

The Impact of Electroencephalogram-Guided General Anesthesia on Postoperative Delirium and Recovery in Patients Over 60 with Hip Fractures: A Retrospective Cohort Study

Yang Liu^{1,*}, Hong Fan^{1,*}, Guohua Wei², Yinyin Shu¹, Jigang Zhang²

¹Department of Anesthesiology, Jinling Hospital Affiliated to Nanjing University School of Medicine, Nanjing, Jiangsu, 210002, People's Republic of China; ²Department of Anesthesia and Perioperative Medicine, the First Affiliated Hospital of Nanjing Medical University, Nanjing, Jiangsu, 210029, People's Republic of China

*These authors contributed equally to this work

Correspondence: Jigang Zhang, Department of Anesthesia and Perioperative Medicine, the First Affiliated Hospital of Nanjing Medical University, No. 300 Guangzhou Road, Nanjing, Jiangsu, 210002, People's Republic of China, Email 18752035417@163.com

Background: Hip fractures in the elderly often lead to high morbidity, prolonged hospitalization, and postoperative delirium—a prevalence noted to affect up to 50% of such patients. This study evaluates whether electroencephalogram (EEG)-guided general anesthesia can reduce postoperative delirium and enhance recovery in elderly hip fracture cases.

Methods: This retrospective cohort study analyzed patients aged ≥ 60 years who underwent hip fracture surgery under general anesthesia from November 2022 to May 2024. After propensity score matching, patients were divided into two groups: routine anesthesia ($n=118$) and EEG-guided anesthesia ($n=105$). Outcomes measured included the incidence of delirium (Confusion Assessment Method), cognitive recovery (SLUMS, Saint Louis University Mental Status Examination), hospital stay duration, post-anesthesia care unit (PACU) stay duration, and patient satisfaction.

Results: The EEG-guided group showed significant reductions in the incidence of postoperative delirium on the first and third days (8.57% vs 20.34%, $P=0.014$, and 8.57% vs 22.88%, $P=0.004$, respectively). However, this difference was no longer significant on the fifth day and thereafter. The EEG-guided group also demonstrated better early cognitive recovery with higher SLUMS scores on postoperative days 1 and 3 (both $P=0.008$). Hospitalization outcomes favored the EEG-guided group, with shorter PACU retention and hospital stays ($P < 0.001$ and $P=0.008$, respectively). Patient satisfaction was significantly higher in the EEG-guided group ($P=0.007$). Logistic regression identified EEG-guided anesthesia as a protective factor against delirium (OR 0.316; 95% CI, 0.134–0.685; $P=0.005$), reduced burst suppression duration, and reduced propofol dosage.

Conclusion: EEG-guided general anesthesia seems to be associated with lower rates of early postoperative delirium and improved cognitive recovery in elderly patients with hip fractures.

Keywords: electroencephalography, anesthesia, elderly patients, delirium, cognition disorders, patient satisfaction

Introduction

With the rapid aging of the global population, the incidence of hip fractures in the elderly is a common and challenging clinical issue.^{1,2} Such fractures are often associated with prolonged hospital stays, increased morbidity, and higher mortality rates, imposing a significant economic burden on healthcare systems and society.³ Among these, postoperative delirium (POD) is particularly concerning, affecting up to 50% of elderly hip fracture patients and leading to worse clinical outcomes, including prolonged recovery and increased healthcare costs.⁴

The etiology of POD was multifactorial, involving pre-existing cognitive impairments, polypharmacy, and the use of general anesthesia, among other factors.^{5,6} Elderly patients are especially vulnerable to the neurocognitive effects of

general anesthesia due to age-related physiological changes and reduced pharmacological resilience.⁷ Traditional anesthesia methods that rely on standardized dosing can lead to excessive anesthetic depth, resulting in over-suppression of cortical activity, impaired cerebral blood flow autoregulation, and even induction of neuroinflammatory responses. These mechanisms collectively increase the risk of postoperative cognitive dysfunction and can contribute to delirium and delayed recovery.

In recent years, the use of electroencephalogram (EEG) monitoring to guide the administration of general anesthesia has garnered considerable interest.⁸ Unlike the common practice of using EEG indices (such as BIS), this study employed raw EEG monitoring, which provides richer electrophysiological information, including direct detection of delta wave oscillations and burst suppression patterns. This raw EEG monitoring allows anesthesiologists to more intuitively and accurately assess the depth of anesthesia, particularly aiding in the identification and avoidance of deep anesthesia states closely associated with postoperative neurocognitive disorders.⁹ By tailoring anesthetic depth to each individual's needs, EEG-guided anesthesia has the potential to minimize the risk of over-sedation and its associated complications.¹⁰ Several studies have suggested that EEG-guided anesthesia can reduce the incidence of POD, particularly in the elderly population.^{11,12} However, the evidence remains mixed, with some studies showing significant benefits, while others indicate no notable reduction in delirium rates. This inconsistency highlights areas that require further research.^{13,14}

The mechanistic foundation for EEG-guided anesthesia lies in the ability to maintain an optimal anesthetic depth that balances adequate sedation with minimal neuronal impact.¹⁵ An optimal level of sedation can preserve the functionality of neurotransmitters and protect against neural cytotoxicity.¹⁶ Furthermore, the potential neuroprotective aspects of EEG-guided anesthesia align with broader efforts to enhance recovery in surgical patients. Enhanced Recovery After Surgery (ERAS) protocols have incorporated EEG guidance as a component to improve perioperative outcomes, with positive preliminary results.¹⁷ Although hip fracture surgery often prefers spinal anesthesia, in certain specific situations such as difficulty in positioning the patient, anticoagulation therapy, or the presence of specific anesthesia contraindications, general anesthesia is still a necessary choice.

This study seeks to explore the impact of EEG-guided general anesthesia on POD and recovery in elderly patients with hip fractures. The innovation of this study lies in focusing on elderly hip fracture patients, a high-risk subgroup distinct from general surgical populations. Methodologically, we use propensity score matching to balance baseline differences, enhancing inter-group comparability and result reliability. By combining delirium assessment with cognitive recovery evaluation, we comprehensively depict postoperative neurocognitive trajectories. Additionally, we explore intraoperative burst suppression and anesthetic drug dosing, providing more precise and reliable evidence for the value of EEG-guided anesthesia in this specific population.

Materials and Methods

Study Design and Patients

This study employed a retrospective cohort design to assess patients who underwent hip fracture surgery under general anesthesia, with data collection spanning from November 2022 to May 2024. This study employed a retrospective design. Our institution is a hospital that integrates clinical care, teaching, and research, and all management of hip fracture patients follows standardized clinical pathways. All patient assessments and anesthesia protocols are part of routine clinical practice. Collect patient information through the hospital's electronic medical record system, including basic patient information, medication use, treatment outcomes, length of hospital stay, etc. The inclusion criteria specified participants aged 60 years or older, possessing effective communication skills, classified as American Society of Anesthesiologists (ASA) grade I–III, and achieving normal scores on the preoperative Saint Louis University Mental Status Examination (SLUMS), defined as a score greater than 20. The study excluded patients who had neurological or psychiatric disorders, were on medications impacting the central nervous system (eg, antidepressants), had follow-up challenges, or demonstrated poor compliance. During the study period, a total of 350 patients undergoing hip fracture surgery were screened, of which 298 met the inclusion criteria. Thirty-one patients were excluded for receiving spinal

anesthesia, and 20 were excluded for not meeting other selection criteria. Ultimately, 247 patients were included in the analysis cohort before propensity score matching (Figure 1).

This study included both intra- and extracapsular hip fractures because they are common types of hip fractures in elderly patients and are both associated with an increased risk of postoperative delirium. Through propensity score matching (PSM), we ensured that there were no significant differences in the distribution of fracture types between the two groups, thereby controlling for this potential confounding factor.

Patients were divided into the Routine group and the EEG-guided group based on the treatment they received. To reduce potential selection bias and balance baseline characteristics between the two groups, we employed PSM. The covariates included age, gender, body mass index (BMI), history of hypertension, history of diabetes, and others. The 1:1 nearest neighbor matching method was used with a caliper value of 0.02. Before matching, there were 129 patients in the conventional group and 118 patients in the EEG-guided group. After propensity score matching, a total of 223 patients were successfully matched, including 118 patients in the conventional group and 105 patients in the EEG-guided group. Eleven patients who failed to match were excluded from subsequent analyses. After matching, the standardized mean difference of all covariates was less than 0.1, indicating that the baseline characteristics of the two groups were well balanced. The sample size calculation was based on the effect size ($OR = 0.45$) of EEG-guided anesthesia on delirium incidence observed in a previous study, with α set to 0.05 and β set to 0.2.¹⁸ Using G*Power software, we determined that at least 98 patients per group were required. We ultimately included 223 patients, which meets the statistical requirements.

The study received approval from the Institutional Review Board and Ethics Committee of the hospital (Ethical Approval Number: 2024-SR-205). The requirement for informed consent was waived, as the study utilized de-identified

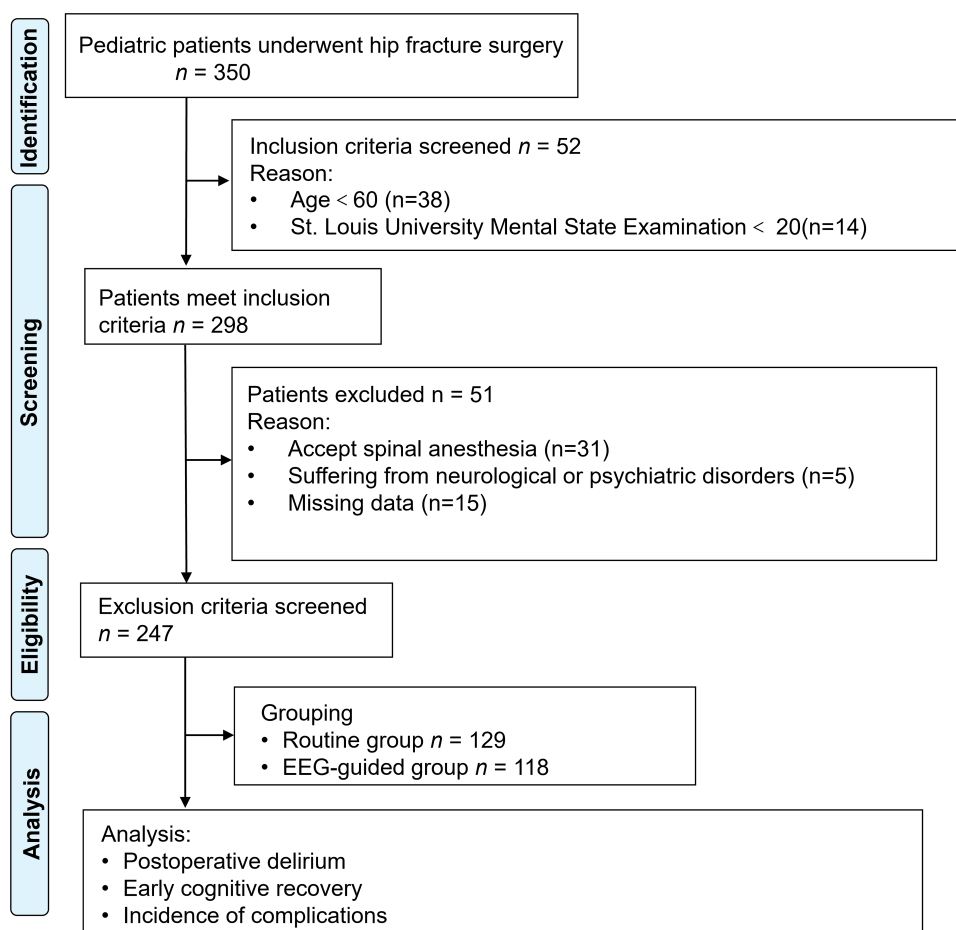


Figure 1 Incorporate into the process.

patient data, with no potential impact on patient care. Our research adheres to regulatory and ethical guidelines applicable to retrospective studies, including compliance with the Declaration of Helsinki.

Treatment Approach

Upon the participants' entry into the operating room, continuous monitoring of the five-lead electrocardiogram (ECG), invasive blood pressure via the radial artery, and pulse oxygen saturation (SpO₂) was implemented. Sensors (M-LNCS Aidx, Masimo, USA) were affixed to the foreheads of all subjects. The sensor has superior motion artifact resistance and low-perfusion performance, which enhances signal reliability in elderly patients with potential peripheral circulatory compromise. Induction of general anesthesia involved administration of midazolam (0.02 mg/kg, Jiangsu Enhua Pharmaceutical Co., Ltd, Approval No: H20143222, China), etomidate (0.2 mg/kg, Jiangsu Enhua Pharmaceutical Co., Ltd, Approval No: H32022992, China), sufentanil (0.5 µg/kg, Jiangsu Enhua Pharmaceutical Co., Ltd, Approval No: H20203650, China), and cisatracurium (0.2 mg/kg, Jiangsu Hengrui Pharmaceutical Co., Ltd, Approval No: H20183042, China). Anesthesia maintenance was achieved using propofol infusion (Sichuan Guorui Pharmaceutical Co., Ltd, Approval No: H20030115, China) at 4–12 mg/kg/h and remifentanyl at 0.1–0.3 µg/kg/min (Yichang Renfu Pharmaceutical Co., Ltd, Approval No: H20030197, China) following intubation, with no volatile anesthetic agents administered to either group.

During the surgery, the EEG-guided group continuously monitored raw EEG to adjust the infusion rate of propofol to maintain stable slow-wave/delta oscillations (corresponding to C-D stage anesthesia depth). When the anesthesia depth deviated from the target band, the propofol dose was adjusted in 0.5 mg/kg increments to ensure continuous and stable delta wave oscillations. Propofol, as a GABA-A receptor agonist, has anesthetic effects that are closely related to the induction of delta waves and the suppression of beta waves (12–25 Hz). An adequate dose of propofol results in high-amplitude delta wave oscillations in the EEG, similar to those observed during natural slow-wave sleep. Therefore, maintaining stable delta wave activity is a reliable indicator for assessing the depth of propofol anesthesia. EEG data were acquired using a 4-channel Sedline brain function monitor (Masimo, Irvine, CA, USA), with electrodes placed at Fp1, Fp2, F7, and F8, a ground electrode at Fpz, and a reference electrode positioned approximately 1 cm above Fpz. The EEG data were recorded at a sampling rate of 178 Hz with a preamplifier bandwidth of 0.5–92 Hz. Burst suppression referred to a phenomenon in which the EEG exhibited alternating periods of high-amplitude discharges (bursts) and low-amplitude or no activity (suppression) for an extended duration, typically exceeding 2 seconds. We employed a spectral analysis-based method to identify burst suppression. An event was defined as burst suppression when the power spectral density of the EEG signal fell below the background noise level for a continuous period of 2 seconds or longer, and this state persisted for at least 2 seconds. Burst suppression identification was performed using an automated algorithm. All EEG recordings were retrospectively reviewed and analyzed by experienced researchers after surgery to confirm burst suppression events and calculate their duration. The mean duration represented the average duration (in seconds) of all burst suppression events for each patient. An experienced researcher manually reviewed the EEG data of all patients to verify precise time points and anesthesia levels. Spectral analysis was performed on 10-second segments of intraoperative, artifact-free, non-burst suppression EEG using the multitaper method with the MATLAB Chronux toolbox.^{19,20} Parameters for spectral analysis included five tapers (K=5), a window length of 2 seconds with a 1.95-second overlap, a spectral resolution of 3 Hz, and a time-bandwidth product of TW=3.

In the routine group, anesthesia depth was adjusted based on clinical experience to maintain stable vital signs. For both groups, vasoactive drugs were administered as necessary to ensure mean arterial pressure (MAP) fluctuations remained within ±20% of the patient's baseline. Postoperative pain management employed a patient-controlled intravenous analgesia pump (PCIA, 150 mL) containing flurbiprofen (Shanghai Zhongxi 3D Pharmaceutical Co., Ltd, Approval No: H19980113, China) at 1.5–2 mg/kg and sufentanil at 3.5–4.5 µg/kg. The pump settings included a locking time of 15 minutes, a background infusion rate of 2 mL/h, and a controlled dose of 2 mL. An additional intravenous injection of 50 mg flurbiprofen was available as a rescue analgesic if required. Postoperative monitoring included hourly vital sign checks and delirium assessments using Confusion Assessment Method for the Intensive Care Unit (CAM-ICU). Assessments were performed three times daily (8 AM, 2 PM, 8 PM) by trained staff.

Intraoperative parameters, anesthetic dosages, and the incidence and duration of burst suppression were documented for both groups.

The primary outcomes were incidence of postoperative delirium (days 1–7) and early cognitive recovery (SLUMS scores), while secondary outcomes included intraoperative situation, anesthesia drug dosage, hospitalization status, and complication rates.

POD Assessment

The incidence of delirium in patients between the first and seventh postoperative days was evaluated using the Confusion Assessment Method for the Intensive Care Unit (CAM-ICU). The CAM-ICU evaluates four key features: (1) acute onset or fluctuating course of mental status changes, (2) inattention, (3) disorganized thinking, and (4) altered level of consciousness. Accumulate ratings based on the above characteristics. Delirium observation scores were collected three times daily, and the daily average was calculated to represent the delirium score for that day. The kappa statistic, indicating assessment reliability, was 0.96.²¹ For patients who scored 3 or higher, a psychiatric consultation was conducted to confirm the diagnosis of POD in accordance with the Diagnostic and Statistical Manual of Mental Disorders (DSM) criteria.²² Patients who developed delirium within the first three postoperative days were assigned to the delirium group (n=36), while those who did not were placed in the non-delirium group (n=187).

Hospital Discharge Status and Postoperative Complications

The criteria for transferring patients from the Post-Anesthesia Care Unit (PACU) to a regular ward were based on the Modified Aldrete Score, a scoring system used to assess whether patients are fit to be transferred from the recovery room to a regular ward.²³ The scoring items included mobility, respiration, circulatory stability, level of consciousness, and oxygen saturation. A total score of 9 or higher indicated that the patient was suitable for transfer from the PACU to a regular ward. Additionally, clinicians made individual assessments based on specific conditions, such as stable vital signs, manageable pain, and the absence of severe complications.

The incidence of postoperative complications, including bradycardia, postoperative respiratory depression, and hypotension, was recorded.

Postoperative Cognitive Function Evaluation

Cognitive function in patients was assessed using the SLUMS between the first and seventh postoperative days. SLUMS is a brief 11-item questionnaire that evaluates cognitive domains such as orientation, memory, attention, and executive function. The total score for SLUMS is 30 points. A score of 27–30 indicates normal cognitive function (no cognitive impairment), scores between 21 and 26 indicate mild cognitive impairment (MCI), and scores of 20 or below indicate dementia. The reliability of the SLUMS, as measured by Cronbach's alpha, is 0.71.²⁴

Patients Satisfaction Survey

Patient satisfaction with treatment in both groups was evaluated using a hospital-developed questionnaire. The questionnaire includes the following contents: postoperative pain control, doctor-patient communication, patient comfort, and overall experience, with a maximum score of 25 points for each item. Patient satisfaction is evaluated based on the total score and divided into the following levels: very satisfied (90–100 points), satisfied (60–89 points), and dissatisfied (below 60 points). The higher the score, the higher the satisfaction of the participants. We conducted reliability and validity testing on the questionnaire used. Internal consistency was assessed using Cronbach's alpha, and the results showed that the questionnaire had good reliability (Cronbach's alpha = 0.830). Additionally, structural validity was confirmed through factor analysis (KMO = 0.785), which indicated that all indicators of the questionnaire aligned with the expected theoretical framework.

Statistical Analysis

Statistical analyses were conducted using SPSS version 29.0 (SPSS, Inc., Chicago, IL, USA). The Shapiro–Wilk test was applied to assess the normality of continuous data. Quantitative data were presented as either mean \pm standard deviation (SD) or median with interquartile range, depending on their distribution. Categorical variables are represented by n (%). For

normally distributed data, an independent two-sample *t*-test was utilized, while the Mann–Whitney *U*-test was employed for non-normally distributed data. To compare categorical variables between the two groups, the Pearson χ^2 -test or Fisher's exact test was used. A *p*-value of less than 0.05 was considered statistically significant across all analyses. In the logistic regression analysis, we focused on three core variables directly related to our research hypothesis: treatment method (EEG-guided anesthesia), propofol dose, and burst suppression duration. This analytical strategy was determined based on previous clinical theory, aiming to examine the potential mechanism by which EEG-guided anesthesia reduces the risk of delirium by decreasing propofol dosage and burst suppression events. This approach avoids the problem of over-adjustment that can result from including too many variables. Logistic regression was applied to identify the risk factors for developing POD, with odds ratios (OR) and 95% confidence intervals (CIs) reported. Receiver operating characteristic (ROC) curves were constructed to evaluate the predictive performance of identified risk factors for POD. The area under the curve (AUC) was calculated to quantify the discriminatory ability of these factors.

Results

Propensity Score Matching

In the comparison of demographic and baseline data between the Routine group and the EEG-guided group before propensity score matching, significant differences were observed in BMI ($p = 0.033$), history of diabetes ($p = 0.045$), and baseline SLUMS scores ($p = 0.045$; Table 1). We found no significant differences in other parameters including age, gender distribution, hypertension, cardiovascular diseases, respiratory diseases, history of stroke, osteoporosis, smoking history, drinking history, cause of injury, fracture type, ASA grade, educational level, living independently status, and surgical interventions (all *p* values > 0.05).

Table 1 Comparison of Demographic and Baseline Data Between the Two Groups Before Propensity Score Matching

Parameters	Routine Group (n=129)	EEG-Guided Group (n=118)	<i>t</i> / χ^2	<i>P</i>
Age (years)	70.62 ± 2.65	70.14 ± 2.46	1.470	0.143
Gender (Male (%)/Female (%))	81 (62.79%) / 48 (37.21%)	73 (61.86%) / 45 (38.14%)	0.023	0.881
BMI (kg/m ²)	22.84 ± 2.42	23.52 ± 2.56	2.139	0.033
Hypertension [n (%)]	62 (48.06%)	61 (51.69%)	0.325	0.568
Diabetes [n (%)]	29 (22.48%)	15 (12.71%)	4.017	0.045
Cardiovascular disease [n (%)]	73 (56.59%)	61 (51.69%)	0.595	0.441
Respiratory disease [n (%)]	36 (27.91%)	39 (33.05%)	0.771	0.380
History of Stroke [n (%)]	9 (6.98%)	12 (10.17%)	0.808	0.369
Osteoporosis [n (%)]	37 (28.68%)	38 (32.20%)	0.361	0.548
Smoking history [n (%)]	15 (11.63%)	18 (15.25%)	0.700	0.403
Drinking history [n (%)]	13 (10.08%)	9 (7.63%)	0.456	0.499
Pathogeny of injury [n (%)]			1.508	0.471
Fall injury	108 (83.72%)	94 (79.66%)		
Motor vehicle accident	20 (15.50%)	21 (17.80%)		
Others	1 (0.78%)	3 (2.54%)		
Fracture type [n (%)]			1.491	0.684
Femoral neck	76 (58.91%)	67 (56.78%)		
Pertrochanteric	49 (37.98%)	44 (37.29%)		
Subtrochanteric	3 (2.33%)	4 (3.39%)		
Periprosthetic	1 (0.78%)	3 (2.54%)		
ASA grade [n (%)]			0.168	0.682
II	100 (77.52%)	94 (79.66%)		
III	29 (22.48%)	24 (20.34%)		

(Continued)

Table 1 (Continued).

Parameters	Routine Group (n=129)	EEG-Guided Group (n=118)	t/ χ^2	P
Educational level [n (%)]			0.508	0.776
Illiterate	14 (10.85%)	15 (12.71%)		
Primary school	56 (43.41%)	54 (45.76%)		
Middle school and above	59 (45.74%)	49 (41.53%)		
Living independently [n (%)]	85 (65.89%)	87 (73.73%)	1.790	0.181
Surgical intervention [n (%)]			0.544	0.969
Hemiarthroplasty	56 (43.41%)	52 (44.07%)		
Intramedullary nailing	46 (35.66%)	44 (37.29%)		
Dynamic hip screw	13 (10.08%)	12 (10.17%)		
Total hip arthroplasty	12 (9.30%)	8 (6.78%)		
Revision arthroplasty	2 (1.55%)	2 (1.69%)		
SLUMS score at baseline	25.64 ± 2.33	26.29 ± 2.76	2.011	0.045

Abbreviations: BMI, body mass index; ASA, American Society of Anesthesiologists classification; SLUMS, Saint Louis University Mental Status Examination; EEG, Electroencephalogram.

In the comparison of demographic and baseline data between the Routine group and the EEG-guided group before propensity score matching, we observed significant differences in BMI ($p = 0.033$), history of diabetes ($p = 0.045$), and baseline SLUMS scores ($p = 0.045$; [Table 1](#)).

Demographic and Basic Data

In this study examining the impact of EEG-guided general anesthesia on POD and recovery in elderly patients with hip fractures, we found that after propensity score matching, baseline demographic and clinical characteristics were comparable between the routine group ($n=118$) and the EEG-guided group ($n=105$) ([Table 2](#)). We observed no significant differences in age, gender, BMI, comorbidities (hypertension, diabetes, cardiovascular or respiratory disease), fracture type, ASA grade, or baseline SLUMS scores (all $p > 0.05$).

Table 2 Comparison of Demographic and Basic Data Between the Two Groups

Parameters	Routine Group (n=118)	EEG-Guided Group (n=105)	t/ χ^2	P
Age (years)	70.36±2.58	69.82±2.34	1.628	0.105
Gender (Male %)/Female (%)	76 (64.41%)/42 (35.59%)	70 (66.67%) /35 (33.33%)	0.126	0.723
BMI (kg/m ²)	22.81±2.31	23.02±2.29	0.685	0.494
Hypertension [n (%)]	57 (48.31%)	54 (51.43%)	0.217	0.641
Diabetes [n (%)]	19 (16.1%)	14 (13.33%)	0.338	0.561
Cardiovascular disease [n (%)]	67 (56.78%)	55 (52.38%)	0.434	0.510
Respiratory disease [n (%)]	33 (27.97%)	35 (33.33%)	0.755	0.385
History of Stroke [n (%)]	8 (6.78%)	11 (10.48%)	0.974	0.324
Osteoporosis [n (%)]	34 (28.81%)	34 (32.38%)	0.334	0.564
Smoking history [n (%)]	14 (11.86%)	16 (15.24%)	0.543	0.461
Drinking history [n (%)]	12 (10.17%)	8 (7.62%)	0.443	0.506
Pathogeny of injury [n (%)]			1.477	0.478
Fall injury	99 (83.90%)	84 (80.00%)		
Motor vehicle accident	18 (15.25%)	18 (17.14%)		
Others	1 (0.85%)	3 (2.86%)		

(Continued)

Table 2 (Continued).

Parameters	Routine Group (n=118)	EEG-Guided Group (n=105)	t/ χ^2	P
Fracture type [n (%)]			2.283	0.516
Femoral neck	70 (59.32%)	59 (56.19%)		
Pertrochanteric	45 (38.14%)	39 (37.14%)		
Subtrochanteric	2 (1.69%)	4 (3.81%)		
Periprosthetic	1 (0.85%)	3 (2.86%)		
ASA grade [n (%)]			0.138	0.710
II	92 (77.97%)	84 (80%)		
III	26 (22.03%)	21 (20%)		
Educational level [n (%)]			0.355	0.837
Illiterate	13 (11.02%)	13 (12.38%)		
Primary school	51 (43.22%)	48 (45.71%)		
Middle school and above	54 (45.76%)	44 (41.90%)		
Living independently [n (%)]	78 (66.10%)	78 (74.29%)	1.771	0.183
Surgical intervention [n (%)]			0.545	0.969
Hemiarthroplasty	51 (43.22%)	46 (43.81%)		
Intramedullary nailing	42 (35.59%)	39 (37.14%)		
Dynamic hip screw	12 (10.17%)	11 (10.48%)		
Total hip arthroplasty	11 (9.32%)	7 (6.67%)		
Revision arthroplasty	2 (1.69%)	2 (1.90%)		
SLUMS score at baseline	26.18 \pm 2.35	26.23 \pm 2.42	0.149	0.882

Pod

On the first postoperative day, we observed delirium in 20.34% of patients in the routine group, whereas only 8.57% of patients in the EEG-guided group experienced delirium ($p=0.014$) (Table 3). By the third postoperative day, we found that the difference remained significant ($p=0.004$). Although there was a numerical reduction in delirium on the fifth day (8.47% vs 2.86%), we noted that this did not reach statistical significance ($p=0.074$). By the seventh postoperative day, we observed that none of the patients in the EEG-guided group experienced delirium, compared to 4.24% in the routine group, though this difference was not statistically significant ($p=0.093$).

Postoperative SLUMS Score

On the first postoperative day, we observed that the EEG-guided group demonstrated significantly higher SLUMS scores compared to the routine group ($p=0.008$) (Figure 2). This trend continued on the third postoperative day, with us finding that the EEG-guided group maintained superior cognitive performance relative to the routine group ($p=0.008$). However, by the fifth ($p=0.388$) and seventh postoperative days ($p=0.439$), we noted that the differences in SLUMS scores between the two groups were no longer statistically significant, indicating convergence in cognitive recovery.

Table 3 Comparison of POD Between the Two Groups

Parameters	Routine Group (n=118)	EEG-Guided Group (n=105)	χ^2	P
Postoperatively 1st day [n (%)]	24 (20.34%)	9 (8.57%)	6.102	0.014
Postoperatively 3rd day [n (%)]	27 (22.88%)	9 (8.57%)	8.404	0.004
Postoperatively 5th day [n (%)]	10 (8.47%)	3 (2.86%)	3.194	0.074
Postoperatively 7th day [n (%)]	5 (4.24%)	0 (0.00%)	2.823	0.093

Abbreviation: EEG, Electroencephalogram.

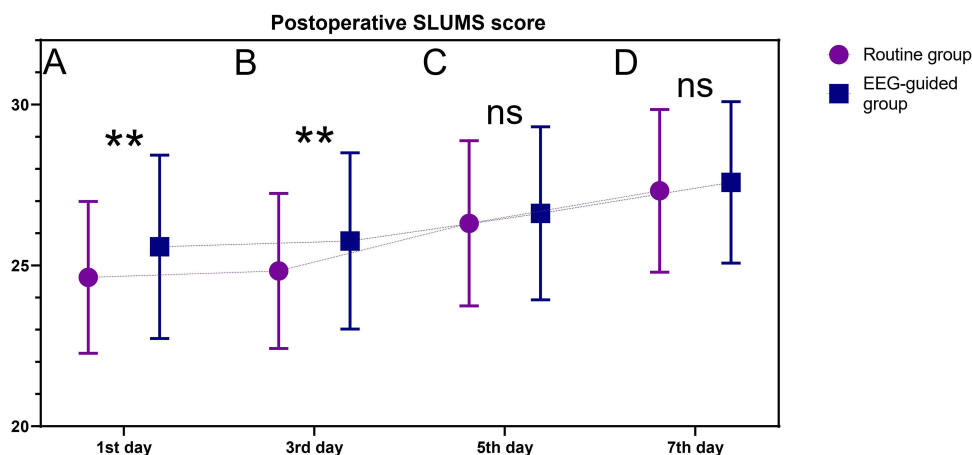


Figure 2 Comparison of Postoperative SLUMS score between the two groups. (A) SLUMS 1st day postoperatively; (B) SLUMS 3rd day postoperatively; (C) SLUMS 5th day postoperatively; (D) SLUMS 7th day postoperatively. ** $P < 0.01$.

Abbreviations: EEG, Electroencephalogram; SLUMS, Saint Louis University Mental Status Examination; ns, no significant difference.

Intraoperative Situation

The duration of surgery was notably shorter in the EEG-guided group ($p=0.001$) (Table 4). Similarly, we observed that anesthesia duration was reduced with EEG guidance ($p=0.005$). We found no significant difference in fluid infusion volume, estimated blood loss, or urine volume. Notably, we observed that the incidence of BS was significantly lower in the EEG-guided group, with only 7.62% compared to 17.80% in the routine group ($p=0.024$). Furthermore, we noted that the duration of burst suppression episodes was markedly shorter in the EEG-guided group, lasting 5.31 ± 2.62 seconds versus 15.38 ± 3.41 seconds in the routine group ($p < 0.001$).

Anesthesia Drug Dosage

In the analysis of anesthesia drug dosages between the routine and EEG-guided groups, we observed a significant reduction in the EEG-guided group, with a mean dosage of 352.9 ± 56.91 mg compared to 409.82 ± 56.78 mg in the routine group ($p < 0.001$) (Figure 3A). We found no statistically significant differences in the dosages of sufentanil (29.15 ± 8.35 μg vs 30.47 ± 8.24 μg , $p=0.236$) (Figure 3B), remifentanyl (1350.42 ± 325.24 μg vs 1373.38 ± 305.42 μg , $p=0.587$) (Figure 3C), or cisatracurium (9.67 ± 2.69 mg vs 10.19 ± 2.25 mg, $p=0.122$) (Figure 3D) between the groups.

Hospitalization Status

The total length of hospital stay was significantly shorter for patients in the EEG-guided group ($P=0.008$) (Table 5). Additionally, we observed that patients in the EEG-guided group had a reduced retention time in the postanesthesia care

Table 4 Comparison of Intraoperative Situation Between the Two Groups

Parameters	Routine Group (n=118)	EEG-Guided Group (n=105)	t/χ^2	P
Duration of surgery (min)	65.14 \pm 8.15	61.36 \pm 9.24	3.246	0.001
Duration of anesthesia (min)	95.38 \pm 10.84	91.14 \pm 11.35	2.853	0.005
Fluid infusion volume (mL)	1500.46 \pm 312.48	1450.39 \pm 328.69	1.166	0.245
Estimated blood loss volume (mL)	230.34 \pm 57.36	217.69 \pm 57.14	1.646	0.101
Urine volume (mL)	205.42 \pm 62.14	190.11 \pm 62.37	1.833	0.068
BS [n (%)]	21 (17.80%)	8 (7.62%)	5.087	0.024
Mean duration of BS (s)	15.38 \pm 3.41	5.31 \pm 2.62	24.87	< 0.001

Abbreviations: BS, burst suppression; EEG, Electroencephalogram.

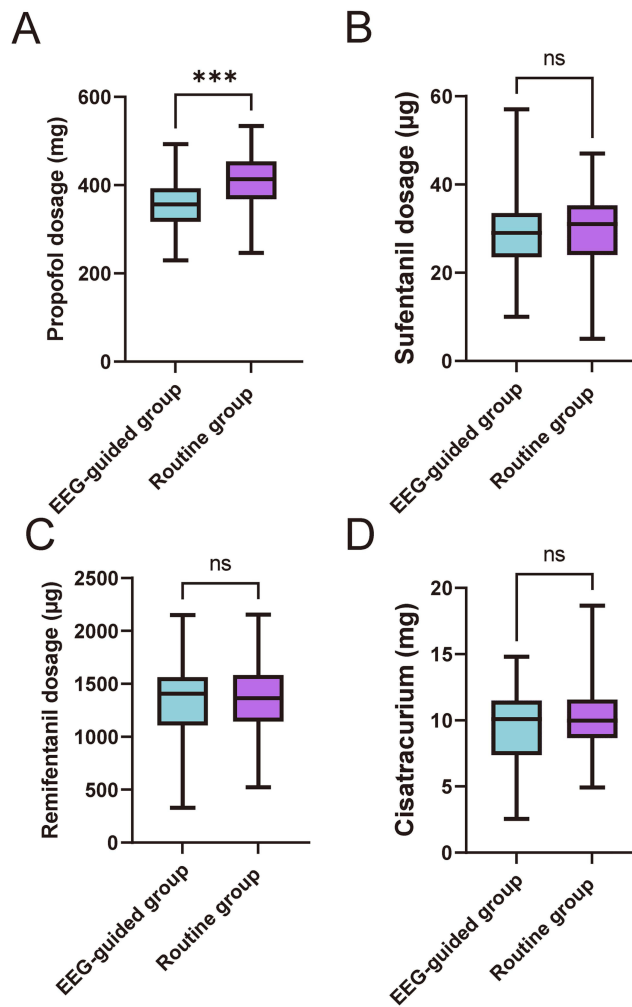


Figure 3 Comparison of Anesthesia drug dosage between the two groups. (A) Propofol dosage; (B) Sufentanil dosage; (C) Remifentanyl dose; (D) Cisatracurium. *** $P < 0.001$. **Abbreviations:** EEG, Electroencephalogram; Ns, no significant difference.

unit (PACU) ($P < 0.001$). Furthermore, we found that the incidence of prolonged hospitalization was significantly lower in the EEG-guided group at 10.48% compared to 21.19% in the routine group ($P=0.030$).

Patient Satisfaction

We observed that the percentage of patients who reported being “very satisfied” was significantly higher in the EEG-guided group (30.48%) compared to the routine group (16.95%) (Table 6). Additionally, we found a greater overall satisfaction rate in the EEG-guided group, with 92.38% of patients expressing satisfaction, in contrast to 79.66% in the routine group ($P=0.007$). We noted that the proportion of dissatisfied patients was markedly lower in the EEG-guided group compared to the routine group.

Table 5 Comparison of Hospitalization Status Between the Two Groups

Parameters	Routine Group (n=118)	EEG-guided Group (n=105)	t/χ^2	P
Total hospital length of stay (days)	7.45±1.56	6.84±1.85	2.675	0.008
PACU retention time (min)	34.28±8.69	28.13±8.52	5.322	< 0.001
Prolonged hospitalization [n (%)]	25 (21.19%)	11 (10.48%)	4.708	0.030

Abbreviations: PACU, postanesthesia care unit; EEG, Electroencephalogram.

Table 6 Comparison of Patient Satisfaction Between the Two Groups

Parameters	Routine Group (n=118)	EEG-Guided Group (n=105)	χ^2	P
Very satisfied	20 (16.95%)	32 (30.48%)		
Satisfied	74 (62.71%)	65 (61.90%)		
Dissatisfied	24 (20.34%)	8 (7.62%)		
Satisfaction rate [n (%)]	94 (79.66%)	97 (92.38%)	7.314	0.007

Abbreviation: EEG, Electroencephalogram.

Postoperative Complications

The incidence of bradycardia was significantly lower in the EEG-guided group, affecting only 1.90% of patients compared to 11.86% in the routine group ($p=0.004$) (Table 7). Postoperative respiratory depression was also less frequent among the EEG-guided group, occurring in 7.62% of cases versus 16.95% in the routine group ($p=0.036$). Similarly, the occurrence of hypotension was reduced in the EEG-guided group, with 5.71% compared to 17.80% in the routine group ($p=0.006$). These findings indicate that EEG-guided general anesthesia was associated with a lower incidence of common postoperative complications in elderly patients undergoing hip fracture surgery.

Logistic Regression Analysis of POD

The univariate logistic regression analysis identified several significant predictors of POD (Table 8). The treatment approach, with EEG-guided anesthesia, was significantly associated with a reduced risk of delirium, as indicated by an odds ratio (OR) of 0.316 (95% CI, 0.134–0.685; $p=0.005$), demonstrating a protective effect compared to the routine approach. Additionally, a longer duration of BS was associated with an increased risk of delirium, with an OR of 1.085 per second increase (95% CI, 1.020–1.158; $p=0.011$). Higher propofol dosages were also linked to a greater likelihood of developing delirium (OR, 1.006; 95% CI, 1.001–1.013; $p=0.038$). This analysis underscores the importance of EEG-guided strategies and careful management of BS duration and propofol levels in minimizing POD among elderly patients with hip fractures.

The multivariate logistic regression analysis identified key variables influencing the risk of POD (Table 9). The use of EEG-guided anesthesia significantly decreased the likelihood of delirium, with an OR of 0.380 (95% CI, 0.106–0.998; $p=0.028$), indicating a protective role when adjusted for other factors. Additionally, an increase in the duration of burst

Table 7 Comparison of Postoperative Complications Between the Two Groups

Parameters	Routine Group (n=118)	EEG-Guided Group (n=105)	χ^2	P
Bradycardia [n (%)]	14 (11.86%)	2 (1.90%)	8.275	0.004
Postoperative respiratory depression [n (%)]	20 (16.95%)	8 (7.62%)	4.405	0.036
Hypotension [n (%)]	21 (17.80%)	6 (5.71%)	7.622	0.006

Abbreviation: EEG, Electroencephalogram.

Table 8 Univariate Logistic Regression Analysis of POD

Parameters	SE	Wald	OR	95% CI	P
Treatment approach (0: routine; 1: EEG-guided)	0.412	-2.798	0.316	0.134–0.685	0.005
Duration of BS (s)	0.032	2.551	1.085	1.020–1.158	0.011
Propofol dosage (mg)	0.003	2.077	1.006	1.001–1.013	0.038

Abbreviations: BS, burst suppression; EEG, Electroencephalogram.

Table 9 Multivariate Logistic Regression Analysis of POD

Parameters	SE	Wald	OR	95% CI	P
Treatment approach (0: routine; 1: EEG-guided)	0.650	-0.974	0.380	0.106–0.998	0.028
Duration of BS (s)	0.057	0.392	1.028	1.002–1.155	0.042
Propofol dosage (mg)	0.003	1.020	1.006	1.001–1.012	0.045

Abbreviations: BS, burst suppression; EEG, Electroencephalogram.

suppression (BS) was associated with a higher risk of delirium (OR, 1.028; 95% CI, 1.002–1.155; $p=0.042$). The propofol dosage also exhibited a modest influence on delirium risk (OR, 1.006; 95% CI, 1.001–1.012; $p=0.045$). These findings suggest that reducing the duration of BS and optimizing propofol dosing, alongside implementing EEG-guided strategies, were critical in minimizing the incidence of POD in this patient cohort. The Receiver Operating Characteristic (ROC) curve presents that evaluates the performance of a predictive model, with an area under the curve (AUC) of 0.815 (95% CI: 0.764–0.876), indicating good discriminatory power (Figure 4).

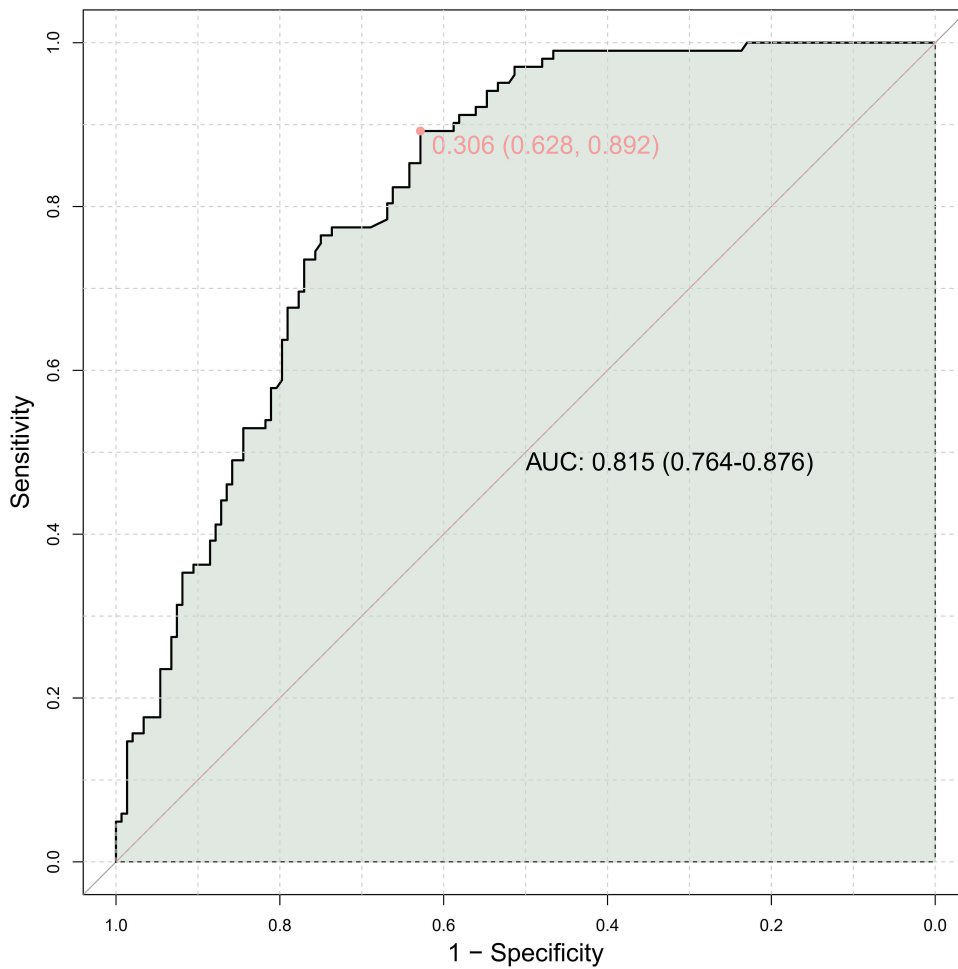


Figure 4 Receiver operating characteristic curve of the postoperative delirium prediction model based on multivariate logistic regression.
Abbreviation: AUC, area under the curve.

Discussion

This study suggests that EEG-guided general anesthesia may be associated with improved postoperative outcomes in elderly patients undergoing hip fracture surgery. The EEG-guided group exhibited a lower incidence of delirium, better cognitive recovery, and shorter hospital stays compared to those receiving routine anesthesia.

This study is based on the hypothesis that real-time monitoring of anesthesia depth through EEG can reduce neurological suppression and hemodynamic fluctuations caused by excessive anesthetic drugs, thereby lowering the risk of POD and accelerating recovery.

The research results validated this hypothesis and revealed the following underlying mechanisms:

EEG guidance in anesthesia provides a real-time assessment of brain activity, allowing for more precise titration of anesthetic agents.^{25,26} This approach contrasts with traditional methods, which rely heavily on the anesthesiologist's experience and vital sign monitoring.²⁷ The notable reduction in propofol dosage in the EEG-guided group suggests that this method allows for sparing use of anesthetic agents without compromising patient comfort or surgical conditions.²⁸ The sparing use of agents like propofol could reduce the risk of neurotoxicity and contribute to the observed decrease in POD. The prolonged sedative effects associated with higher dosages of anesthetic agents were well-documented, and reducing these agents aligns with the notion of minimizing pharmacological depression of the central nervous system, which was a known risk factor for delirium.²⁹

Although the goal of EEG-guided anesthesia is to maintain stable delta wave activity, some patients still experienced burst suppression. This may be due to individual differences in propofol sensitivity, transient changes in surgical stimulation, hemodynamic fluctuations affecting cerebral perfusion, or instantaneous delays in monitoring and intervention. The EEG-guided anesthesia group's significant decrease in the incidence and duration of intraoperative burst suppression hints at a potential mechanism for reducing POD. Burst suppression was a pattern observed in EEG readings indicative of significant suppression of cerebral activity, often linked to deep anesthesia or brain injury.³⁰ The shorter duration of burst suppression in the EEG-guided group may suggest a lesser degree of anesthetic-induced cerebral suppression, potentially translating to less postoperative cognitive dysfunction. Preservation of the brain's natural oscillatory activity during surgery, as facilitated by careful monitoring and adjustment through EEG, may help maintain cognitive functionality postoperatively.³¹

In the EEG-guided group, the observed reduction in early POD may partly stem from a more stable postoperative recovery process brought about by this strategy. EEG guidance, by optimizing anesthesia depth, not only directly protects neurological function but may also indirectly promote the stabilization of postoperative physiological status. Although there were no significant differences between the two groups in terms of fluid management and blood loss, precise titration of anesthetics could more consistently maintain cerebral perfusion pressure, thereby reducing the risks associated with cerebral hypoperfusion. Given that unstable postoperative physiological status is a known trigger for delirium, this more stable recovery process may be one of the synergistic mechanisms through which EEG guidance exerts its benefits.

From a neurobiological perspective, EEG-guided anesthesia might also contribute to altered neuroinflammation dynamics. Delirium was increasingly recognized as being associated with neuroinflammation,^{32,33} where surgical stress can exacerbate inflammatory responses within the central nervous system. By maintaining appropriate anesthetic depths and minimizing excessive doses of anesthetics, EEG guidance could indirectly modulate the inflammatory response pathways, thus reducing the likelihood of delirium onset.³⁴ Neuroinflammation was often a result of blood-brain barrier disruption during stress responses; EEG monitoring, by ensuring optimal anesthetic depth, might help in preserving the integrity of this barrier.

For cognitive recovery post-surgery, the improved SLUMS scores in the early postoperative days for the EEG-guided group were particularly revealing. This outcome could potentially be explained by less exposure to neurotoxic levels of anesthetics and the avoidance of supra-therapeutic sedation.^{35,36} Early cognitive recovery may provide an added benefit of faster functional recovery and discharge readiness, as cognitive function was a critical determinant of a patient's ability to engage in postoperative rehabilitation, an essential component of recovery from hip fractures in the elderly.^{37,38}

Unlike prior trials attributing delirium reduction solely to EEG-guided anesthesia, our findings highlight the predominance of patient-specific factors. Sensitivity analyses confirmed robustness across EEG metrics. This underscores

the need for multimodal prevention strategies targeting intrinsic brain resilience, beyond EEG suppression avoidance.³⁹ This study uniquely focuses on elderly hip fracture patients. Unlike earlier trials showing limited outcomes, it demonstrates EEG-guided anesthesia reduces early postoperative delirium and improves cognitive recovery.¹⁶ It also highlights shorter hospital stays and lower propofol use, identifying EEG guidance as an independent protective factor against delirium. This fills a critical evidence gap by emphasizing tailored anesthesia optimization for frail geriatric patients in orthopedic surgery.⁴⁰

It should be interpreted with caution that our multivariate logistic regression analysis showed that the lower limits of the confidence intervals for certain risk factors were very close to 1. This phenomenon indicates that, although these variables show statistically significant associations, there is some uncertainty in the precise estimation of their effects. The strength of evidence for these factors as independent risk factors for delirium is relatively limited. This may be due to the sample size of this study being insufficient to detect these relatively weak effects. In contrast, EEG-guided anesthesia demonstrated a more robust performance as a protective factor, supporting its role as a core strategy for reducing POD.

While our study provides valuable insights into the benefits of EEG-guided anesthesia in reducing POD and enhancing recovery among elderly patients with hip fractures, several limitations must be acknowledged. It is important to note that the retrospective design inherently limits the establishment of causal relationships. The associations observed should be interpreted with caution, as they may be influenced by unmeasured confounding factors or biases inherent to observational studies. The sample size, though adequate for primary analysis, may not capture all potential variables influencing delirium or recovery rates. Additionally, the study was conducted at a single center, which may limit the generalizability of the findings to other populations or healthcare settings. The study's observational nature also precludes definitive conclusions about causality. Potential performance bias due to anesthesiologist differences. In the EEG-guided group, anesthetic depth was controlled using EEG monitoring, whereas in the routine group, it was controlled based on each anesthesiologist's experience. This means that the skill level or clinical judgment of the anesthesiologists might influence the outcomes, and performance bias cannot be excluded. This potential performance bias represents a significant limitation of our study and needs to be addressed in future research. Finally, while we accounted for various confounding factors, it was possible that unmeasured variables, such as pre-existing cognitive impairment or detailed intraoperative factors, could have influenced the results. This study primarily focuses on short-term outcomes and lacks long-term follow-up data to assess the enduring impact of EEG-guided anesthesia on cognitive function. These limitations need to be addressed in future prospective studies.

Future research should focus on exploring the neurophysiological changes associated with EEG monitoring and their correlation with long-term outcomes. Given the limitations of our retrospective study design, we will conduct prospective experiments and incorporate multicenter randomized controlled trials with larger cohorts to validate these findings and further explore the underlying mechanisms.

Conclusion

This study explores the potential advantages of EEG-guided anesthesia in elderly hip fracture patients. EEG monitoring, by optimizing anesthetic dosages and reducing burst suppression events, is associated with reduced delirium incidence, faster cognitive recovery, and lower complication rates, suggesting clinical benefits over conventional anesthesia. However, it focuses on short-term outcomes and lacks long-term follow-up data to verify sustained cognitive improvements. These limitations should be addressed in future prospective studies.

Data Sharing Statement

The datasets used during the present study are available from the corresponding author upon reasonable request.

Ethics Approval and Consent to Participate

The study received approval from the Institutional Review Board and Ethics Committee of the Jinling Hospital Affiliated to Nanjing University School of Medicine (No.2024-SR-205). The requirement for informed consent was waived, as the

study utilized de-identified patient data, with no potential impact on patient care, adhering to regulatory and ethical guidelines applicable to retrospective research.

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.

Disclosure

The authors report no conflicts of interest in this work.

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