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Research Progress and Application of Electroencephalographic Monitoring in Pediatric Anesthesia

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Abstract

Electroencephalography (EEG), as a non-invasive technique enabling real-time reflection of cerebral cortical neuronal electrical activity, has substantial value in perioperative cerebral function monitoring in children. However, processed EEG (pEEG) indices are not directly reliable for pediatric populations. Consequently, domestic and international guidelines recommend that anesthesiologists master the ability to interpret raw EEG. Anesthetic management guided by EEG can reduce drug dosage, shorten recovery duration, and help lower the incidence of perioperative adverse events. Nevertheless, the promotion of EEG monitoring in pediatric anesthesia currently faces challenges, including inadequate equipment configuration, insufficient understanding among anesthesiologists, and the absence of unified reference standards. This review comprehensively analyzes the application effects and existing limitations of EEG monitoring in pediatric anesthesia and explores its impact on postoperative outcomes, aiming to provide a theoretical basis for clinical practice and scientific research.

Keywords

Electroencephalography, Pediatric Anesthesia, Depth of Anesthesia

Abbreviations

BIS: Bispectral Index; EEG: Electroencephalography; pEEG: Processed Electroencephalography.

Introduction

Children, as a special patient cohort, have a nervous system, particularly the brain, at a critical stage of rapid development. During general anesthesia, children are exposed to multiple neurological risks: on the one hand, anesthetic agents may exert potential neurotoxic effects on developing brain tissue; on the other hand, due to age-related differences in physiological and pharmacological responses, children are more susceptible to perioperative complications such as intraoperative awareness and emergence delirium. These risks are not only associated with intraoperative safety but may also exert profound impacts on children's long-term neurodevelopment. Therefore, achieving accurate monitoring and effective management of cerebral function during anesthesia has become an urgent and crucial issue in the field of pediatric anesthesia.

Electroencephalography (EEG), a non-invasive and real-time technique for reflecting cerebral cortical electrophysiological activity, provides an important means for perioperative cerebral function monitoring. Commercial anesthetic depth monitoring devices developed based on EEG, such as the Bispectral Index (BIS) [1], Patient State Index (PSI) [2], and Entropy Index [3], represent important milestones in the perioperative application of EEG monitoring technology. Through proprietary algorithms, these devices convert complex raw EEG signals into a single, easy-to-interpret quantitative index, which significantly reduces the threshold for EEG interpretation and assists anesthesiologists in quantitatively evaluating anesthetic depth. Previous studies have demonstrated that the application of anesthetic depth monitoring devices in adult patients can reduce anesthetic drug consumption and shorten patient recovery time [4]. However, compared with adults, children's EEG activity presents distinct age-dependent characteristics. Conventional EEG processing algorithms and derived indices based on adult data are often insufficiently reliable in children and may even lead to misleading clinical judgments.

Several surveys have indicated that 31.7%-50.7% of anesthesiologists rarely or never use anesthetic depth monitoring devices in children, and the proportion of users decreases with decreasing age of the children [5,6]. These surveys also showed that 50% of anesthesiologists lack confidence in interpreting processed electroencephalography (pEEG) indices in children under 1 year of age [6]. This lack of confidence largely stems from fundamental differences in EEG characteristics between children, especially infants, and adults. Studies have confirmed that the EEG of infants under 6 months of age lacks the typical frontal alpha wave dominance observed during anesthetic maintenance in adults, and its spectral characteristics undergo systematic changes with age and neurodevelopment. This casts doubt on the reliability of EEG indices developed based on adult data when applied to infants [7]. Furthermore, there remains a lack of age-matched reference data and interpretation standards for pediatric EEG characteristics, which also limits the practical application of perioperative EEG monitoring.

In recent years, multiple domestic and international professional guidelines have explicitly recommended that anesthesiologists should possess the ability to directly interpret raw EEG to achieve individualized and precise anesthetic management. Against this backdrop, EEG-guided anesthetic management in children has demonstrated potential advantages in various aspects: by optimizing anesthetic depth, it may reduce drug exposure, shorten recovery time, and help decrease the incidence of adverse events such as intraoperative awareness and postoperative delirium. However, the popularization of EEG monitoring in pediatric anesthesia still confronts numerous practical challenges, including limited equipment resources, insufficient understanding of pediatric EEG characteristics among anesthesiologists, and the lack of unified pediatric reference standards.

Systematically summarizing the application progress of EEG in pediatric anesthesia and clarifying its clinical value and existing limitations are of important theoretical and practical significance for promoting the standardized application of this technology and improving children's perioperative outcomes. This review aims to comprehensively analyze the research progress and application status of EEG monitoring in pediatric anesthesia, explore its potential impacts on anesthetic management and postoperative outcomes, thereby providing a scientific basis for clinical practice, and prospect future research directions to facilitate the optimization and development of perioperative cerebral function monitoring in pediatrics.

Application of EEG Monitoring in Pediatric Anesthesia

pEEG-Guided Anesthetic Management in Pediatrics:

Currently, a variety of commercial anesthetic depth monitors are utilized in pediatric anesthesia, including BIS, PSI, Narcotrend Index, Entropy Index, qCON Index, and Wavelet Index. These monitors are developed based on adult frontal EEG data, with smaller sensor sizes designed for pediatric use. After processing raw EEG signals via proprietary algorithms, these devices display pEEG indices. The pEEG index is a dimensionless numerical value quantifying anesthetic depth, ranging from 0 to 100, with lower values indicating deeper anesthesia. Manufacturers provide recommended ranges of pEEG indices for "optimal anesthetic depth" based on their respective algorithms, such as a BIS value of 40-60 and a PSI value of 25-50. The advantage of this indicator lies in its simplicity and ease of interpretation; users do not require complex training, and anesthetic management is performed by adjusting drug dosage to maintain the index within the recommended range.

Previous studies have shown that, for children undergoing intravenous sedation with propofol, Weber et al. observed in 37 children aged 12-17 years undergoing gastrointestinal endoscopy that Narcotrend-guided anesthetic management (maintained within the range of 60-70) helped avoid excessive sedation, reduced propofol consumption, and shortened children's recovery time [8]. Another retrospective study involving 206 children aged 2-8 years undergoing dental treatment found that BIS-guided anesthetic management could reduce the incidence of intraoperative hypoxia, apnea, and recurrent cough and shorten discharge time [9]. For children undergoing elective surgery under general anesthesia, Oliveira et al. conducted a meta-analysis of 10 randomized controlled trials to evaluate the clinical value of BIS-guided anesthetic management compared with standard management strategies. The results showed that the end-tidal sevoflurane concentration in the BIS-guided group during anesthetic maintenance was reduced by 0.49%, the duration of BIS values maintained within the target range was longer, and the time to extubation, recovery time, and post-anesthesia care unit (PACU) stay duration were all significantly shortened [10]. In addition, the study found no statistically significant difference in Pediatric Anesthesia Emergence Delirium (PAED) scores between the two groups at 10 minutes and 30 minutes postoperatively.

However, this approach may lead anesthesiologists to over-rely on pEEG indices, thereby lacking a clear understanding of raw EEG fundamentals and index limitations. First, the process of nervous system development is reflected in age-related differences in EEG, but it remains unclear whether the algorithms of these devices have corrected for the impact of age. Existing studies have confirmed that pEEG indices such as BIS and PSI are inaccurate when directly applied to children, especially neonates and infants under 1 year of age [11,12]. Second, adult-based studies have shown that pEEG indices are insensitive to increases in inhaled anesthetic concentration [13,14]. An observational study involving children aged 6 months-12 years obtained similar results: as the sevoflurane concentration increased from 1% to 3%, BIS values decreased accordingly; when the sevoflurane concentration increased from 3% to 5%, BIS values exhibited an abnormal increase [15]. Furthermore, studies have found that different anesthetic depth monitors display inconsistent recommendations for the same patient's EEG data during the recovery phase, and more than one-third of patients were misjudged as excessively anesthetized by at least one device [16]. More importantly, although muscle relaxants and their antagonists do not act on the central nervous system, in awake volunteers receiving muscle relaxants, BIS, Entropy Index, and qCON Index all decreased to levels consistent with sedation or general anesthesia and returned to normal values after muscle relaxation reversal [17]. This indicates that some devices cannot distinguish myoelectric signals, and pEEG indices cannot reliably predict intraoperative awareness.

The aforementioned limitations suggest that anesthesiologists cannot rely solely on pEEG indices to assess the anesthetic depth of children. Most anesthetic depth monitors display EEG waveforms, density spectral array (DSA), 95% spectral edge frequency (SEF95), and burst suppression ratio (BSR) alongside pEEG indices. The combined application of these indicators can, to a certain extent, avoid misleading interpretations of pEEG values.

Raw EEG-Guided Anesthetic Management in Pediatrics:

With the continuous advancement of research on pediatric EEG, an increasing number of researchers have attempted to implement EEG-guided anesthetic management to improve children's perioperative outcomes. The main approaches include anesthetic management based on raw EEG-related indicators (such as DSA, SEF, etc.), for example, maintaining DSA to present a continuous and stable alpha-wave and delta-wave pattern, maintaining SEF at 10-15 Hz, and avoiding the occurrence of burst suppression [18,19]. During sevoflurane and propofol anesthetic maintenance, a "double-track sign" composed of high-power delta waves and alpha waves usually appears in the DSA of children over 4 months of age. As anesthetic depth deepens, delta-wave power increases, accompanied by a decrease in alpha-wave power; conversely, beta-wave power increases, accompanied by a decrease in alpha-wave power. SEF95 refers to the frequency that cumulatively contains 95% of the total power in the EEG power spectrum. A shift of SEF95 to lower frequencies often indicates deeper anesthesia, while a shift to higher frequencies indicates lighter anesthesia.

A meta-analysis incorporating randomized controlled studies of both BIS guidance and raw EEG guidance drew different conclusions: compared with standard management strategies, EEG-guided anesthetic management not only reduced PAED scores at 5 minutes and 10 minutes postoperatively but also decreased the risk of emergence delirium (ED, defined as a PAED score >10) by 60% (OR = 0.4, 95% CI: 0.27-0.59) [20]. The inconsistency in ED-related outcomes between the two meta-analyses may stem from differences in the intervention methods of the original studies; the former focused solely on BIS guidance, while the latter integrated studies related to raw EEG guidance on this basis. This suggests that different EEG-guided strategies may have heterogeneous impacts on ED. Therefore, it is necessary to further explore and verify the impact of standardized EEG-guided strategies on postoperative outcomes to achieve individualized and precise drug administration.

Conclusion

With the deepening of research on pediatric EEG, EEG-guided anesthetic management strategies have attracted increasing attention, aiming to optimize children's perioperative safety and outcomes. This review comprehensively analyzes the application effects and existing limitations of EEG monitoring in pediatric anesthesia and explores its impact on postoperative outcomes. From the perspective of implementation pathways, relevant research and practice are mainly divided into two directions: early studies focused on relying on pEEG indices (such as BIS and PSI), titrating anesthetic drugs by maintaining indices within a predetermined target range (such as BIS 40-60); recent studies have paid greater attention to raw EEG interpretation, using indicators such as spectral analysis, density spectral array, or spectral edge frequency for individualized anesthetic management [18,19]. These two application models have their own characteristics in terms of effects: pEEG indices provide intuitive quantitative targets, which are conducive to the formation of standardized management processes, helping to reduce total drug dosage, shorten recovery time, and potentially lower the risk of events such as intraoperative awareness; raw EEG guidance can more sensitively and individually reflect the dynamic changes of the cerebral cortex, which is particularly suitable for children with significantly age-dependent EEG characteristics and is expected to achieve more accurate regulation of anesthetic depth.

However, the limitations of both models are equally prominent: the algorithm validation of pEEG indices in infants and children is insufficient, and their interpretation is associated with age-dependent errors; raw EEG interpretation is highly dependent on the professional knowledge of users, and there is currently a lack of unified quantitative reference standards and operating guidelines corresponding to age and anesthetic depth. Subjective differences in implementation may affect its reliability and promotion. Furthermore, these application models and their limitations are directly associated with their impacts on children's postoperative outcomes. Although standardized pEEG management helps stabilize intraoperative cerebral status, its reliability and validity issues in children may hinder the effective exertion of neuroprotective effects; although raw EEG guidance is more physiologically reasonable in theory, due to the lack of standards and inconsistent implementation, its benefits in improving postoperative delirium and promoting neurocognitive recovery still require more high-quality clinical evidence.

Therefore, promoting the systematic development of pediatric EEG monitoring, from method standardization and personnel training to outcome research, is of important clinical and research significance for improving the quality of pediatric anesthesia and the long-term prognosis of children.

Conflict of Interest

The author has read and approved the final version of the manuscript. The author declares no conflicts of interest.

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