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Effects of EEG-guided anesthetic depth monitoring on delirium incidence across different age groups: a systematic review and meta-analysis

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Abstract

Background Postoperative delirium (POD) and emergence delirium (ED) commonly occur in elderly and pediatric patients undergoing anesthesia. Electroencephalography (EEG)-based monitoring technologies, including Bispectral Index (BIS), SedLine EEG monitoring, and other EEG techniques, have been proposed as potential strategies for reducing delirium risk, but current evidence remains controversial. Therefore, this systematic review and meta-analysis aimed to evaluate the impact of EEG-guided anesthesia on delirium incidence in patients of various age groups.

Methods PubMed, Embase, Web of Science, and the Cochrane Library were searched upto August 2025 for studies investigating EEG-guided anesthesia depth and delirium outcomes. The primary outcomes included incidence of POD and Pediatric Anesthesia Emergence Delirium (PAED) scores. Meta-analysis and subgroup analyses based on EEG monitoring techniques were conducted using Stata software. Publication bias was assessed with Begg's and Egger's tests.

Results Twenty studies involving 7344 adult patients and 463 pediatric patients were included. Pooled analyses indicated that deep anesthesia significantly increased POD risk in elderly patients ($P=0.008$). For adult patients, EEG-guided anesthesia was associated with a significant reduction in POD compared with usual care ($P=0.001$). In elderly patients, EEG-guided anesthesia was associated with a non-significant trend toward lower postoperative delirium ($P=0.123$). For pediatric patients, EEG monitoring did not significantly affect PAED scores overall ($P=0.143$); however, subgroup analysis revealed that non-BIS modality may have reduced PAED scores ($P<0.001$).

Conclusions The effectiveness of EEG-guided anesthesia in reducing delirium risk varies across age groups. EEG monitoring effectively decreases POD incidence in adults. Among elderly patients, EEG-guided anesthesia did not significantly reduce the risk of POD, whereas non-BIS modality may confer greater benefit for pediatric emergence delirium. These findings are hypothesis-generating; future studies should define age-tailored EEG monitoring strategies and clarify indications across patient groups.

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Keywords EEG monitoring, Bispectral index, Anesthesia depth, Postoperative delirium, Emergence delirium, Meta-analysis

Introduction

General anesthesia is a drug-induced state of unconsciousness, primarily caused by anesthetic agents disrupting normal cortical-thalamic communication [1]. Delirium, characterized by disturbances of consciousness and cognition, presents with fluctuations affecting attention, cognitive function, emotional regulation, and the sleep-wake cycle [2, 3]. Postoperative delirium (POD) and emergence delirium (ED) are common neuropsychiatric complications observed in patients undergoing anesthesia and surgery, particularly prevalent among elderly and pre-school pediatric populations [4, 5]. With a global demographic shift toward an aging population, an increasing number of elderly patients are undergoing surgery, making POD a significant global health challenge. POD prolongs hospital stays, increases medical costs, and substantially elevates the risk of long-term cognitive impairment, postoperative complications, and mortality [6–8]. ED is a frequently encountered complication following general anesthesia in pediatric patients, with an incidence ranging from 2% to 80%, significantly complicating postoperative management and increasing psychological burdens on both patients and their families [9, 10].

Inappropriate control of anesthetic depth has been identified as a critical risk factor for delirium [11, 12]. General anesthesia modulates thalamo-cortical networks and produces characteristic oscillatory patterns (e.g., alpha and slow delta oscillations, burst suppression) [13, 14]. The neurobiology of delirium differs by age. Among older adults, factors such as diminished brain reserve, cholinergic system vulnerability, microvascular dysregulation, and an increased propensity for burst suppression may contribute to a higher risk of POD [15, 16]. In children, emergence delirium (ED) is thought to reflect rapid state transitions within the developing brain [17].

Electroencephalography (EEG) monitoring provides opportunities to track dynamic changes in cerebral activity during general anesthesia, offering critical insight into anesthetic depth [18]. EEG-based objective monitoring techniques, such as Bispectral Index (BIS), SedLine EEG (Patient State Index, PSI), and Entropy monitoring, enable real-time quantification of cerebral activity and accurately reflect the patient's consciousness state, thus facilitating precise intraoperative anesthetic depth management [17, 19, 20]. Previous studies have indicated that BIS-guided anesthesia can reduce anesthetic dosage, consequently decreasing the risk of POD [21, 22]. EEG-guided anesthesia monitoring has therefore been proposed as a promising approach for reducing the incidence of POD [23].

Although several meta-analyses have evaluated the relationship between EEG-guided anesthetic depth and delirium, their findings remain controversial [24, 25]. Specifically, a meta-analysis by MacKenzie et al. concluded that EEG-guided anesthesia could reduce POD incidence by nearly 38% [25]. However, another study suggested that BIS-guided anesthesia was not associated with a reduced risk of POD in elderly patients [24]. Moreover, there have been no meta-analyses evaluating the clinical efficacy of EEG-guided anesthesia on ED in pediatric patients. Additionally, existing meta-analyses have mostly focused exclusively on elderly populations, seldom incorporating comprehensive data on pediatric and adult patients, thereby limiting the generalizability and clinical applicability of current evidence.

Therefore, this systematic review and meta-analysis aimed to evaluate the role of EEG-guided anesthesia depth monitoring in delirium prevention across different age groups. This is the first meta-analysis of randomized controlled trials (RCTs) involving different age groups, providing the latest clinical evidence for optimizing delirium prevention strategies and improving the prognosis of patients.

Methods

Information sources and literature search

This systematic review and meta-analysis were conducted in accordance with the 2020 Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines [26].

A comprehensive literature search was conducted to identify studies evaluating the effect of EEG-guided anesthesia on the incidence of postoperative delirium. Two researchers independently searched PubMed, Embase, Web of Science, and Cochrane Library online databases from inception to August 26th, 2025, using Medical Subject Headings (MeSH) and relevant free-text keywords. The PubMed search strategy was presented in Table 1, while the search strategies for other databases were adapted from PubMed. There were no restrictions on the countries and regions studied. Additionally, reference lists of relevant meta-analyses were manually screened to ensure no potentially eligible studies were overlooked (Table 2).

Inclusion and exclusion criteria

We included randomized controlled trials (RCTs) that investigated the effect of EEG-guided anesthesia

Table 1 PubMed search strategy

#	Searches	Results
1	"Electroencephalography"[MeSH] OR "Bispectral Index"[MeSH] OR " Monitoring, Intraoperative "[MeSH] OR "depth of anesthesia"[Title/Abstract] OR "anesthesia depth"[Title/Abstract] OR "bispectral index "[Title/Abstract] OR "BIS"[Title/Abstract] OR "electroencephalogram"[Title/Abstract] OR "EEG"[Title/Abstract] OR "entropy"[Title/Abstract] OR "sedation depth"[Title/Abstract] OR "depth of sedation"[Title/Abstract] OR "anesthesia monitoring"[Title/Abstract]	403,438
2	"Delirium"[Mesh] OR "post-anesthesia delirium"[Title/Abstract] OR "postoperative delirium"[Title/Abstract] OR "emergence delirium"[Title/Abstract] OR "delirium after anesthesia"[Title/Abstract] OR "POD"[Title/Abstract] OR "postanesthetic delirium"[Title/Abstract] OR "subacute delirium"[Title/Abstract]	34,965
3	"Randomized Controlled Trial"[Publication Type] OR "Controlled Clinical Trial"[Publication Type] OR "randomized controlled trial"[Title/Abstract]	791,519
4	#1 AND #2 AND #3	96

monitoring on delirium. Patients included were those undergoing general anesthesia, with no age restrictions. In this study, we divided patients into BIS group and non-BIS group based on EEG monitoring. PSI, entropy, raw EEG, multiparameter EGG, and other EEG modalities were included in the non BIS group. Anesthetic depth was classified into deep or light anesthesia based on BIS values reported by included studies. The primary outcomes were defined as the incidence of postoperative delirium (POD) among adult and elderly patients, and the Pediatric Anesthesia Emergence Delirium (PAED) score for pediatric patients.

Studies were excluded based on the following criteria: (1) case reports, reviews, letters, conference abstracts, and clinical trial protocols; (2) studies involving non-human subjects; (3) incomplete or non-extractable data; (4) duplicate publications from the same trial; (5) patients undergoing spinal anesthesia; (6)patients in the control group and the intervention group received different anesthetic protocol; and (7) articles not published in English.

After removal of duplicates, two independent researchers screened study titles and abstracts to identify potentially eligible studies, followed by full-text review for eligibility confirmation. Disagreements were resolved by consensus after discussion within the research team.

Data extraction

Relevant data were independently extracted by two reviewers from the included studies. First, study characteristics, including first author, publication year, study region, sample size, and study design, were collected. Patient demographic and clinical characteristics including age, gender, type of surgery, and EEG modalities were also recorded. Clinical outcomes extracted included the incidence of postoperative delirium, and Pediatric Anesthesia Emergence Delirium (PAED) scores.

Bias risk assessment of included studies

For RCTs, the risk of bias was assessed according to the Cochrane Collaboration Risk of Bias Tool 2.0 [27]. Five domains were evaluated: (1) the randomization process, (2) deviations from intended interventions, (3) missing outcome data, (4) measurement of outcomes, and (5) selection of the reported result.

Statistical analysis

All statistical analyses were performed using STATA SE14.0 software. Dichotomous outcomes were summarized using odds ratios (ORs) and corresponding 95% confidence intervals (95% CIs). Continuous outcomes measured in consistent units were analyzed using weighted mean differences (WMDs) with corresponding 95% CIs. Statistical heterogeneity among studies was assessed using the I^2 statistic, with I^2 values interpreted as low (< 30%), moderate (30%–75%), or high heterogeneity (≥ 75%) [28]. Fixed-effects or random-effects models were applied based on an I^2 threshold of 50%. To evaluate whether EEG modality, anesthetic protocol, POD assessment, or age influenced POD and contributed to between-study heterogeneity, we conducted prespecified subgroup analyses. Sensitivity analyses were conducted to assess the robustness of the pooled results. Furthermore, when the number of included studies was ≥ 5, publication bias was assessed using Begg's and Egger's tests [29].

Results

Study identification

Using the defined search strategy, we initially identified 547 publications from the electronic databases and 3 publications from other sources. After removing duplicates, 294 studies remained. After screening titles and abstracts, we excluded 211 irrelevant studies, including reviews, commentaries, animal experiments, and case reports. We then conducted a full-text assessment of 83 studies for further eligibility evaluation, ultimately including 20 studies in this meta-analysis [6, 7, 17, 22, 30–45]. The selection process is illustrated in detail in the flow diagram (Fig. 1).

Characteristics and quality of included studies

The main characteristics of the 20 included studies are summarized in Table 1. These studies involved a total of 7807 patients, published between 2010 and 2025, with sample sizes ranging from 76 to 1545 participants. Studies were conducted in various regions, including USA, China, Hong Kong, Taiwan, Czechia, Spain, Germany, the United Kingdom, Singapore, and Netherlands.

Table 2 Overview and characteristics of the included studies

Author	Country/region	Sample	Gender (M/F)	Age (years)	EEG modality	Anesthetic protocol	Type of surgery	POD/ED
Evered et al. 2021 [7]	USA	515	332/183	70.95 ± 6.84	BIS 50,35	Inhalation of volatile anesthetics	Major surgery	3D-CAM/CAM-ICU
Long et al. 2024 [32]	China	78	48/30	69.6 ± 4.6	BIS 55,40	Inhalation of volatile anesthetics	Major noncardiac surgery	CAM
Zhou et al. 2018 [42]	China	81	56/25	68.59 ± 2.90	BIS (40–60)	TIVA	Radical surgery for colon carcinoma	CAM
Templeton et al. 2025 [30]	USA	105	N/A	N/A	BIS (45–60)	Inhalation of volatile anesthetics	Elective Surgery	PAED
Huang et al. 2024 [33]	China	120	55/65	51.56 ± 17.09	BIS (40–60)	Mix (volatile anesthetics + TIVA)	Elective surgery	SAS
Frelich et al. 2024 [34]	Czechia	163	105/58	4.69 ± 1.30	BIS (40–60)	Inhalation of volatile anesthetics	Endoscopic adenoidectomy	PAED
Pérez-Otal et al. 2022 [6]	Spain	200	101/99	75.38 ± 6.53	BIS (40–60)	Inhalation of volatile anesthetics	General Surgery, Vascular Surgery, Urology Surgery, Otorhinolaryngology and Maxillofacial Surgery	CAM/CAM-ICU
Chen et al. 2022–1 [38]	China	197	122/75	62.34 ± 10.52	BIS (40–60)	TIVA	Laparoscopic gastrointestinal surgery	CAM
Whitlock et al. 2014 [43]	USA	310	194/116	61.55 ± 14.0	BIS (40–60)	Inhalation of volatile anesthetics	Cardiac or thoracic surgery	CAM-ICU
Chan et al. 2013 [45]	Hong Kong	902	553/349	67.85 ± 8.25	BIS (40–60)	Mix (volatile anesthetics + TIVA)	Elective major surgery	CAM
Radtke et al. 2013 [44]	Germany	1155	622/533	69.90 ± 6.40	BIS	Mix (volatile anesthetics + TIVA)	elective surgery expected to last at least 60 min	DSM-IV
Kunst et al. 2020 [22]	United Kingdom	82	64/15	71.80 ± 4.65	BIS 50 ± 10	Inhalation of volatile anesthetics	Coronary artery bypass graft surgery	CAM
He et al. 2023 [36]	China	125	82/43	68.5 (65, 73.5)	Raw electroencephalogram	TIVA	Abdominal major surgery	NR
Wildes et al. 2019 [41]	USA	1232	669/563	69.4 (64.8, 75.2)	Electroencephalogram waveforms and derived parameters	Inhalation of volatile anesthetics	Major surgery with general anesthesia	CAM/CAM-ICU
Long et al. 2022 [17]	Singapore	195	143/52	3.54 ± 1.58	Primary guidance was from the unprocessed EEG, secondary guidance from the spectrogram and tertiary guidance from the PSI	Inhalation of volatile anesthetics	Routine minor surgery (not involving the cranial or thoracic cavities)	PAED
Wang et al. 2022 [37]	China	1545	N/A	N/A	Electroencephalography Spectral Edge Frequency and PSI-Guided	TIVA	Laparoscopic surgery	CAM
Chen et al. 2022–2 [39]	Taiwan	76	37/39	59.99 ± 15.55	Spectral Entropy Monitoring	Inhalation of volatile anesthetics	Video-assisted thoracoscopic surgery for lung resections	CAM

Table 2 (continued)

Author	Country/region	Sample	Gender (M/F)	Age (years)	EEG modality	Anesthetic protocol	Type of surgery	POD/ED
Xu et al. 2021 [40]	China	255	222/33	62.74 ± 7.60	PSI combined with DSA-guided monitoring	TIVA	Carotid Endarterectomy	CAM
Fraiture et al. 2024 [35]	Netherlands	388	153/235	81 (76–86)	EEG-based brainwave analysis	Mix (volatile anesthetics + TIVA)	Surgery for hip fracture	DMS/CAM
Shi et al. 2025 [31]	China	83	35/48	68.11 ± 5.19	BIS (40–60)	TIVA	Laparoscopic surgery	CAM

M male, *F* female, *PSI* patient state index, *DSA* density spectral array, *RCT* randomized controlled trial, *BIS* bispectral index, *EEG* Electroencephalography, *TIVA* Total intravenous anesthesia, *CAM* confusion assessment method, *PAED* pediatric anesthesia emergence delirium, *SAS* ricker sedation-agitation scale, *DSM IV* the diagnostic and statistical manual of mental disorders

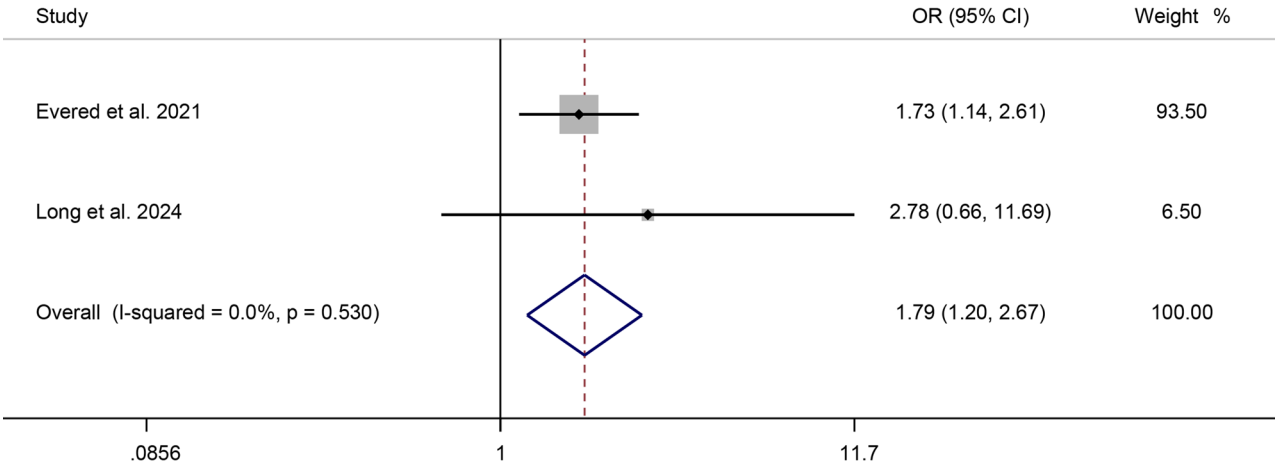


Fig. 1 PRISMA flow diagram of the search strategy and study selection for eligible studies

There was no age limit for the enrolled patients, with a total of 463 patients aged 1 to 12 years old and 7344 patients aged ≥ 18 years old. Among the 7344 patients, 4841 patients were specifically identified as over 60 years old. Among these, two studies assessed the relationship between anesthesia depth (BIS-defined) and POD in elderly patients. Eighteen studies evaluated the association between EEG monitoring and delirium occurrence; of these, eleven employed BIS monitoring, while the other seven utilized other EEG techniques. Regarding anesthetic depth, all studies used BIS values as the assessment criterion. Regarding the anesthetic protocol, patients in 10 studies received inhalational volatile anesthesia, those in 6 studies received total intravenous anesthesia (TIVA), and those in 4 studies received a mixed regimen combining volatile inhalation with TIVA.

Across 20 trials, the overall RoB2 assessment was low risk in 9/20 (45%), some concerns in 9/20 (45%), and high risk in 2/20 (10%). The most common problem was uncertainty in selective reporting (D5), with lesser but notable concerns about the randomisation process (D1a). The latter largely reflected trials that stated participants were randomly allocated without describing the specific randomisation method. No study was rated high risk for missing outcome data (D3) (Fig. 2).

Anesthetic depth and delirium

Two studies compared the incidence of POD in elderly patients under deep anesthesia versus light anesthesia. A fixed-effects model (I^2 = 0.0%, P = 0.530) revealed that deep anesthesia significantly increased the risk of POD compared to light anesthesia (OR = 1.79, 95% CI: 1.20–2.67, P = 0.008) (Fig. 3).

EEG monitoring and delirium in adult patients

Six studies involving 2503 patients evaluated the impact of EEG monitoring on POD incidence in adult patients. Due to moderate heterogeneity among these studies (I^2 = 51.5%, P = 0.067), a random-effects model was employed. The pooled results indicated that EEG-guided anesthesia was associated with a significant reduction in POD compared with conventional monitoring (OR = 0.43, 95% CI: 0.25–0.75, P = 0.001) (Fig. 4A). As shown in Fig. 4B, our results exhibit robustness.

We conducted prespecified subgroup analyses by EEG modality, anesthetic protocol, POD assessment, and age (Supplementary Fig. 1). Use of BIS was associated with a significant reduction in POD (OR 0.57, 95% CI 0.37–0.87; I^2=0%, p = 0.880). A similar benefit was observed in studies that assessed POD with CAM (OR 0.43, 95% CI 0.23–0.80; I^2=61.0%, p = 0.036). Trials enrolling adults ≥ 18

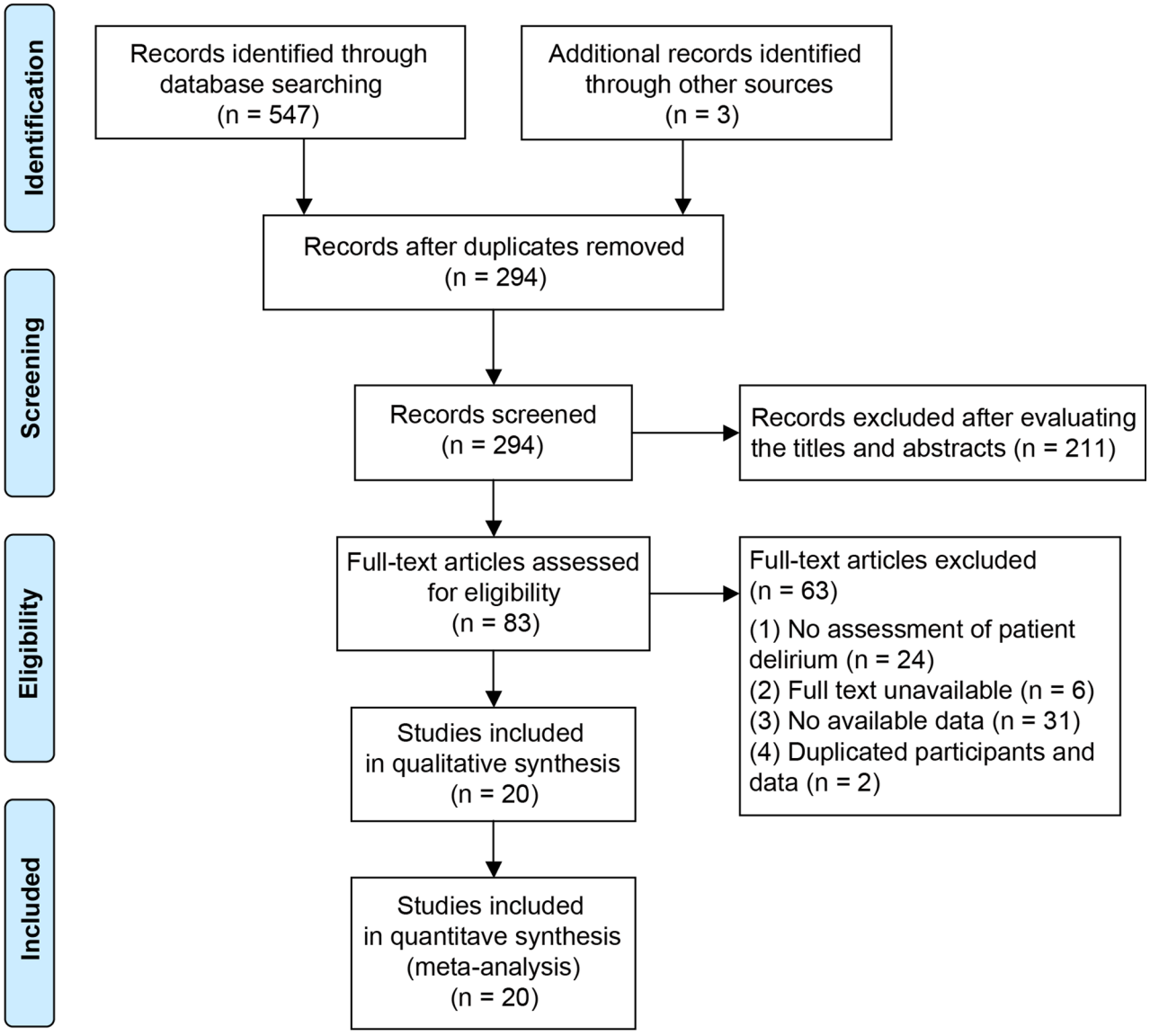


Fig. 2 Risk of bias assessment of included studies. Green (+), low risk of bias; Red (-), high risk of bias; Yellow (!), some concerns

years (OR 0.42, 95% CI 0.22–0.81; I^2=62.5%, p = 0.070) and ≥ 20 years (OR 0.19, 95% CI 0.04–0.97; I^2=34.4%, p = 0.217) also showed significant reductions (Table 3). By contrast, the effect did not differ materially across anesthetic protocols (volatile inhalational anesthesia, TIVA, or mixed volatile + TIVA). In addition, subgroup analysis results showed that EEG modality, anxitic protocol, POD assessment, and age were not sources of heterogeneity.

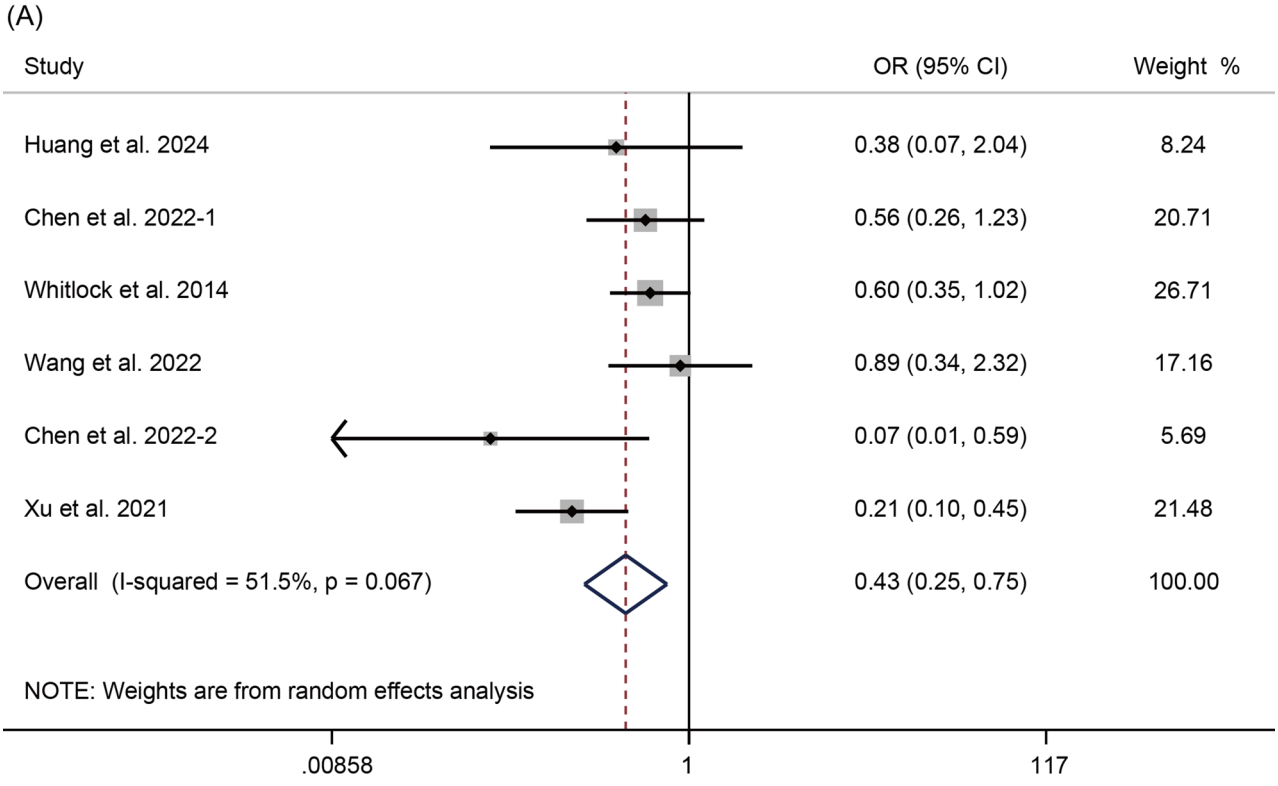
EEG monitoring and delirium in elderly patients

Across nine RCTs in elderly patients, between-study heterogeneity was moderate (I^2 = 63.8%%, P = 0.005), a random-effects model was applied. The pooled OR was 0.76 (95% CI: 0.60–1.06, P = 0.123), suggesting that EEG-guided anesthesia was associated with a non-significant trend toward lower postoperative delirium compared with conventional monitoring (Fig. 5A). Sensitivity analysis showed that the results were robust.

In subgroup analyses restricted to elderly patients, none of the examined factors—EEG modality, anesthetic protocol, POD assessment, or age thresholds—significantly affected POD incidence (Table 4). Tests for subgroup differences were not significant, indicating that these factors did not explain the observed between-study heterogeneity. Supplementary Fig. 2 shown the forest plot of subgroup analyses for elderly patients.

EEG monitoring and delirium in pediatric patient

The Pediatric Anesthesia Emergence Delirium (PAED) scale was used to measure ED severity in children [46].



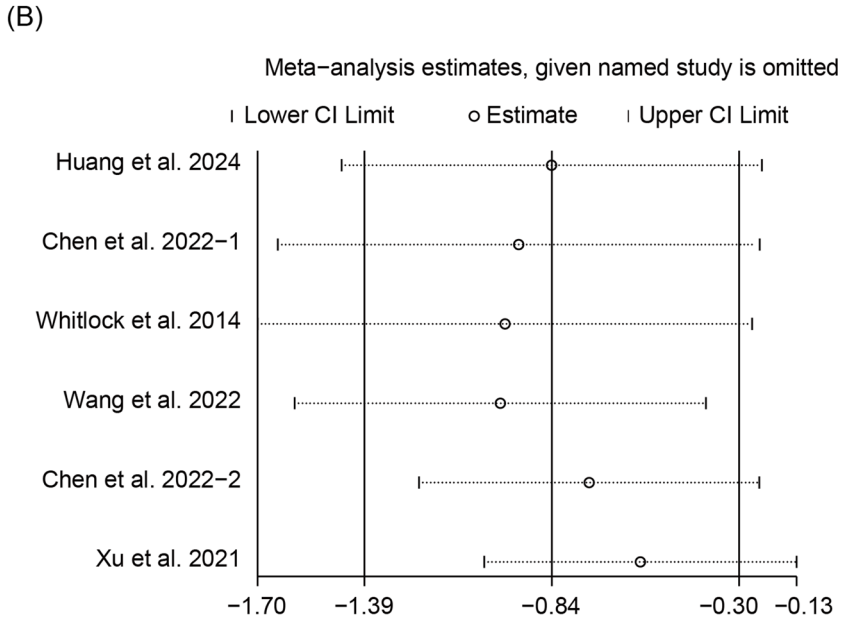


Fig. 3 Association between anaesthesia depth and incidence of delirium. Forest plot of the pooled analysis showing association between BIS monitoring and delirium across two independent studies. BIS, bispectral index

Fig. 4 Association between EEG and incidence of delirium in adult patients. **A** Forest plot of the pooled analysis showing association between EEG monitoring and delirium across five independent studies. **B** Sensitivity analysis showed the robustness of the results. EEG, electroencephalography

Table 3 Subgroup analyses by EEG modality, anesthetic protocol, POD assessment, and age in adult patients

Subgroup	Study	OR (95% CI)	I^2 (%), *P*
EEG			
BIS	3	0.57 (0.37, 0.87)	0.0%, *P* = 0.880
Non-BIS	3	0.29 (0.08, 1.04)	73.8%, *P* = 0.022
Anesthetics			
Inhalation of volatile anesthetics	2	0.26 (0.03, 2.07)	73.5%, *P* = 0.052
TIVA	3	0.46 (0.20, 1.05)	67.6%, *P* = 0.046
Mix (volatile anesthetics + TIVA)	1	0.38 (0.07, 2.04)	NA
POD			
CAM	5	0.43 (0.23, 0.80)	61.0%, *P* = 0.036
Other	1	0.38 (0.07, 2.04)	NA
Years			
≥ 18	3	0.42 (0.22, 0.81)	62.5%, *P* = 0.070
≥ 20	2	0.19 (0.04, 0.97)	34.4%, *P* = 0.217
≥ 50	1	0.89 (0.34, 2.32)	NA

Three studies including 600 pediatric patients reported PAED scores, with high heterogeneity observed (I^2 = 80.2%, P = 0.006). For pediatric ED, continuous PAED scores were synthesized as WMD. The pooled analysis using a random-effects model found that EEG monitoring did not significantly reduce PAED scores in children (WMD = −1.01, 95% CI: −2.29–0.28, P = 0.126) (Fig. 6A). In the subgroup analyses by EEG modalities, BIS monitoring had no significant effect on PAED scores (WMD = −1.54, 95% CI: −3.59–0.52, P = 0.143), whereas the non-BIS category suggested a potential reduction in PAED (WMD = −0.30, 95% CI: −0.38–−0.22, P < 0.001) (Fig. 6B). However, this subgroup (non-BIS) included only one study and the between-study heterogeneity was substantial (I^2 ≈ 80%). Therefore, this result should be interpreted with caution.

Publication bias

Publication bias was assessed by Begg's and Egger's tests for pooled analyses with five or more included studies. No significant publication bias was detected among studies in adult (P from Begg's test = 0.707, P from Egger's test = 0.400) and elderly patient groups (P from Begg's test = 0.348, P from Egger's test = 0.302).

Discussion

EEG, as an objective measure of cerebral activity, plays a crucial role in anesthetic depth management. This systematic review and meta-analysis aimed to assess the effects of EEG monitoring on POD and ED. We included 20 studies involving a total of 7807 patients, comprehensively examining the impacts of EEG monitoring and BIS-defined anesthetic depth on POD incidence and PAED scores.

Our meta-analysis demonstrated that, in elderly patients, deep anesthesia significantly increased the risk of POD compared to lighter anesthesia. However, this result contrasts with a previously published meta-analysis [47], likely due to differences in patient inclusion criteria. Specifically, the study by Wang et al. included anesthesia depth targets guided by both BIS values and the Observer's Assessment of Alertness/Sedation (OAA/S) scale. The higher incidence of POD associated with deeper anesthesia could be attributed to excessive central nervous system suppression by anesthetic agents, increased frequency of EEG burst suppression patterns, and prolonged intraoperative hypotension leading to cerebral ischemia and hypoxia [48, 49]. Burst suppression on EEG, indicative of excessively deep anesthesia, has been associated with adverse cognitive outcomes [50]. In older adults, pre-induction EEG patterns may serve as early markers of vulnerability to POD, indicating that burst suppression alone does not account for the observed risk [51]. Furthermore, certain anesthetic agents (e.g., desflurane) have been associated with an increased risk of POD independent of burst suppression duration [52]. These observations highlight the need for EEG guidance strategies that integrate both depth-related patterns and drug effects, motivating our analyses.

Both the American Geriatrics Society and the European Society of Anaesthesiology recommend intraoperative EEG monitoring to prevent excessive anesthetic administration in patients at high risk for POD [53, 54]. Our results confirmed that EEG monitoring significantly reduced the incidence of POD in adult patients overall. Nevertheless, for elderly patients, there was no significant difference in the incidence of POD between EEG-guided anesthesia and conventional monitoring, which was contradictory with the previous meta-analysis findings [25, 55]. One study reported no significant difference in POD incidence between groups guided by raw EEG versus routine care [36]. Likewise, SedLine EEG indices such as spectral edge frequency and PSI-guided anesthesia did not reduce delirium incidence after laparoscopic surgery [37]. These findings suggest that although EEG-based monitoring provides richer cerebral information, it may not necessarily translate into greater clinical benefit. Possible explanations include algorithmic complexity, differences in study objectives, anesthetic depth control strategies, and variability in EEG interpretation criteria across studies [35, 36].

Notably, our meta-analysis indicated that BIS-guided anesthesia had no significant impact on pediatric PAED scores. This might reflect the developing nature of

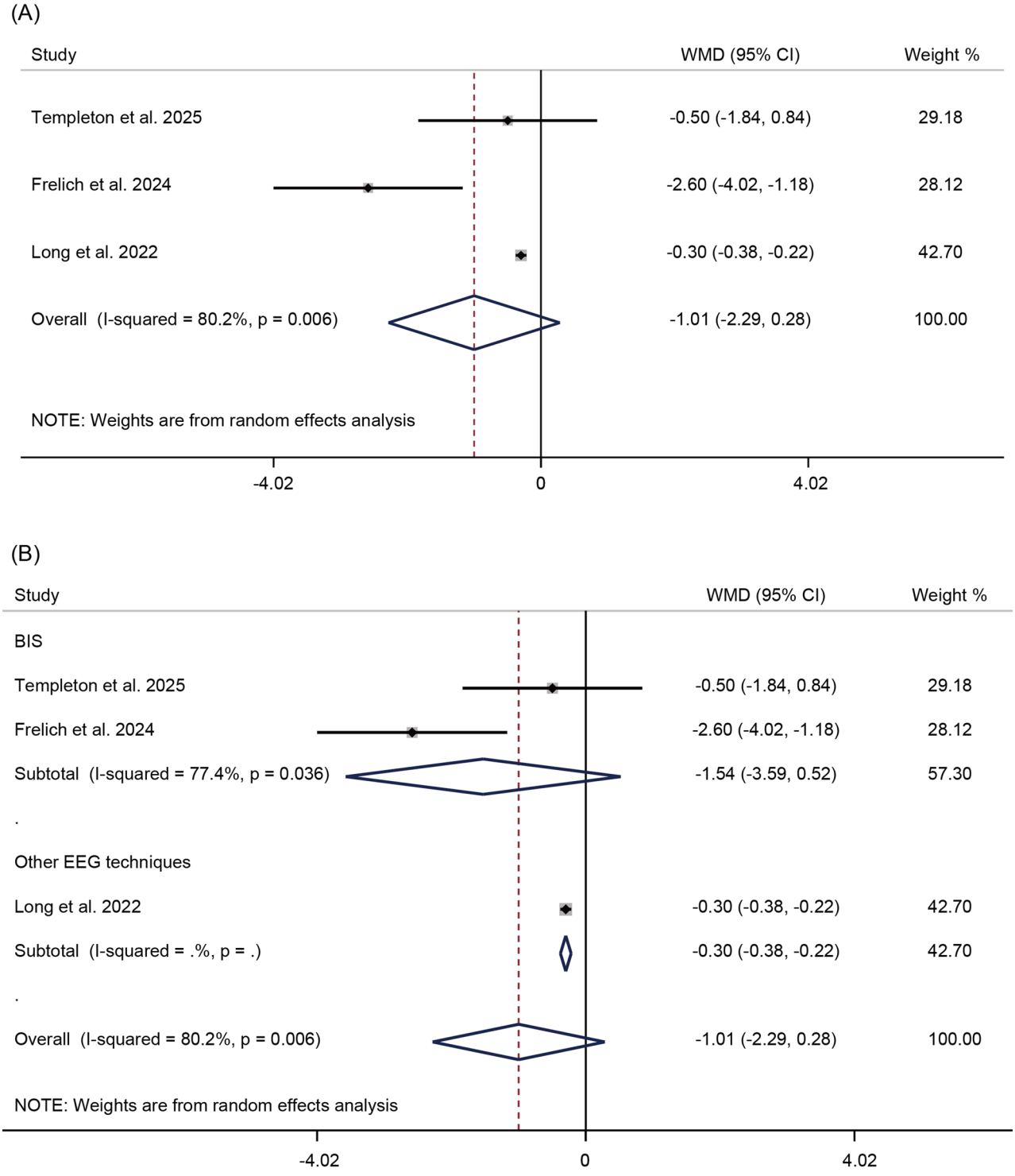


Fig. 5 Association between EEG and incidence of delirium in elderly patients. **A** Forest plot of the pooled analysis showing association between EEG monitoring and delirium across ten independent studies. **B** Sensitivity analysis showed the robustness of the results. EEG, electroencephalography

Table 4 Subgroup analyses by EEG modality, anesthetic protocol, POD assessment, and age in elderly patients

Subgroup	Study	OR (95% CI)	I^2 (%), *P*
EEG			
BIS	7	0.74 (0.52, 1.05)	67.8%, *P* = 0.005
Non-BIS	2	0.70 (0.18, 2.66)	63.5%, *P* = 0.098
Anesthetics			
Inhalation of volatile anesthetics	3	0.63 (0.26, 1.52)	80.3%, *P* = 0.006
TIVA	3	0.75 (0.32, 1.74)	24.5%, *P* = 0.266
Mix (volatile anesthetics + TIVA)	3	0.75 (0.54, 1.04)	58.0%, *P* = 0.093
POD			
CAM	6	0.73 (0.45, 1.17)	72.2%, *P* = 0.003
Other	3	0.80 (0.50, 1.28)	49.3%, *P* = 0.139
Years			
≥ 60	5	0.79 (0.54, 1.18)	72.7%, *P* = 0.006
≥ 65	3	0.50 (0.25, 1.02)	29.5%, *P* = 0.242
≥ 70	1	1.15 (0.68, 1.93)	NA

pediatric brain function; anesthetic requirements and sensitivities can vary substantially during different stages of brain maturation, potentially limiting the precision of BIS in capturing children's true consciousness status and emergence quality [9, 56]. The etiology of ED is multifactorial, influenced by preoperative anxiety, postoperative pain management, and anesthetic choices [10, 57]. Thus, relying solely on BIS values may not adequately prevent ED in pediatric populations. Han et al. showed that proprietary quantitative indices such as BIS may not be suitable for children, while raw EEG/spectrogram guided care may more accurately reflect anesthesia depth [58]. Long et al. utilized comprehensive EEG monitoring, including raw EEG, spectrograms, and PSI indices, which significantly reduced the occurrence of burst suppression in children [17]. However, in our analysis, only one non-BIS trial was included, and the results should be treated with caution. In the later stage, richer spectral/continuous EEG approaches and adequately powered RCTs may be needed. Additionally, increased frontal delta activity and decreased alpha and beta frequencies have been reported during ED episodes in pediatric patients [59]. Since alpha wave frequencies represent cortical cognitive and memory functions within thalamo-cortical feedback loops, decreased alpha and increased delta power during emergence may impair cognitive and memory processes, contributing to ED [59, 60]. Future studies should further investigate alternative EEG monitoring tools and combined strategies to effectively reduce ED risk in pediatric anesthesia management.

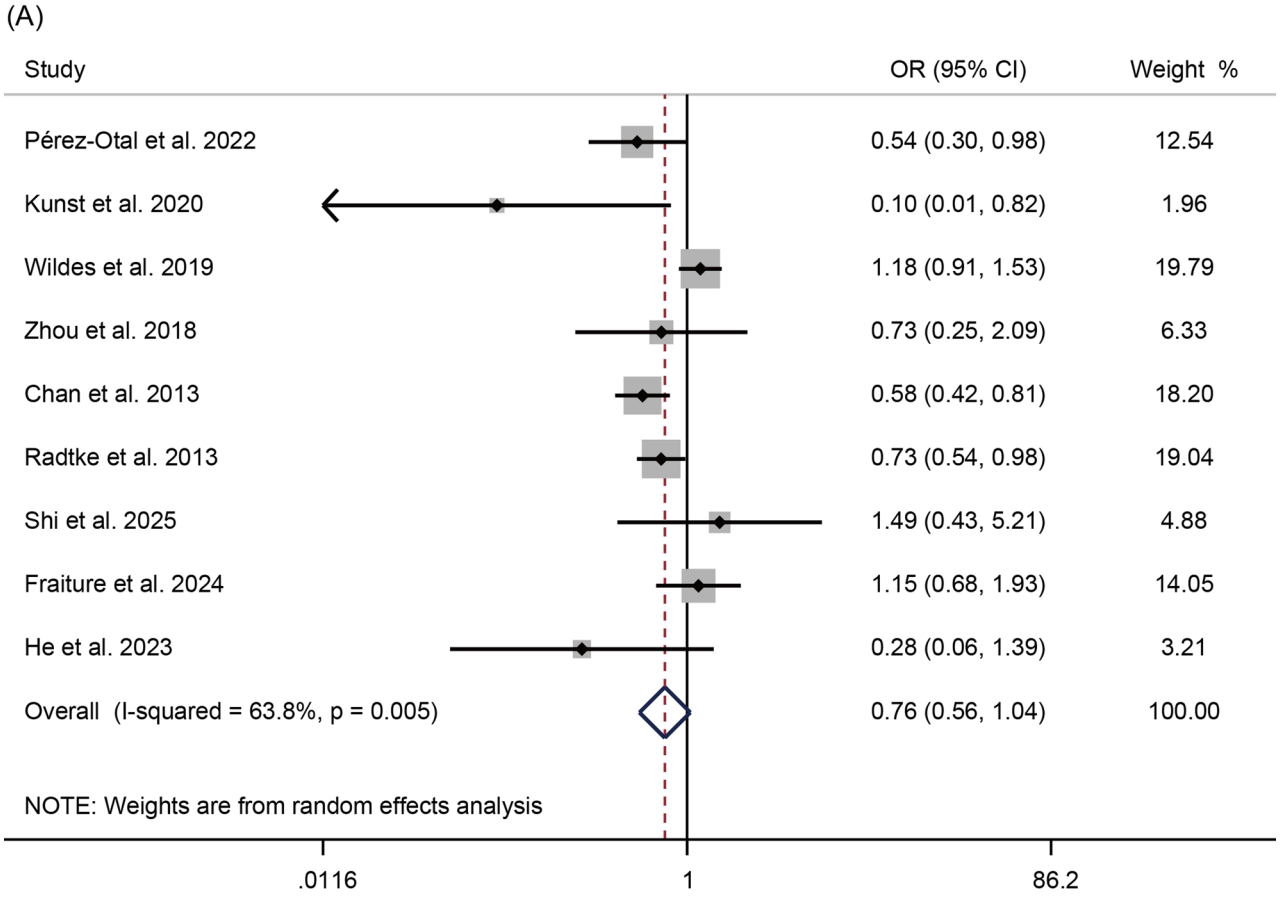
Strengths and limitations

This systematic review and meta-analysis investigated the roles of BIS-based anesthetic depth and EEG-guided anesthesia in preventing delirium across different age groups, and for the first time evaluated the effect of EEG-guided anesthesia on Pediatric Anesthesia Emergence Delirium (PAED) scores. Through subgroup analysis, we provide more targeted and personalized recommendations for anesthetic management, emphasizing the significant role of BIS monitoring in reducing POD among elderly patients, and suggesting that other EEG monitoring techniques may play a critical role in preventing ED in pediatric patients. All included studies were RCTs, and the risk of bias was systematically assessed to enhance the robustness of the evidence.

However, this meta-analysis has several limitations. First, The POD evaluation criteria for included studies include not only CAM/CAM-ICU/3D-CAM, but also DSM, SAS, etc. This may be a potential confounding factor. Second, significant differences in delirium incidence across various surgical procedures could contribute to the high heterogeneity observed in our analysis [61, 62]. Heterogeneity may also arise from different EEG monitoring methods and varied brain maturation stages among pediatric patients, resulting in distinct anesthetic requirements. Anesthesia protocols are not entirely consistent between studies. Although we performed subgroup analysis and sensitivity analyses, the results need to be treated with caution. Moreover, the absence of standardized definitions distinguishing deep from light anesthesia across included studies might have further contributed to heterogeneity.

Future directions

Our findings highlight that EEG-guided anesthesia is particularly effective in preventing POD among adult patients, whereas has no significant improvement effect on elderly patients. Non-BIS modality might have effects in preventing pediatric ED, indicating that distinct EEG modalities may be optimal for different patient populations. Future research should include more high-quality, large-scale randomized controlled trials to further validate the preventive effects of EEG-guided anesthesia monitoring on delirium across diverse age groups. Additionally, clarifying the optimal target populations and combined effects of various EEG monitoring techniques (such as BIS, PSI, and Entropy) is essential to achieve more precise and individualized anesthetic management strategies.



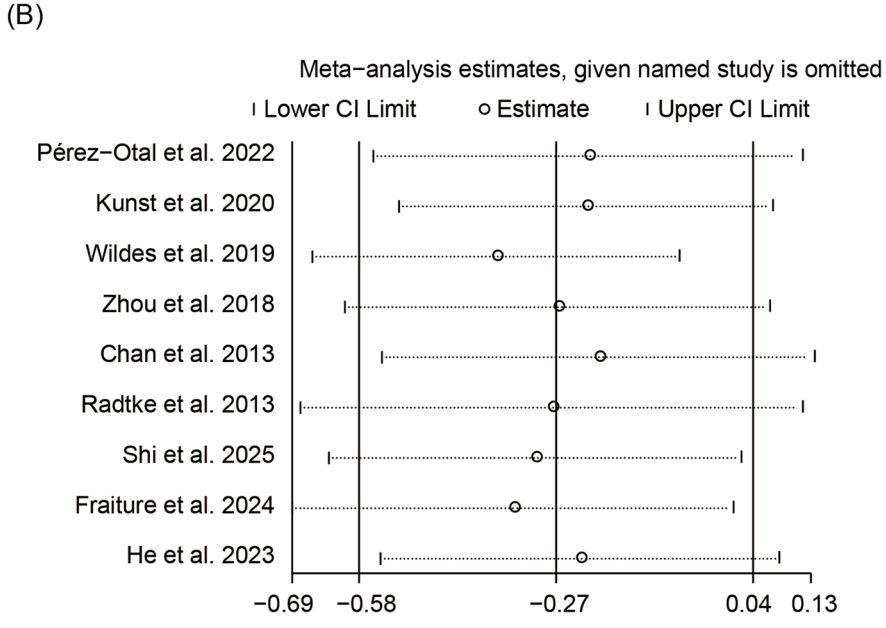


Fig. 6 Association between EEG and delirium in children. **A** Forest plot of the pooled analysis showing association between EEG monitoring and PAED scores across three independent studies. **B** Subgroup analysis based on EEG monitoring modality. The studies were stratified into two subgroups: BIS monitoring and other EEG techniques. EEG, electroencephalography; PAED, pediatric anesthesia emergence delirium; BIS, bispectral index

Conclusions

In conclusion, this meta-analysis shows that light anesthesia defined by BIS targets effectively reduces the risk of POD in elderly patients. EEG-guided anesthesia can reduce the risk of POD in adult patients, but it has no significant effect on elderly patients. In pediatric cohorts, BIS monitoring did not significantly improve emergence delirium outcomes. Future randomized controlled trials should focus on determining appropriate EEG monitoring techniques tailored for different patient populations, so as to optimize delirium prevention strategies.

Supplementary Information

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Supplementary Material 1:Supplementary Fig.1. Subgroup analyses of association between EEG and incidence of delirium in adult patients according to the EEG modality (A), anesthetic protocol (B), POD assessment (C), and age (D). EEG, Electroencephalography. POD, Postoperative delirium.

Supplementary Material 2:Supplementary Fig.2. Subgroup analyses of association between EEG and incidence of delirium in elderly patients according to the EEG modality (A), anesthetic protocol (B), POD assessment (C), and age (D). EEG, Electroencephalography. POD, Postoperative delirium.

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None.

Authors' contributions
CYR, ZY, and ZL: Substantial contribution to the conception and design of the work; CYR, and ZY: manuscript drafting; CYR, ZY, ZXY, and ZL: Acquisition, analysis, and interpretation of the data; CYR, ZY, ZXY, ZL: Critical revision of the manuscript. All authors revised the manuscript critically, and confirmed the final version to be published.

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

Declarations

Ethics approval and consent to participate
Ethical approval was not needed because this is a meta-analysis.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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