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Evaluation of nociceptive responses to skull pin fixation during craniotomy: a prospective observational study

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Abstract

Background

Skull pin fixation during craniotomy is an intense nociceptive stimulus that may evoke cortical and autonomic responses despite general anesthesia, which may not be fully reflected by hemodynamic parameters alone. We compared cortical spectral and hemodynamic responses to Mayfield skull pin fixation among three routinely used analgesic strategies using density spectral array (DSA) monitoring with image-based hue analysis of band-specific spectral-pattern changes.

Methods

This prospective observational study included 120 adults undergoing elective craniotomy with Mayfield skull pin fixation. The analgesic technique was selected at the discretion of the attending anesthesiologist: scalp nerve block (Group S, n = 39), intravenous opioid (Group O, n = 41), or local anesthetic infiltration (Group L, n = 40). The primary outcome was the pre- to post-fixation change in alpha-band hue. DSA recordings were analyzed using image-based hue scoring of the alpha, beta, and delta frequency bands as an ordinal indicator of spectral-pattern change rather than absolute spectral power. Alpha dropout and hemodynamic responses were assessed as secondary outcomes.

Results

In Group S, alpha-, beta-, and delta-band hue values did not change significantly after pin fixation ($P = 0.248$, $P = 0.235$, and $P = 0.465$, respectively). In Groups O and L, alpha- and beta-band hue values changed significantly (all $P \leq 0.001$), whereas delta-band hue changed only in Group L ($P = 0.011$). Alpha dropout occurred less frequently in Group S than in Groups O and L (12.8% vs. 70.7% and 72.5%, respectively; $P < 0.001$). Heart rate and mean arterial pressure increased significantly after pin fixation in Groups O and L but not in Group S ($P < 0.001$). Additional intraoperative opioid requirements were lower in Group S (6.7% vs. 31.7% and 40.0%, respectively; $P = 0.006$).

Conclusions

Scalp nerve block was associated with greater cortical spectral stability, less alpha dropout, and attenuated hemodynamic responses to Mayfield skull pin fixation. Image-based hue analysis of routinely available DSA output detected between-group differences in cortical spectral responses and may provide complementary information to conventional processed EEG indices. Its role in intraoperative nociception assessment requires prospective confirmation.

Trial registration

ClinicalTrials.gov, NCT06811701. Registered 5 February 2025 (prospectively registered).

Introduction

Craniotomy anesthesia requires maintenance of cortical and hemodynamic stability while preserving cerebral perfusion and minimizing fluctuations in intracranial pressure. Intense nociceptive stimuli, including skull pin fixation and surgical incisions, may evoke marked cortical and autonomic responses [1, 2]. Assessment of nociceptive responses is important in intraoperative anesthetic management.

Skull pin fixation during craniotomy produces abrupt and intense nociceptive stimulation associated with rapid alterations in cortical network dynamics and pronounced hemodynamic responses. Although hemodynamic parameters reflect autonomic responses to nociception, they are not specific markers of nociceptive processing. Intraoperative hemodynamic responses are influenced by multiple factors, including anesthetic depth, intensity of surgical stimulation, intravascular volume status, and administered drugs [3, 4].

Several autonomic nervous systems–based monitors, including the Analgesia Nociception Index (ANI), Nociception Level Index (NoL), Surgical Pleth Index (SPI), pupillometry, and skin conductance monitoring, have been developed for intraoperative nociception assessment [3, 5]. However, these physiological measures cannot directly reflect cortical responses. EEG-based approaches directly assess cortical responses associated with nociceptive stimulation [6]. Several numerical indices derived from frontal EEG activity, including the Bispectral Index (BIS), Brain Anesthesia Response Index (BAR), Composite Variability Index (CVI), and Quantitative Index of Nociception (qNOX), have been developed to evaluate cortical responses during anesthesia [7]. However, these indices reduce complex EEG patterns to single numerical values, limiting the assessment of frequency band-specific alterations such as alpha, beta, and delta activity [8, 9].

More recently, density spectral array (DSA) monitoring enables continuous time–frequency visualization of EEG activity and more detailed assessment of anesthetic-induced cortical dynamics than conventional one-dimensional indices. Nociceptive stimulation during general anesthesia produces characteristic EEG frequency alterations on DSA, including reductions in frontal alpha-band power (alpha dropout) accompanied by increases in beta and delta activity (arousal responses) [7, 10].

The aim of this study was to evaluate cortical spectral responses to Mayfield skull pin fixation using DSA analysis and to determine whether these responses differed according to the analgesic strategy used before pin fixation. We hypothesized that the pre- to post-fixation change in alpha-band hue, defined as the primary outcome, would differ among patients receiving scalp nerve block, intravenous opioid, or local anesthetic infiltration. Alpha dropout and hemodynamic responses were evaluated as secondary outcomes.

Materials and Methods

This single-center prospective observational study was approved by the Ankara Etlik City Hospital Ethics Committee (Approval No. AEŞH-BADEK-2024-1016; October 30, 2024) and was conducted in accordance with the Declaration of Helsinki. The study was prospectively registered at ClinicalTrials.gov (NCT06811701; registered on February 5, 2025). Patients were enrolled between February 28, 2025, and October 30, 2025. Written informed consent was obtained from all participants prior to enrollment.

Inclusion criteria

Patients aged 18–70 years with American Society of Anesthesiologists (ASA) physical status I–III who were scheduled for elective craniotomy under general anesthesia with skull pin fixation were included in the study.

Exclusion criteria

Patients with ASA physical status IV or higher, neurological disorders (including Parkinson’s disease, epilepsy, or previous stroke), psychiatric disorders (including severe depression or schizophrenia), sleep disorders, known allergies to local anesthetics or opioids, chronic opioid use, pregnancy, severe cardiovascular or pulmonary disease, or a surgical incision site or infection at the BIS sensor application area were excluded from the study.

Following admission to the operating room, electroencephalography and body temperature monitoring were performed in addition to standard anesthesia monitoring while patients were awake prior to induction. The BIS™ Quatro sensor was placed in a frontal montage configuration in accordance with the manufacturer's instructions. Sensor placement was performed to cover the frontal and frontotemporal regions anatomically corresponding to the international 10–20 system. Electrode impedances were maintained within the manufacturer-recommended range, and the signal quality index was verified prior to induction before commencing signal recording.

Anesthesia induction was achieved with intravenous bolus administration of propofol (2–2.5 mg/kg), fentanyl (1–2 µg/kg), and rocuronium (0.6 mg/kg). Following intubation, anesthesia maintenance was continued as total intravenous anesthesia (TIVA) with propofol and remifentanil infusions administered via independent syringe pumps. Propofol infusion was initiated at 4–8 mg/kg/h and remifentanil infusion was initiated at 0.05–0.2 µg/kg/min; infusion rates were titrated according to hemodynamic parameters and DSA findings. Throughout the procedure, anesthetic depth was titrated to a target BIS range of 40–60 in all groups. SEF95 was concurrently recorded as a complementary indicator of cortical spectral activity. A rescue analgesic dose of intravenous remifentanil 0.5 µg/kg bolus was planned in the event of a 20% or greater increase in hemodynamic variables from baseline.

Following anesthesia induction, radial arterial cannulation and internal jugular central venous catheterization were performed in all patients. The skull was secured by the surgical team using a Mayfield three-pin head fixation device (pin head holder). Surgical procedures were commenced following placement of the pin head holder.

The analgesic technique used before Mayfield pin fixation was determined at the discretion of the attending anesthesiologist as part of routine clinical practice, without investigator involvement in its selection. In our institution, scalp nerve block, local anesthetic infiltration, and intravenous opioid techniques are routinely used to provide analgesia during Mayfield pin fixation.

In the scalp nerve block protocol, bilateral scalp nerve block was performed approximately 15–20 min before Mayfield pin fixation. Three milliliters of 0.5% bupivacaine was injected at each nerve block site, for a total volume of 36 mL (180 mg).

In the intravenous opioid protocol, a fixed intravenous bolus of 50 μg fentanyl was administered 3–5 min before Mayfield pin fixation.

In the local infiltration protocol, 1 mL of 2% lidocaine was infiltrated at each pin insertion site approximately 3–5 min before Mayfield pin fixation, for a total dose of 60 mg.

Hemodynamic parameters

Hemodynamic parameters (mean arterial pressure [MAP] and heart rate [HR]) were recorded 5 and 3 minutes before Mayfield pin fixation (pre-MPF), at the time of fixation, 30 seconds, 1 minute, and 5 minutes after fixation (post-MPF), and subsequently at 3-minute intervals. The mean of the measurements obtained 5 and 3 minutes before fixation was used as the hemodynamic baseline.

DSA Analysis

Processed EEG parameters were recorded using the BIS Complete Monitoring System (P/N 185 – 0151; Application Revision 3.50; Medtronic). The monitor outputs included DSA displays and numerical indices (Bispectral index [BIS] and spectral edge frequency [SEF95]). The recordings were exported in PDF format using the manufacturer's software and subsequently converted to JPEG format for visual analysis. As the frequency–time scaling of the DSA is fixed by the manufacturer, no additional rescaling was performed.

Quantitative analyses were performed using ImageJ software (National Institutes of Health). For each patient, DSA regions corresponding to the delta (0–4 Hz), alpha (8–13 Hz), and beta (13–30 Hz) frequency bands were selected in a standardized manner during the 5-minute period prior to (pre-MPF) and the 5-minute period following (post-MPF) Mayfield pin fixation. The mean RGB (red-green-blue) pixel intensities were measured from these regions and converted to hue values using the following formula: [11]

$$\tan(h) = \frac{\sqrt{3} \cdot (G - B)}{2R - G - B}$$

In the formula, h denotes the hue angle in radians; the results were converted to degrees (h° = h × 180/π). The resulting hue values were interpreted not as absolute spectral power measurements, but as an indicator reflecting relative changes within frequency bands. All measurements were performed using standardized regions corresponding to predefined frequency bands, following an identical analysis protocol throughout.

The color distribution on the DSA provides a visual representation of spectral power within frequency bands [8]. Quantitative color analysis was performed according to the image-based methodology described by Luo et al. [11]. Mean red-green-blue (RGB) values obtained from standardized regions of interest were converted to hue values using the transformation described by Luo et al. [11]. The resulting hue values were used to evaluate relative color changes within predefined frequency bands between the pre-MPF and post-MPF periods.

In addition to hue analysis, DSA recordings were independently reviewed by an anesthesiologist experienced in processed EEG interpretation. The reviewing investigator was blinded to the analgesic technique used and to the timing of the recordings. DSA

outputs were qualitatively assessed for the presence of alpha dropout according to predefined criteria. Alpha dropout was defined as a visually discernible decrease in alpha band power (8–13 Hz) on the spectral array display relative to the baseline appearance during the prestimulus period. All recordings were examined at identical time resolutions and frequency scales throughout the assessment. Each recording segment (prestimulus and poststimulus) was classified as either "alpha dropout present" or "alpha dropout absent", and the resulting classifications were recorded for statistical analysis.

The anesthetic depth was titrated to target a BIS value of 40–60 throughout the procedure. SEF95 was simultaneously recorded as a supplementary spectral parameter. Patient demographics, total anesthetic and analgesic agent consumption, and operative duration were recorded for all patients.

Sample size calculation

The sample size was calculated a priori using the primary outcome of alpha-hue change (post-MPF − pre-MPF). As no prior study has examined this specific outcome, the calculation was based on preliminary observational data obtained from routine clinical monitoring at our institution, yielding a mean Δalpha-hue of 14.22 ± 17.52. A conservative small-to-moderate effect size (Cohen's $d_z = 0.33$) was assumed. The sample size was calculated using G*Power 3.1.9.6 with a two-tailed paired-samples t-test model, $\alpha = 0.05$, and 90% power ($1 - \beta = 0.90$). The minimum required sample size was determined to be 99 patients, and a total of 120 patients were enrolled.

Statistical analysis

Statistical analyses were performed via IBM SPSS Statistics version 27.0 (IBM Corp.) and MedCalc version 15.8 (MedCalc Software). Descriptive statistics are presented as frequency, percentage, means, standard deviation, median, and minimum–maximum values. The normality of the data distribution was assessed using the Shapiro–Wilk test. For normally distributed variables, intergroup comparisons were performed using one-way ANOVA with Tukey's HSD post hoc test, and intragroup comparisons were performed using repeated measures ANOVA with Bonferroni correction. For non-normally distributed variables, intergroup comparisons were performed using the Kruskal–Wallis test with Bonferroni-adjusted pairwise comparisons, and intragroup comparisons were performed using the Wilcoxon test. Categorical variables were compared using the Pearson chi-square test or Fisher's exact test, as appropriate. A P value < 0.05 was considered statistically significant.

Results

A total of 120 patients were included in the study. Patients were grouped according to the analgesic technique administered at the discretion of the attending anesthesiologist: Group S (scalp nerve block, n = 39), Group O (intravenous opioid, n = 41), and Group L (local anesthetic infiltration, n = 40). Patient enrollment, group assignment, and analysis are summarized in Fig. 1.

The patients' demographic characteristics are presented in Table 1. No statistically significant differences were observed among the groups with respect to sex, age, body weight, height, ASA physical status, or comorbidities (P > 0.05).

EEG

Alpha Hue

No significant difference was observed between pre-MPF and post-MPF alpha hue values in the scalp nerve block group (P = 0.248). In the opioid and local anesthetic groups, a significant difference was found between pre-MPF and post-MPF alpha hue values, with post-MPF alpha hue values being higher (P = 0.001, P < 0.001, respectively). Intergroup comparisons revealed that post-MPF and Δ (pre-MPF–post-MPF) alpha hue values were significantly higher in Groups O and L compared to Group S (P = 0.028 and P = 0.001, respectively; **Table 2; Fig. 2**).

Alpha dropout was observed in 63 of 120 patients (52.5%). Visual analysis revealed a statistically significant difference between groups with respect to the presence of alpha dropout (P < 0.001). The rate of alpha wave dropout in the scalp block group was 12.8%, whereas the rates in the opioid and local infiltration groups were 70.7% and 72.5%, respectively; the rate was markedly lower in the scalp block group (Table 2; Fig. 3).

Beta hue

No significant difference was observed between pre-MPF and post-MPF beta hue values in the scalp nerve block group (P = 0.235). In the opioid and local anesthetic groups, the post-MPF beta hue values were found to be higher than pre-MPF beta hue values (P < 0.001 for both). Inter-group comparison of beta hue values revealed that Δ(pre-MPF–post-MPF) beta hue value in Group O was significantly higher compared to Group S (P = 0.001, Table 2).

Delta Hue

No significant difference was observed between pre-MPF and post-MPF delta hue values in the scalp block and opioid groups (P = 0.465 and P = 0.074, respectively), whereas post-MPF delta hue values were found to be significantly higher than pre-MPF values in the local anesthetic group (P = 0.011). Inter-group comparison revealed that Δ (pre-MPF–post-MPF) delta hue values in Groups O and L were significantly higher compared to Group S (P = 0.010, Table 2).

The changes in alpha, beta, and delta hue values before and after MPF across the three groups are shown in Fig. 2.

Hemodynamic Responses

When each group was evaluated individually, statistically significant changes in HR and MAP over time were observed in all three groups (P < 0.001). Compared with those at baseline, no hemodynamic changes were observed in the scalp block group during the first 5 minutes post-MPF; however, both HR and MAP decreased at the post-MPF 5-minute measurement (*P*< 0.001 for both). In the opioid and local infiltration groups, HR was significantly elevated compared with baseline at the 30-second and 1-minute post-MPF measurements, and MAP was significantly elevated at the 1-minute post-MPF measurement (*P* < 0.001 for all; Table 3). Inter-group comparisons demonstrated that the baseline values were similar across groups, whereas the HR and MAP in the scalp block group were significantly lower than those in the other groups at the 30-second and 1-minute post-MPF measurements (Table 3). No significant difference was observed between groups at the remaining time points (Table 3).

Additional Opioid Requirement

The requirement for additional intraoperative opioid bolus differed significantly between groups (P = 0.006). Additional opioid was required in 6.7% of patients in Group S, 31.7% in Group O, and 40.0% in Group L. No significant difference was found between groups with respect to total propofol consumption (Group S: 2421.9 ± 905.4 mg, Group O: 2286.1 ± 921.0 mg, Group L: 2494.4 ± 568.7 mg; P = 0.507), total remifentanil consumption (Group S: 1435.5, Group O: 1444.0, Group L: 1755.0 μg; median values; P = 0.222), or operation duration (320.9 ± 92.8, 297.2 ± 71.7, and 330.0 ± 68.8 minutes, respectively; P = 0.154).

Discussion

In this study, the nociceptive response elicited by Mayfield pin fixation during craniotomy was assessed using qualitative (alpha dropout) assessment, image-based hue analysis of DSA spectral patterns, and hemodynamic variables. The incidence of alpha dropout was significantly lower in the scalp nerve block group than in the other two groups. When patients were analyzed according to the analgesic technique, alpha, beta, and delta hue values did not differ significantly between the pre-MPF and post-MPF periods in the scalp nerve block group, whereas all three hue values differed significantly following pin fixation in the local infiltration group. In the opioid group, alpha and beta hue values differed significantly after MPF, whereas delta hue values remained unchanged.

Nociception-related changes in the DSA have been described in several experimental and clinical studies. Raw EEG spectral analyses have shown that noxious stimulation during general anesthesia is associated with reduced frontal alpha-band power and, less consistently, with increased beta- and delta-band activity [7]. Image-based hue analysis provides an ordinal representation of within-band changes in the DSA spectral pattern rather than a measure of absolute spectral power. The hue changes observed in the present study should therefore be interpreted as relative stimulus-related alterations of the DSA spectral pattern. Consistent with this interpretation, alpha hue differed significantly between the pre- and post-MPF periods in the opioid and local infiltration groups, whereas no significant change was observed in the scalp nerve block group, suggesting greater alpha-band spectral stability with scalp nerve block.

Alpha dropout is characterized by a transient reduction in frontal alpha-band power during general anesthesia in response to nociceptive stimulation and has been described by Hight et al. [12] and discussed in the context of nociception by García et al. [7]. In the present study, alpha dropout was assessed visually on the DSA as a categorical finding, independently of the image-based hue analysis, and occurred markedly less frequently in the scalp nerve block group than in the opioid and local infiltration groups (12.8% vs. 70.7% and 72.5%). In contrast, hue analysis provided an ordinal evaluation of stimulus-related changes in the DSA spectral pattern rather than a measure of absolute spectral power.

Accordingly, alpha dropout and hue analysis should not be regarded as mutually confirmatory measurements of the same physiological variable but as complementary approaches that evaluate different aspects of the cortical response. Despite these methodological differences, both approaches indicated a more limited cortical response to pin fixation in the scalp nerve block group. Because processed EEG indices condense cortical activity into a single numerical value, combining the qualitative assessment of alpha dropout with ordinal analysis of DSA spectral patterns may provide additional information regarding stimulus-related cortical responses beyond conventional processed EEG indices.

In the scalp nerve block group, alpha hue showed no significant change after skull pin fixation, and visual DSA assessment revealed a low incidence of alpha dropout, together indicating a stable cortical spectral pattern in the alpha band. Given that propofol-induced alpha oscillations are generated by thalamocortical networks [8] and may be disrupted by nociceptive stimulation [7], preservation of alpha activity is consistent with effective attenuation of nociceptive input and maintenance of thalamocortical oscillatory stability. In contrast, alpha dropout occurred frequently in the opioid and local infiltration groups, suggesting less effective suppression of nociceptive transmission. Previous studies have shown that noxious stimulation may disrupt frontal alpha oscillations and generate arousal-related EEG responses, findings consistent with the electrophysiological pattern observed in the present study [7, 12].

Beta arousal, an increase in beta-band power evoked by nociceptive stimulation under general anesthesia, is characteristically observed during light anesthesia and inadequate analgesia [7]. Accordingly, beta-band activity may not constitute a specific marker of nociceptive response in isolation. Indeed, Anders et al. reported that consistent spectral changes in the EEG following nociceptive stimulation could not be demonstrated using 32-channel raw EEG under clinical anesthesia conditions and that changes in the beta frequency band did not reach statistical significance [13]. Because beta oscillations are high-frequency, low-amplitude signals with amplitudes substantially smaller than those of slow and alpha oscillations [8], image-based hue analysis was used to provide an ordinal assessment of within-band changes in the DSA spectral pattern rather than absolute spectral power. Significant changes in beta hue values were observed in the opioid and local infiltration groups, whereas no significant change was detected in the scalp nerve block group. These findings suggest greater preservation of cortical spectral stability with scalp nerve block following nociceptive stimulation.

Delta arousal refers to increased delta-band power that may develop in response to nociceptive stimulation under general anesthesia, particularly when high anesthetic drug concentrations coincide with insufficient opioid effect [7]. Previous studies have suggested that cortical delta responses may vary according to the intensity of nociceptive stimulation [14]. On the DSA, delta-band activity is a prominent low-frequency feature that may be influenced by both nociceptive stimulation and anesthetic depth [7]. In the present study, anesthesia was titrated to maintain a BIS value between 40 and 60 in all groups; therefore, differences in anesthetic depth are less likely to explain the observed intergroup differences in delta hue. Delta-band changes were evaluated using image-based hue analysis. Delta hue showed no significant change in the scalp nerve block and opioid groups, whereas a significant change was observed in the local infiltration group following pin fixation. The absence of a significant delta hue change in the opioid group may reflect attenuation of nociceptive transmission at spinal and supraspinal levels by opioids [7], whereas the significant change in the local infiltration group suggests that infiltration limited to the pin sites may be insufficient to completely block nociceptive input [15]. Collectively, these findings further support greater preservation of cortical spectral stability with scalp nerve block following pin fixation.

Mayfield pin fixation represents one of the most intense nociceptive stimuli encountered during craniotomy and is typically associated with pronounced hemodynamic responses [1]. In the present study, no significant changes in HR or MAP were observed following Mayfield pin fixation in the scalp nerve block group, whereas both parameters increased significantly in the opioid and local infiltration groups. These findings suggest that scalp nerve block was associated with more effective attenuation of the hemodynamic response to pin fixation than the other analgesic strategies.

Scalp nerve block maintains hemodynamic stability during periods of significant sympathetic activation, such as Mayfield pin fixation and patient positioning, by blocking the transmission of nociceptive signals to the central nervous system and attenuating the cardiovascular response [15–17]. Systemic pharmacological strategies may also attenuate this response. Berger et al. reported that a remifentanil bolus blunted the hemodynamic response to Mayfield pin fixation more effectively than a propofol bolus [18]. In the present study, however, hemodynamic control was less consistent in the opioid group than in the scalp nerve block group, suggesting that regional blockade may provide more consistent attenuation of the hemodynamic response than systemic analgesic strategies alone.

In the present study, increases in HR and MAP from baseline were observed at 30 seconds and 1 minute following Mayfield pin fixation in the opioid and local infiltration groups. Arunashree et al. demonstrated that scalp nerve block was more effective than intravenous fentanyl alone in suppressing heart rate and blood pressure responses to nociceptive stimulation during Mayfield pin fixation and provided superior hemodynamic stability [19]. Similarly, Theerth et al. showed that scalp nerve block more effectively attenuated nociceptive and hemodynamic responses associated with Mayfield pin fixation than pin-site infiltration [2]. These findings are consistent with these observations and suggest that opioid administration or local infiltration alone may be insufficient to consistently suppress the sympathetic response to Mayfield pin fixation. This may be explained by the more comprehensive blockade of peripheral nociceptive afferent input achieved by scalp nerve block.

The present study has several methodological limitations. First, it was conducted at a single center, which may limit the generalizability of the findings. As an observational study, the analgesic technique reflected routine clinical practice and was determined at the discretion of the attending anesthesiologist. Baseline characteristics were comparable among groups, and anesthetic depth was standardized to a target BIS range of 40–60, supporting the internal validity of the between-group comparisons.

Several methodological considerations should also be noted. The hue analysis was based on discrete pre- and post-fixation measurements rather than continuous recording; consequently, very brief early-phase spectral changes may not have been fully captured, and the hue findings are therefore considered to reflect the later, more stable cortical response to nociceptive stimulation. In contrast, the visual alpha-dropout assessment was performed over the post-stimulus DSA segment and was not subject to this constraint, thereby capturing the transient early-phase response. The two approaches therefore provide complementary temporal information. In addition, raw EEG waveform export for offline analysis was not available in our clinical monitor configuration, which provided only DSA, amplitude, and BIS trend displays. Accordingly, image-based hue analysis of the DSA displays was performed using the methodology described by Luo et al. [11].

In the present study, the cortical response to Mayfield pin fixation during craniotomy was evaluated using image-based hue analysis of the DSA together with visual assessment of alpha dropout. In the scalp nerve block group, alpha, beta, and delta hue values did not differ significantly between the pre- and post-fixation periods, whereas significant spectral-pattern changes accompanied by concurrent hemodynamic responses were observed in the opioid and local infiltration groups. The incidence of alpha dropout was also markedly lower in the scalp nerve block group, suggesting a more limited nociceptive cortical response.

Conclusion

The observational findings of the present study suggest that scalp nerve block is associated with a more stable cortical and hemodynamic profile in response to Mayfield pin fixation, and that band-specific DSA analysis may provide information complementary to conventional hemodynamic parameters. Because processed EEG indices summarize cortical activity as a single numerical value, they may obscure band-specific changes in alpha, beta, and delta activity; image-based hue analysis and visual assessment of alpha dropout may therefore serve as useful complementary approaches for intraoperative nociception assessment. Further development of EEG-based monitoring capable of real-time detection of nociceptive responses may enable more specific and reliable assessment of intraoperative nociception under general anesthesia.

Declarations

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Authors' contributions

Ceyda Özhan Çaparlar conceived and designed the study, developed the methodology, collected and analyzed the data, and drafted the manuscript.

Aylin Kılınçarslan participated in data collection and critically reviewed the manuscript.

Fatma Özkan Sipahioğlu participated in data collection and critically reviewed the manuscript.

Derya Özkan supervised the study and critically revised the manuscript.

Jülide Ergil supervised the study and critically revised the manuscript.

All authors read and approved the final manuscript.

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Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

The study was approved by the Ankara Etlik City Hospital Ethics Committee (Approval No. AEŞH-BADEK-2024-1016) and was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants before enrollment in the study.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Tables

Table 1. Demographic and clinical characteristics of the study population		
Age (yr), mean ± SD		51.1 ± 14.7
BMI (kg/m²), median (range)		26.2 (17.5–47.0)
Sex, female/male, n (%)		54 (45.0) / 66 (55.0)
ASA physical status, n (%)	I	34 (28.3)
	II	59 (49.2)
	III	27 (22.5)
Analgesic strategy, n (%)	Group S	39 (32.5)
	Group O	41 (34.2)
	Group L	40 (33.3)
Duration of surgery (min), mean ± SD		311.6 ± 86.8
BMI, Body mass index. Group S, scalp block; Group O, intravenous opioid; Group L, local infiltration.		

Table 2. Within- and between-group comparisons of alpha-, beta-, and delta-hue values and alpha dropout incidence

Alpha-Hue	Group S (n=39)	Group O (n=41)	Group L (n=40)	P [a]
Pre-MPF	50.0 (16.0–166.0)	54.0 (2.0–176.0)	53.5 (7.0–172.0)	0.575
Post-MPF	56.0 (18.0–167.0)	66.0 (6.0–190.0) †	67.5 (8.0–185.0) †	0.028*
Δ Alpha Hue	5.0 (0.0–40.0)	12.0 (0.0–83.0)	13.0 (0.0–86.0)	0.001*
Beta-Hue	Group S (n=39)	Group O (n=41)	Group L (n=40)	P [a]
Pre-MPF	168.0 (81.0–205.0)	164.0 (63.0–221.0)	171.0 (52.0–210.0)	0.458
Post-MPF	178.0 (86.0–207.0)	183.0 (68.0–224.0) †	180.5 (64.0–213.0) †	0.905
Δ Beta Hue	4.0 (1.0–46.0)	12.0 (0.0–79.0)	7.5 (1.0–82.0)	0.001¶
Delta-Hue	Group S (n=39)	Group O (n=41)	Group L (n=40)	P [a]
Pre-MPF	37.0 (1.0–55.0)	27.0 (4.0–353.0)	35.0 (3.0–70.0)	0.357
Post-MPF	40.0 (3.0–87.0)	34.0 (9.0–360.0)	39.5 (14.0–121.0) †	0.835
Δ Delta Hue	5.0 (0.0–32.0)	7.0 (0.0–60.0)	7.5 (0.0–81.0)	0.010*
Alpha dropout	Group S (n=39)	Group O (n=41)	Group L (n=40)	P
n (%)	5 (12.8)	29 (70.7)	29 (72.5)	<0.001Þ

Alpha-, beta-, and delta-hue values are presented as median (range).

a Kruskal–Wallis test for between-group comparisons

, ¶: Bonferroni-corrected post hoc comparisons (: Group S vs Group O and L; ¶: Group S vs Group O).

†: Wilcoxon signed-rank test, $P < 0.05$ compared with pre-MPF.

Þ: Chi-Square test

MPF, Mayfield pin fixation; pre-MPF, 5-min period immediately preceding Mayfield pin fixation; post-MPF, 5-min period immediately following Mayfield pin fixation.

Table 3. Within- and between-group comparisons of heart rate and mean arterial pressure before and after Mayfield pin fixation				
HR (beats/min)	Group S (n=39)	Group O (n=41)	Group L (n=40)	P [a]
Baseline	76.3 ± 14.4	72.3 ± 15.8	77.8 ± 14.7	0.240
MPF	75.0 ± 14.1	76.5 ± 15.4	78.2 ± 18.7	0.686
Post-MPF 30 s	74.5 ± 13.5	84.8 ± 15.5†	85.0 ± 18.3†	0.005*
Post-MPF 1 min	73.1 ± 14.1	86.9 ± 15.6†	87.5 ± 18.6†	<0.001*
Post-MPF 3 min	73.0 ± 14.6	71.0 ± 15.4	73.8 ± 17.0	0.708
Post-MPF 5 min	71.4 ± 13.4†	70.8 ± 16.6	72.4 ± 17.7	0.906
MAP (mmHg)	Group S (n=39)	Group O (n=41)	Group L (n=40)	P [a]
Baseline	83.4 ± 14.6	86.8 ± 13.2	87.4 ± 15.5	0.424
MPF	85.3 ± 16.0	94.6 ± 16.2	90.3 ± 18.6	0.052
Post-MPF 30 s	83.6 ± 17.8	101.5 ± 14.9†	96.4 ± 17.3	<0.001*
Post-MPF 1 min	82.0 ± 17.6	102.1 ± 14.8†	97.2 ± 16.9†	<0.001*
Post-MPF 3 min	79.6 ± 14.2	85.1 ± 17.2	85.1 ± 16.1	0.207
Post-MPF 5 min	75.7 ± 13.5†	79.9 ± 14.1	80.6 ± 13.5	0.246

Values are presented as mean ± standard deviation.

a One-way ANOVA.

* Tukey post hoc comparison (Group S vs Groups O and L).

†: P < 0.001 compared with baseline (repeated-measures ANOVA with Bonferroni correction).

MPF, Mayfield pin fixation; HR, heart rate; MAP, mean arterial pressure.

Figures

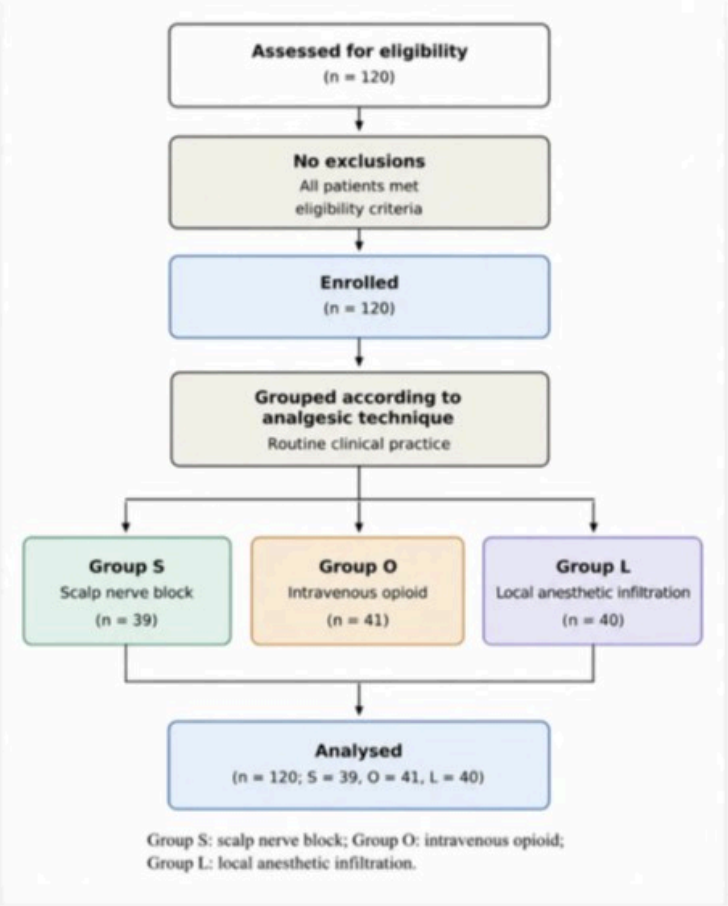


Figure 1

Study flow diagram. All 120 patients assessed for eligibility met the inclusion criteria and were enrolled. Patients were grouped according to the analgesic technique administered at the discretion of the attending anesthesiologist: scalp nerve block (Group S, n = 39), intravenous opioid (Group O, n = 41), or local infiltration (Group L, n = 40). All 120 patients were included in the analysis. Group L, local anesthetic infiltration; Group O, intravenous opioid; Group S, scalp nerve block.

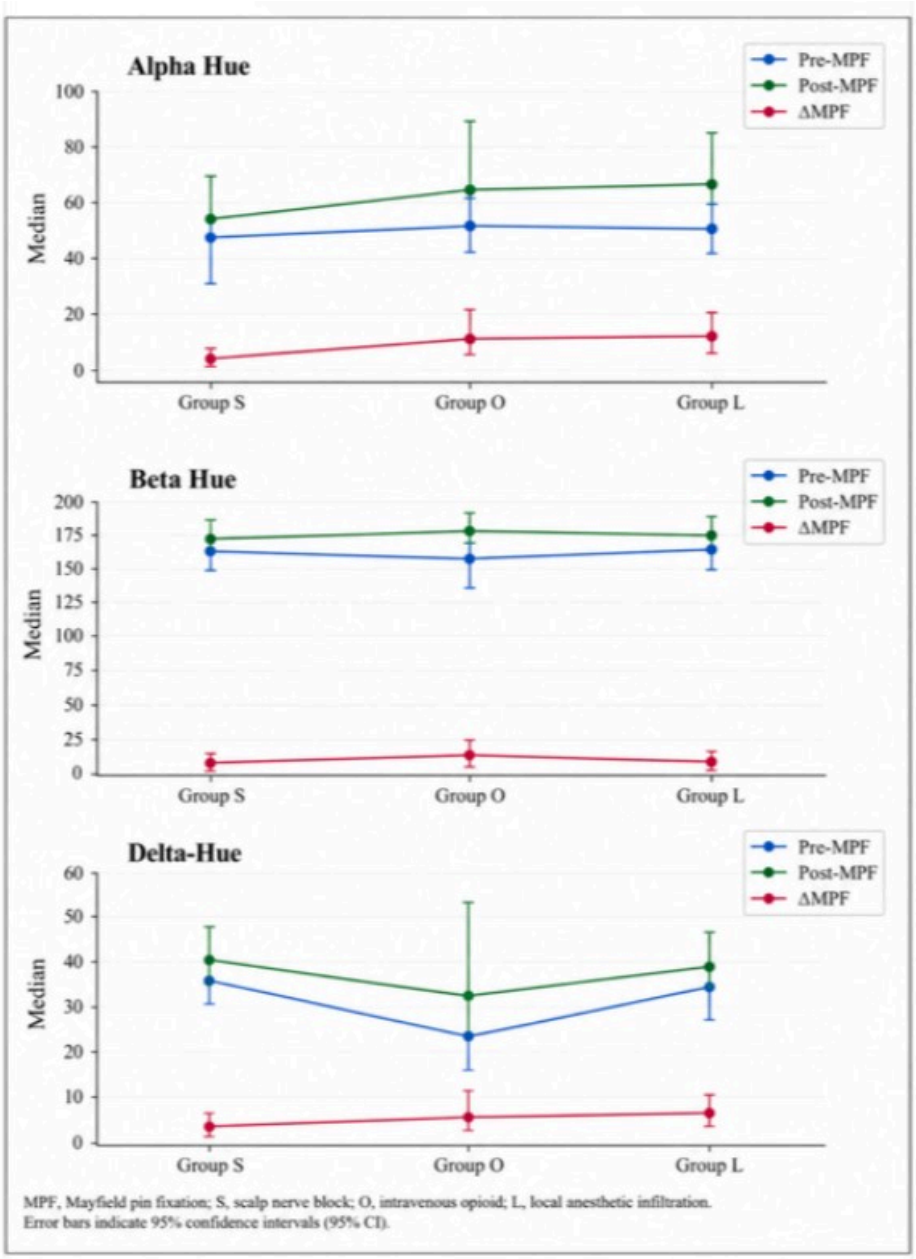


Figure 2

DSA-derived hue values before and after Mayfield pin fixation across analgesic groups. Median hue values (95% CI) for the alpha (8–13 Hz), beta (13–30 Hz), and delta (0–4 Hz) frequency bands are presented for the pre-MPF and post-MPF periods and for the pre- to post-MPF change (Δ). Hue values were interpreted as ordinal indicators of relative within-band color change rather than as absolute measures of spectral power. CI, confidence interval; DSA, density spectral array; Group L, local anesthetic infiltration; Group O, intravenous opioid; Group S, scalp nerve block; MPF, Mayfield pin fixation; pre-MPF, 5-minute period before Mayfield pin fixation; post-MPF, 5-minute period after Mayfield pin fixation.

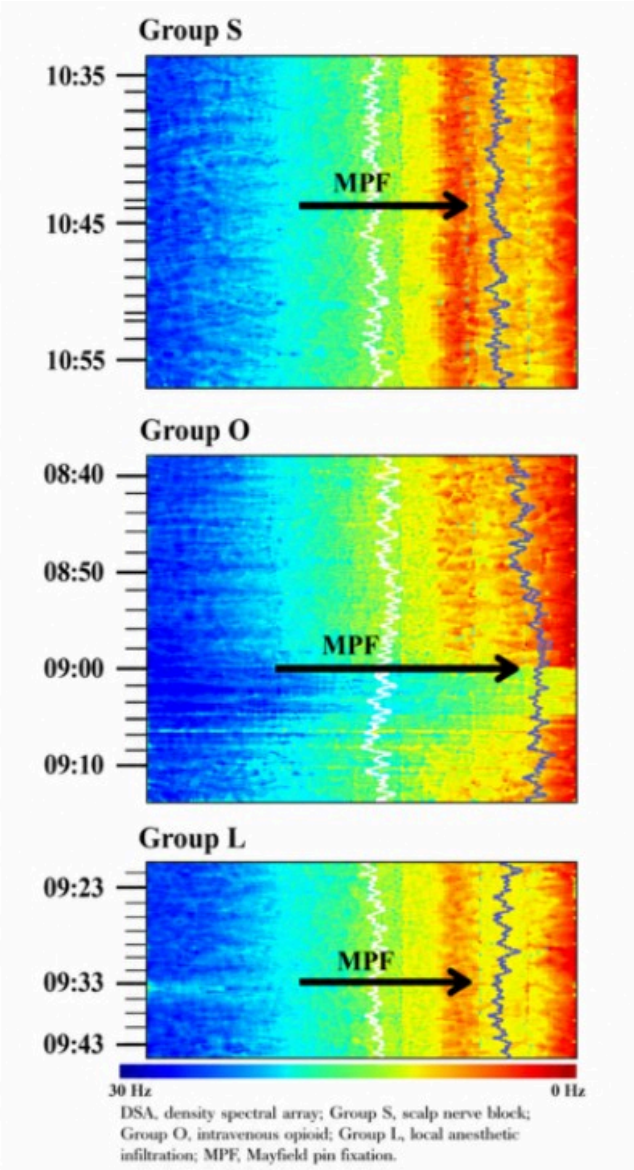


Figure 3

Representative DSA recordings from one patient in each analgesic group. Black arrows indicate the time of Mayfield pin fixation (MPF). Representative alpha dropout following MPF is shown in the intravenous opioid and local anesthetic infiltration groups, whereas relative preservation of the alpha band is demonstrated in the scalp nerve block group. DSA, density spectral array; Group L, local anesthetic infiltration; Group O, intravenous opioid; Group S, scalp nerve block; MPF, Mayfield pin fixation.