due to poor-quality EEG data. Finally, 39 patients were included in each of Group L and Group H (Figure 1). There were no significant differences in clinical and demographic characteristics such as gender, age, weight, ASA classification, and type of surgery between the two groups (p > 0.05). Crucially, there was no statistically significant difference in preoperative resting NRS pain scores between the two groups, and preoperative anxiety and sleep scores were also similar (p > 0.05). This indicates that the observed intergroup difference in postoperative pain was not directly attributable to an imbalance in preoperative pain levels (Table 1).

Table 2 showed the pain experienced by the two groups of patients after surgery. On the first day after operation, the NRS score of the two groups was the highest, and the NRS score of the H group and the L group was statistically different (5.01 ± 0.98: 2.41 ± 0.88, P < 0.01). The scores of anxiety and sleep on the first day after operation were also statistically different (4.64 ± 1.77: 2.90 ± 1.29, P < 0.01; 3.97 ± 1.25: 2.18 ± 1.12, P < 0.01). To further illustrate the postoperative pain trajectory of the two groups, we also assessed NRS scores on postoperative days 2 and 3. The results showed that patients in Group L continued to report significantly lower pain intensity than those in Group H on days 2 and 3 (P < 0.01), indicating that the grouping based on day 1 NRS reflected a sustained difference in pain experience rather than a single-day fluctuation. Similarly, patients in the H group exhibited greater usage of PCA drugs, more frequent PCA bolus attempts, and a higher frequency of postoperative rescue analgesia compared to the L group (P < 0.01). There were no significant statistical differences in operative time or opioid dosage (P > 0.01).

The average power spectral density of the resting-state EEG signals exhibited a typical physiological pattern of eyes-closed wakefulness: a prominent α peak around 10 Hz was observed, and the overall power decreased with increasing

Table 2 Postoperative Pain and Other Information

	Group H (n=39)	Group L (n=39)	*P*
NRS on the 1st day	5.41 ± 0.99	1.92 ± 0.74	<0.01
NRS on the 2nd day	2.69 ± 1.00	0.69 ± 0.77	<0.01
NRS on the 3rd day	1.44 ± 0.85	0.23 ± 0.43	<0.01
SAS on the 1st day	4.64 ± 1.77	2.90 ± 1.29	<0.01
AIS on the 1st day	3.97 ± 1.25	2.18 ± 1.12	<0.01
Operation time (min)	128±17	121±28	0.186
Opioid drug consumption (MME,mg)	102.5±34	108±27.5	0.435
Analgesic pump medication dosage (mL)	89.95 ± 18.73	72.51 ± 28.03	0.002
Pressing times of analgesic pump	10.54 ± 5.67	4.38 ± 4.02	<0.01
Remedy analgesia times	1.00 ± 0.56	0.15 ± 0.37	<0.01

Abbreviations: NRS, numerical rating scale; AIS, Athens Insomnia Scale; SAS, Self–Rating Anxiety Scale; MME, Morphine Milligram Equivalents.

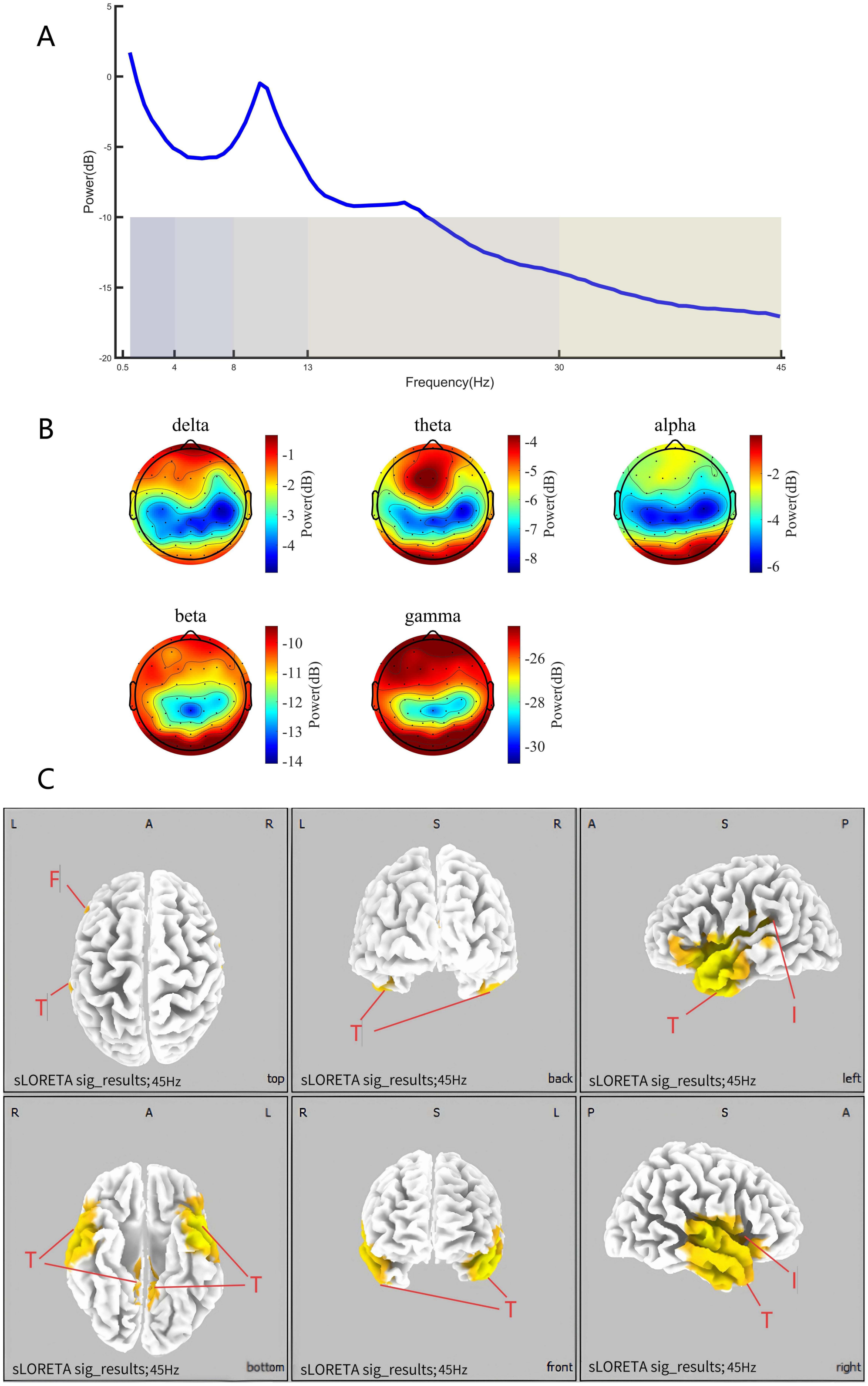

Figure 2 (**A** and **B**) Spectrum and topographic maps of each frequency band of the whole brain. (**C**) Figure of significant difference regions in six positions of the γ-band. L, left; R, right; A, Anterior; S, Superior. The yellow highlighted areas in the figure indicate brain regions with significant differences. $P<0.05$. F, frontal lobe; I, insular lobe; T, temporosphenoid lobe.

https://doi.org/10.2147/JPR.S593873

Table 3 Distribution of Brain Regions with Significant Voxels After FDR Multiple Comparison Correction

Lobe	Structure	Number of Voxels	Peak Voxel MNI Coordinates (x, y, z)	T-value
Sub-lobar	Extra-Nuclear	8	(−42, −14, 12)	3.82
Sub-lobar	Insula	151	(−38, −12, 10)	4.56
Temporal Lobe	Fusiform Gyrus	14	(44, −28, −18)	3.41
Temporal Lobe	Inferior Frontal Gyrus	2	(−52, 12, 6)	3.12
Temporal Lobe	Inferior Temporal Gyrus	50	(−58, −42, −12)	4.03
Temporal Lobe	Insula	1	(40, −14, 8)	4.28
Temporal Lobe	Middle Temporal Gyrus	122	(−60, −34, −8)	3.65
Temporal Lobe	Sub-Gyral	12	(−46, −20, 4)	4.87
Temporal Lobe	Superior Temporal Gyrus	229	(−52, −22, 6)	3.98
Temporal Lobe	Transverse Temporal Gyrus	20	(−48, −18, 8)	3.05

frequency (Figure 2a). Topographic maps indicated stronger activity in the high-frequency bands (β and γ) (Figure 2b). Source localization analysis revealed that only voxels in the γ band showed significant between-group differences after FDR multiple comparison correction, with significantly higher power in the L group compared to the H group (Figure 2c). The brain regions associated with these differences were primarily concentrated in the temporal lobe and insula (Table 3).

Time-frequency analysis combined with point-by-point statistical testing (FDR-corrected) revealed that patients in the L group exhibited significantly higher resting-state EEG oscillatory power in the δ, β, and γ bands compared to those in

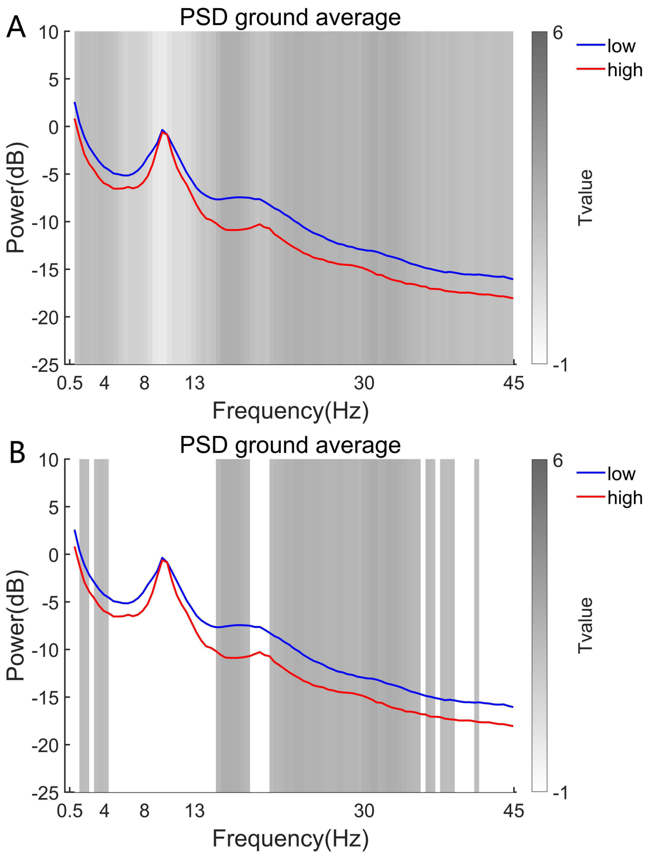

Figure 3 The difference of PSD of resting–state neural oscillations between patients with different levels of acute postoperative pain, i.e., low pain and moderate/high pain. (**A**) is before correction, (**B**) is after correction; PSD, power spectral density.

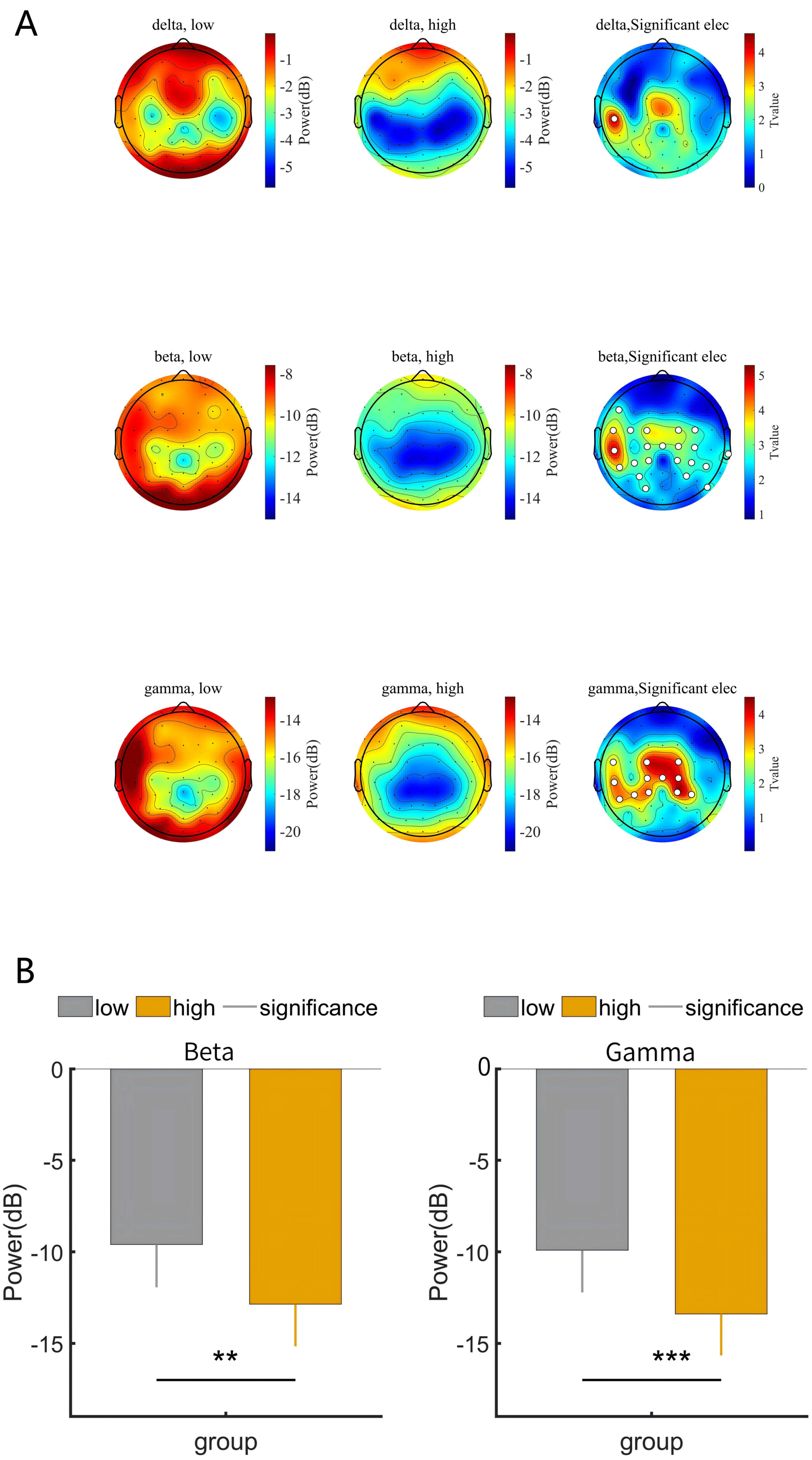

Figure 4 (**A**) There were topographic maps of different frequency bands and different electrodes in L group and M / H group; (**B**) Comparison of mean β-band and γ-band power at significant electrodes between the low-pain group (**L**) and high-pain group (H). **p < 0.01, ***p < 0.001.

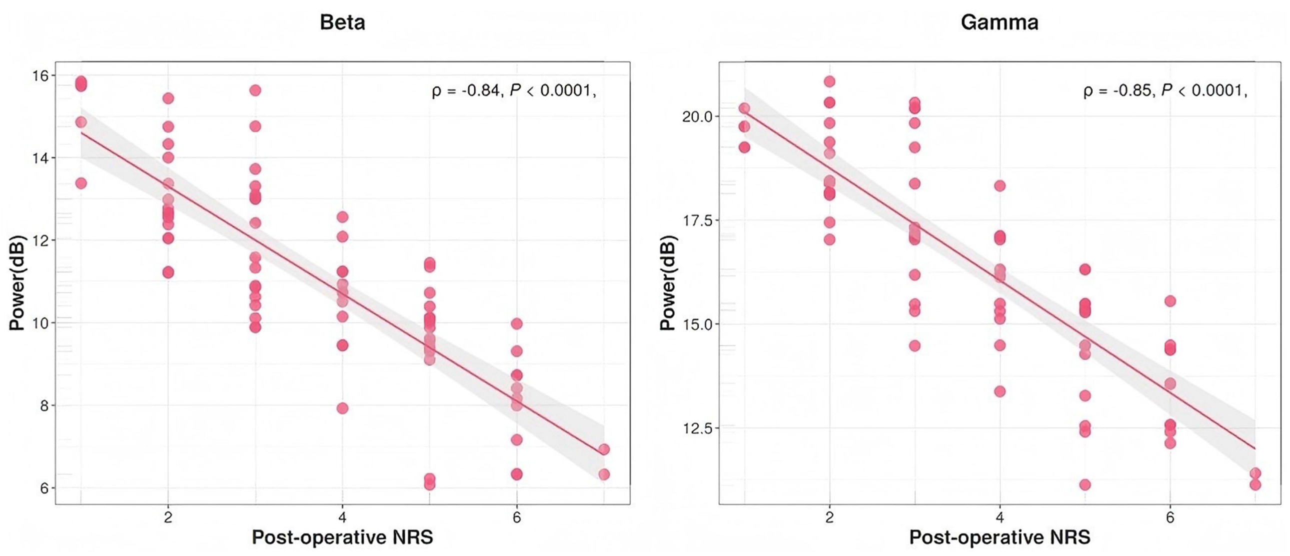

Figure 5 Correlation curve analysis of NRS and resting EEG beta (13–30Hz) and gamma (> 30Hz) band energy at 1 day after surgery.

the H group (Figure 3A and Figure 3B). Topographic maps for each frequency band (Figure 4A) indicated that δ wave differences were confined to electrode C5 in the low central region (L > H). For β waves, differences were observed bilaterally in temporal, parietal, and central regions, while γ wave differences were localized to the left temporal, parietal, and central regions (L > H). Independent samples t-tests conducted on β and γ band power indices at the significant electrodes confirmed statistically significant differences between the two groups across the respective frequency bands (β band: $p < 0.01$; γ band: $p < 0.001$; Figure 4B).

Spearman correlation analysis showed that preoperative β band power ($R = -0.84$, $P < 0.001$) and γ band power ($R = -0.85$, $P < 0.001$) were both significantly negatively correlated with NRS scores on postoperative day 1, suggesting that stronger preoperative EEG activity in these frequency bands may be associated with milder acute postoperative pain (Figure 5).

Hierarchical regression analysis indicated that the model containing only the preoperative NRS score (Model 1) exhibited some predictive ability for postoperative day 1 NRS scores ($R^2 = 0.103$, $p = 0.005$). After adding preoperative β band power (Model 2), the explanatory power of the model increased significantly by 59.3% ($\Delta R^2 = 0.490$, $p < 0.001$), and the preoperative NRS score became non-significant ($p = 0.482$). After further adding γ band power, the model's explanatory power increased to 61.1% ($\Delta R^2 = 0.508$, $p < 0.001$), and the preoperative NRS score became completely non-significant ($p = 0.827$) (Table 4). Multiple linear regression analysis results are presented in Table 5. Among the included predictor variables, only β and γ band power demonstrated significant independent predictive effects ($p < 0.01$). Preoperative pain ($p = 0.081$), anxiety ($p = 0.593$), sleep scores ($p = 0.898$), and opioid consumption ($p = 0.941$) did not show significant independent predictive value. All Variance

Table 4 Hierarchical Regression Analysis Predicting Postoperative Day 1 Pain Intensity (NRS)

Model	Predictors	β (95% CI)	Standardized β	*P*	R^2	Adjusted R^2	ΔR^2	*F*-change	*P*(ΔR^2)
Model 1	Constant	3.16 (2.49, 3.83)	–	<0.001	0.103	0.091	–	–	–
	Preoperative NRS	0.25 (0.08, 0.42)	0.32	0.005					
Model 2a	Constant	12.92 (11.21, 14.63)	–	<0.001	0.593	0.582	0.490	89.21	<0.001
	Preoperative NRS	0.06 (−0.11, 0.23)	0.07	0.482					
	Beta-band power	−0.49 (−0.59, −0.39)	−0.78	<0.001					
Model 2b	Constant	13.65 (11.97, 15.33)	–	<0.001	0.611	0.601	0.508	97.32	<0.001
	Preoperative NRS	0.02 (−0.15, 0.19)	0.02	0.827					
	Gamma-band power	−0.51 (−0.61, −0.41)	−0.79	<0.001					

Notes: ΔR^2 represents the incremental variance explained by adding the EEG predictor to the model containing preoperative NRS.
Abbreviations: NRS, Numerical Rating Scale; CI, Confidence Interval.

Table 5 Multivariate Linear Regression Analysis of Factors Associated with Postoperative Pain

Variables	**β**	**S.E**	**t**	***P***	**β (95% CI)**	**VIF**
Sex						
Male					0.00 (Reference)	–
Female	−0.29	0.45	−0.65	0.515	−1.17–0.58	–
Age	−0.01	0.03	−0.36	0.722	−0.06–0.04	–
Preoperative NRS	−0.01	0.08	−0.15	0.881	−0.16–0.14	1.28
Preoperative SAS	0.04	0.08	0.54	0.593	−0.11–0.19	1.18
Preoperative AIS	0.01	0.10	0.13	0.898	−0.18–0.20	1.09
Opioid drug consumption (MME,mg)	−0.00	0.00	−0.07	0.941	−0.01–0.01	1.21
Beta (dB)	−0.39	0.07	−5.95	0.009	−0.52 – −0.26	1.81
Gamma (dB)	−0.41	0.05	−7.65	0.006	−0.51 – −0.30	1.37

Abbreviations: CI, Confidence Interval; MME, Morphine Milligram Equivalents.

Inflation Factor (VIF) values were below 2, well under the threshold of 5 (Table 5), confirming that the observed predictive value of the EEG biomarkers was not attributable to collinearity with preoperative pain measures or intraoperative opioid use.

ROC curve analysis showed that the β and γ frequency bands achieved AUC values of 0.794 (95% CI: 0.695–0.893) and 0.818 (95% CI: 0.723–0.913), respectively, in predicting severe postoperative pain, with corresponding sensitivities of 0.8 and 0.9, and specificities of 0.684 and 0.632 (Figure 6). The γ band demonstrated the highest predictive value.

Correlation analysis revealed that preoperative β-wave (R= −0.25, $p<0.05$) and γ-wave (R = −0.32, $p<0.05$) activity intensities were both weakly negatively correlated with postoperative anxiety scores. Furthermore, preoperative β and γ wave activities showed stronger negative associations with postoperative sleep quality scores (β-wave: R = −0.79; γ-wave : R = -0.75; both $p < 0.001$) (Figure 7).

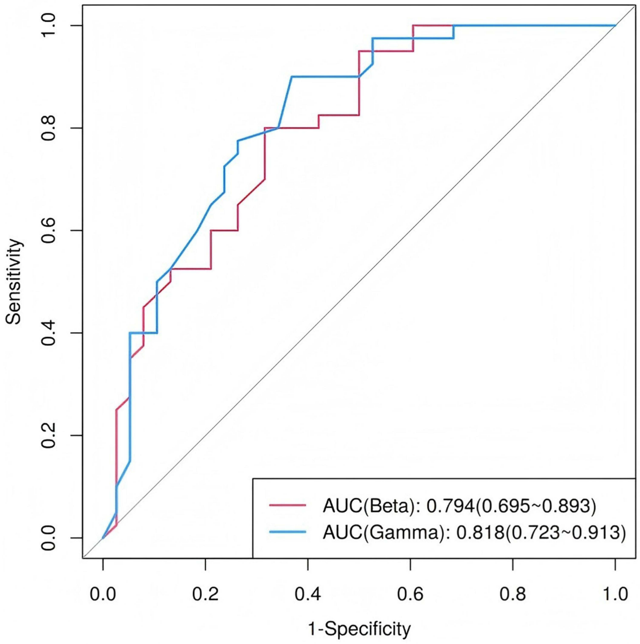

Figure 6 ROC curve was used to analyze the predictive value of preoperative β-band and γ-band for postoperative pain. The cut value of β is 10.8; the cut value of γ is 16.671.

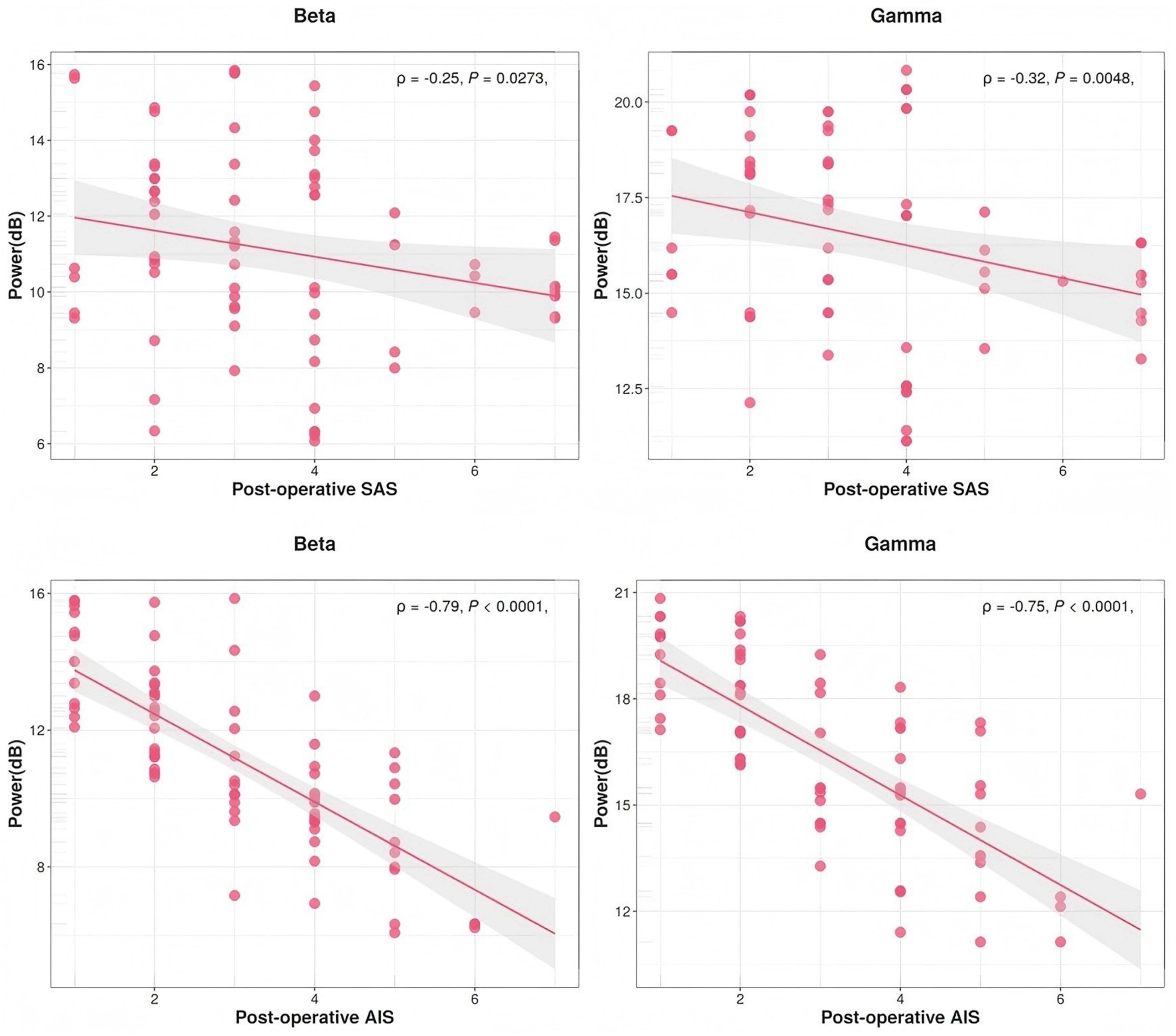

Figure 7 The correlation between SAS, AIS and resting EEG beta (13–30Hz), gamma (> 30Hz) band energy was analyzed one day after operation.
Abbreviations: SAS, Self-Rating Anxiety Scale; AIS, Athens Insomnia Scale.

Discussion

This study confirmed that preoperative resting-state electroencephalographic (EEG) β and γ band power can serve as independent predictors of acute postoperative pain in patients undergoing spine surgery. The lack of significant differences in preoperative pain levels between the two groups preliminarily indicates that the observed EEG differences did not stem from an imbalance in baseline pain. In multivariate analyses, even after controlling for preoperative pain scores, the predictive effects of the β and γ bands remained significant. Furthermore, this study strictly controlled for the confounding effect of opioid-induced hyperalgesia by converting intraoperative opioid dosages into morphine milligram equivalents and including them in the analysis. Results showed no difference in opioid exposure between the groups, and the EEG predictors remained significant after adjustment, further supporting the robustness of the conclusions. Based on these findings, preoperative high-frequency neural oscillations provide an objective, non-invasive biomarker for identifying patients at high risk of postoperative pain. For patients with low preoperative β/γ power, an intensified perioperative analgesic strategy may be considered. This could include scheduled combination therapy with non-opioid analgesics, preferential use of regional anesthesia techniques, and enhanced postoperative pain monitoring with proactive adjustment of analgesic regimens.[20,21] More importantly, this study initially addressed concerns regarding the potential confounding effects of chronic pain related brain remodeling by entering preoperative NRS scores as a covariate in hierarchical regression analysis. These findings collectively demonstrate that the predictive value of preoperative high-frequency oscillatory activity is independent of preoperative transient pain perception. This may reflect stable neural functional characteristics shaped by long-term nociceptive inputs associated with underlying spinal lesions, rather than transient pain perception, and can predict the intensity of individual responses to novel nociceptive stimuli. Additionally, since pain is often accompanied by anxiety and sleep disturbances, psychological interventions or pharmacological support may be appropriately supplemented for such patients, aiming to improve overall recovery and potentially reduce the risk of acute pain transitioning to chronic pain.[22]

Preoperative β band activity showed a significant negative correlation with postoperative pain intensity, reflecting an adaptive regulatory mechanism in which the brain may actively inhibit nociceptive transmission by enhancing beta oscillations. β oscillations primarily originate from the sensorimotor cortex and related thalamocortical circuits, and increased β activity typically indicates enhanced motor preparation inhibition or sensory gating.[23] Therefore, higher preoperative β activity may reflect stronger sensorimotor integration and inhibitory control capacity in the individual's nervous system, leading to more effective "gating" or suppression of nociceptive signal transmission during the post-operative period, ultimately resulting in reduced pain intensity.[24] In contrast to reports in experimental pain studies where γ waves are often positively correlated with pain perception, our findings demonstrated an opposite trend in the context of postoperative pain, which may reflect differences in clinical pain mechanisms and individual regulatory capacity. This difference may reflect a fundamental distinction in the nature of the signals being measured. Experimental pain studies typically capture phasic, stimulus evoked gamma activity in healthy volunteers, which represents the brain's immediate response to external nociceptive input. In contrast, the present study measured preoperative resting-state gamma power, reflecting an individual's baseline neurofunctional status prior to any surgical stimulation. We propose that higher resting-state gamma power, particularly within the temporal insular network, may signify stronger endogenous pain inhibitory capacity. This interpretation aligns with emerging evidence suggesting that gamma oscillations are involved in top-down attentional control, predictive coding, and the maintenance of cortical excitation inhibition balance.[25,26] Specifically, gamma activity mediated by parvalbumin expressing inhibitory interneurons in the insula and anterior cingulate cortex may reflect the brain's baseline inhibitory reserve, which determines the efficiency of subsequent pain inhibitory mechanisms when facing a new nociceptive challenge.[27] Source localization analysis revealed that only the γ band exhibited localized, region-specific differences in pain-related brain areas such as the insula and temporal lobe. This finding suggests that γ oscillations are more concentrated within the core pain-processing network, whereas the influence of β oscillations may be distributed more diffusely across the whole brain. Although significant group differences were also observed in the delta band at a single electrode (C5), this frequency band was not a primary focus of our main analysis. This decision was based on the limited spatial distribution of the delta differences and the lack of a theoretical framework linking delta oscillations to pain prediction. Therefore, the findings in the delta band are more likely to represent random variation or artifacts and were not considered a core biomarker in this study.[28] Meanwhile, α band power showed no significant association with postoperative pain in this cohort, potentially due to its relatively stable activity and lower sensitivity to dynamic changes in acute pain states.[29,30] Therefore, future research should focus on β and γ bands as core biomarkers and further explore interactions between frequency bands in larger sample sizes.

The present study extends the findings of Han et al from thoracoscopic surgery to a cohort of patients undergoing spinal surgery, which is associated with more severe postoperative pain, thereby confirming the robust predictive value of preoperative high-frequency EEG oscillations and offering novel insights.[14] First, the predictive effect of the EEG biomarker persisted after adjustment for preoperative pain levels, suggesting that it reflects a stable neurofunctional trait rather than a transient state. Second, source localization analysis revealed that the predictive capacity of the gamma band is specifically associated with activity in the temporal-insular network, providing new neuroanatomical evidence. This study confirms the independent correlation between preoperative beta and gamma oscillations and postoperative pain intensity; however, acute postoperative pain perception is a complex multidimensional experience modulated by psychological, emotional, and situational factors. Therefore, EEG high-frequency power alone is insufficient to accurately predict individual pain experiences. Future clinical applications are more likely to rely on multimodal predictive models that integrate neurophysiological, psychosocial, and clinical variables. Furthermore, establishing clinically applicable cutoff values will require large-scale, multicenter studies incorporating dose-response analyses or criterion validity designs, and future research should include randomized interventional trials based on EEG stratification.

This study has several limitations. First, the study population consisted of spine surgery patients with prevalent preoperative chronic pain. Long-term pain may induce brain remodeling that influences resting-state EEG signals. Therefore, the biomarkers identified in this study are primarily applicable to this specific population, and their generalizability to patients without baseline pain or to other surgical cohorts requires further validation. Second, despite the standardized anesthetic protocol, differences in surgical duration and complexity might still affect postoperative pain outcomes. Third, although the sample size of 78 met statistical requirements, larger-scale multicenter studies would enhance the generalizability of the findings and allow for subgroup analyses. Additionally, the Spearman correlation coefficients between preoperative β/γ power and postoperative NRS scores ($\rho = -0.84$ and -0.85) were notably high. While these values reflect the strong group differences observed in this cohort, they may be partially attributable to the bimodal distribution of NRS scores resulting from the a priori grouping strategy. Such high correlations in a relatively small sample may overestimate the true predictive strength in the general population. Therefore, these coefficients should be interpreted as indicative of a strong association within the context of a dichotomized sample, and their generalizability requires validation in larger, continuous cohorts. Finally, the observational design cannot establish a causal relationship between EEG activity and pain. Future research should include randomized interventional trials based on EEG stratification.

Conclusion

In conclusion, this study demonstrates that preoperative resting-state EEG β and γ oscillations are independent predictors of acute postoperative pain in patients undergoing spinal decompression surgery. Their predictive effects remained significant after controlling for preoperative pain and intraoperative opioid exposure, suggesting that these high-frequency oscillations reflect stable neurofunctional traits. Source localization further revealed that the predictive capacity of the γ band is specifically associated with temporal-insular network activity. These findings suggest that preoperative EEG metrics could serve as a component of future multi-factorial predictive models for personalized pain management, and that patients with low preoperative β/γ power may benefit from intensified perioperative analgesic strategies. However, given the multifactorial nature of pain perception and the lack of validated clinical thresholds for EEG power, further research is required to establish the practical utility of these biomarkers.

Data Sharing Statement

The datasets generated and analyzed during the current study are included in this published article. Due to the constraints of the ethical approval and the informed consent agreements with the participants, additional individual de-identified participant data will not be shared. Further raw data that support the findings of this study will be made available by the corresponding author, Conghai Fan, upon reasonable request, starting from the date of publication and for a period of six months thereafter. Requests for data access can be directed to FGYXhao@163.com.

Institutional Review Board Statement

The study protocol was approved by the Medical Ethics Committee of Xuzhou Central Hospital (XZXY-LK-20240423-0063), which conforms to the provisions of the Declaration of Helsinki (as revised in Tokyo 2004). The study was registered on the Clinical Trial Registry (https://www.chictr.org.cn/bin/userProject) with the registration number ChiCTR2500101616.

Consent

All patients provided full, informed verbal and written consent to participate.

Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

Funding

The study was supported by Xuzhou Medical Key Talent Training Project (No. XWRCHT20210033); Meiyan Zhou received funding from the Xuzhou Pengcheng Talent Project (XWRCHT20220017 to MYZ). Liwei Wang received funding from the Jiangsu Medical Key Discipline/Laboratory Construction Project (JSDW202231 to LWW).

Disclosure

The authors report no conflicts of interest in this work.

References

1. Tighe PJ, Harle CA, Hurley RW, Aytug H, Boezaart AP, Fillingim RB. Teaching a machine to feel postoperative pain: combining high-dimensional clinical data with machine learning algorithms to forecast acute postoperative pain. *Pain Med*. 2015;16(7):1386–1401. doi:10.1111/pme.12713
2. Gerbershagen HJ, Aduckathil S, van Wijck AJM, Peelen LM, Kalkman CJ, Meissner W. Pain intensity on the first day after surgery: a prospective cohort study comparing 179 surgical procedures. *Anesthesiology*. 2013;118(4):934–944. doi:10.1097/ALN.0b013e31828866b3
3. Ailin H, Jiran ZD, Wenxin Z, et al. Research progress in pain treatment and analgesic targets. *Chin J Pain Med*. 2023;29(7):484–494.
4. Smith ML, Asada N, Malenka RC. Anterior cingulate inputs to nucleus accumbens control the social transfer of pain and analgesia. *Science*. 2021;371(6525):153–159. doi:10.1126/science.abe3040
5. Lieberman MD, Eisenberger NI. The dorsal anterior cingulate cortex is selective for pain: results from large-scale reverse inference. *Proc Natl Acad Sci USA*. 2015;112(49):15250–15255. doi:10.1073/pnas.1515083112
6. Wager TD, Atlas LY, Lindquist MA, Roy M, Woo C-W, Kross E. An fMRI-based neurologic signature of physical pain. *N Engl J Med*. 2013;368(15):1388–1397. doi:10.1056/NEJMoa1204471
7. Zis P, Liampas A, Artemiadis A, et al. EEG recordings as biomarkers of pain perception: where do we stand and where to Go? *Pain Ther*. 2022;11(2):369–380. doi:10.1007/s40122-022-00372-2
8. Xi X, Tao Q, Li J, et al. Emotion-movement relationship: a study using functional brain network and cortico-muscular coupling. *J Neurosci Methods*. 2021;362:109320. doi:10.1016/j.jneumeth.2021.109320
9. Giehl J, Meyer-Brandis G, Kunz M, Lautenbacher S. Responses to tonic heat pain in the ongoing EEG under conditions of controlled attention. *Somatosens Mot Res*. 2014;31(1):40–48. doi:10.3109/08990220.2013.837045
10. Tu Y, Zhang Z, Tan A, et al. Alpha and gamma oscillation amplitudes synergistically predict the perception of forthcoming nociceptive stimuli. *Hum Brain Mapp*. 2016;37(2):501–514. doi:10.1002/hbm.23048
11. Misra G, Wang W-E, Archer DB, Roy A, Coombes SA. Automated classification of pain perception using high-density electroencephalography data. *J Neurophysiol*. 2017;117(2):786–795. doi:10.1152/jn.00650.2016
12. Hartley C, Poorun R, Goksan S, et al. Noxious stimulation in children receiving general anaesthesia evokes an increase in delta frequency brain activity. *Pain*. 2014;155(11):2368–2376. doi:10.1016/j.pain.2014.09.006
13. Sleigh JW, Leslie K, Voss L. The effect of skin incision on the electroencephalogram during general anesthesia maintained with propofol or desflurane. *J Clin Monit Comput*. 2010;24(4):307-318. doi:10.1007/s10877-010-9251-3
14. Han Q, Yue L, Gao F, Zhang L, Hu L, Feng Y. The prediction of acute postoperative pain based on neural oscillations measured before the surgery. *Neural Plast*. 2021;2021:5543974. doi:10.1155/2021/5543974
15. May A. Chronic pain may change the structure of the brain. *Pain*. 2008;137(1):7–15. doi:10.1016/j.pain.2008.02.034
16. Apkarian AV, Sosa Y, Sonty S, et al. Chronic back pain is associated with decreased prefrontal and thalamic gray matter density. *J Neurosci*. 2004;24(46):10410–10415. doi:10.1523/JNEUROSCI.2541-04.2004
17. Napadow V, LaCount L, Park K, As-Sanie S, Clauw DJ, Harris RE. Intrinsic brain connectivity in fibromyalgia is associated with chronic pain intensity. *Arthritis Rheum*. 2010;62(8):2545–2555. doi:10.1002/art.27497
18. Ferreira-Valente MA, Pais-Ribeiro JL, Jensen MP. Validity of four pain intensity rating scales. *Pain*. 2011;152(10):2399–2404. doi:10.1016/j.pain.2011.07.005
19. Duan W, Chen X, Wang Y-J, Zhao W, Yuan H, Lei X. Reproducibility of power spectrum, functional connectivity and network construction in resting-state EEG. *J Neurosci Methods*. 2021;348:108985. doi:10.1016/j.jneumeth.2020.108985
20. Schulz E, Zherdin A, Tiemann L, Plant C, Ploner M. Decoding an individual's sensitivity to pain from the multivariate analysis of EEG data. *Cerebral Cortex*. 2012;22(5):1118–1123. doi:10.1093/cercor/bhr186
21. Chunduri A, Aggarwal AK. Multimodal pain management in orthopedic surgery. *J Clin Med*. 2022;11(21):6386. doi:10.3390/jcm11216386
22. Scott AJ, Correa AB, Bisby MA, et al. Cognitive behavioral therapy for insomnia in people with chronic disease: a systematic review and meta-analysis. *JAMA Intern Med*. 2025;22. doi:10.1001/jamainternmed.2025.4610
23. Muralidharan V, Aron AR. Behavioral induction of a high beta state in sensorimotor cortex leads to movement slowing. *J Cogn Neurosci*. 2021;33(7):1311–1328. doi:10.1162/jocn_a_01717
24. Engel AK, Fries P. Beta-band oscillations — signalling the status quo? *Curr Opin Neurobiol*. 2010;20(2):156–165. doi:10.1016/j.conb.2010.02.015

25. Bauer M, Stenner M-P, Friston KJ, Dolan RJ. Attentional modulation of alpha/beta and gamma oscillations reflect functionally distinct processes. *J Neurosci*. 2014;34(48):16117–16125. doi:10.1523/JNEUROSCI.3474-13.2014
26. Ploner M, Sorg C, Gross J. Brain rhythms of pain. *Trends Cognit Sci*. 2017;21(2):100–110. doi:10.1016/j.tics.2016.12.001
27. Sohal VS, Zhang F, Yizhar O, Deisseroth K. Parvalbumin neurons and gamma rhythms enhance cortical circuit performance. *Nature*. 2009;459(7247):698–702. doi:10.1038/nature07991
28. Lendner JD, Helfrich RF, Mander BA, et al. An electrophysiological marker of arousal level in humans. *Elife*. 2020;9:e55092. doi:10.7554/eLife.55092
29. Millard SK, Furman AJ, Kerr A, et al. Predicting postoperative pain in lung cancer patients using preoperative peak alpha frequency. *Br J Anaesth*. 2022;128(6):e346–e348. doi:10.1016/j.bja.2022.03.006
30. Hauck M, Domnick C, Lorenz J, Gerloff C, Engel AK. Top-down and bottom-up modulation of pain-induced oscillations. *Front Hum Neurosci*. 2015;9:375. doi:10.3389/fnhum.2015.00375