

EEG microstate and functional connectivity analyses for differentiating suicide attempt from suicidal ideation in major depressive disorder

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Abstract

Background: Suicide remains a critical public health issue, with self-report-based clinical assessments often failing to detect imminent risk. This study aimed to identify objective electroencephalography (EEG)-based neurobiological markers for differentiating a suicide attempt (SA) from suicidal ideation (SI) using EEG microstate and microstate-based functional connectivity (FC) analyses.

Methods: From 2017 to 2020, this study enrolled 130 medication-naïve major depressive disorder patients (68 SA, evaluated within 7 days of the attempt; 62 SI) at Soonchunhyang University Cheonan Hospital. Resting-state EEG data were analyzed using microstate analysis to explore temporal dynamics of brain topography and microstate-based FC to assess connectivity in theta, alpha, and beta bands. Correlations between EEG features and psychological measures (e.g., suicidal ideation, depression, emotion regulation) were examined.

Results: Compared with the SI group, the SA group showed a marginally lower frequency of occurrence for microstates A (auditory/language processing) and B (visual processing) ($p = 0.078$ for both). The SA group demonstrated significantly higher alpha-band FC during microstate E (linked to the default mode network (DMN)) for several electrode pairs (e.g., F7–C5, $p = 0.009$; FC5–C5, $p = 0.005$). The SA group also exhibited marginally higher FC in the alpha band during microstates C (DMN-related) and B, and in the theta band during microstate E. A subsequent within-group analysis revealed that in the SI group, alpha-band FC during microstate E positively correlated with scores for difficulties in emotion regulation ($r = 0.433$, $p = 0.017$).

Limitations: Findings are limited by potential physiological confounds in the SA group and by the limited anatomical specificity inherent in sensor-space EEG analysis.

Conclusion: EEG microstate dynamics and microstate-based FC differ between patients with SA and SI. Specifically, enhanced alpha-band connectivity during microstate E in the SA group potentially reflects condition-specific DMN functions. These EEG-based measures show promise as objective markers that complement clinical suicide risk assessment and inform early intervention strategies.

Key words: quantitative EEG, neuroscience, mood disorders, clinical psychiatry, suicidology, clinical psychiatry

Introduction

Suicide remains a critical global public health issue, resulting in over 720 000 deaths annually.¹ Given the multifactorial etiology of suicide, comprehensive frameworks that integrate biological, psychological, and sociocultural determinants are essential for understanding and preventing suicidal behavior.² However, current clinical assessments, which rely predominantly on interviews and self-reported instruments, may fail to detect imminent risks. Indeed, some individuals deny experiencing suicidal thoughts even shortly before an attempt, which underscores the urgent need for objective and reliable biological markers.^{3,4}

Electroencephalography (EEG) has the potential to elucidate the neurophysiological basis of suicidal behavior.⁵ It offers a high temporal resolution, relatively low cost, and widespread accessibility, potentially providing a valuable objective complement to traditional clinical assessments.⁶ Analysis of frontal alpha asymmetry at F7–F8 in patients with major depressive disorder (MDD) revealed distinct patterns of correlation with suicidal behavior depending on the dominant hemisphere. Individuals with left-dominant asymmetry demonstrated significant positive correlations of both low-alpha-band and total-alpha-band asymmetry with suicidal behavior. Conversely, those with right-dominant asymmetry ex-

hibited a significant positive association between high-alpha-band asymmetry and suicidal behavior.⁷ Furthermore, research identified significant differences in high-alpha-band network measures between patients with suicide attempt (SA) and those with suicidal ideation (SI). Specifically, patients with SA demonstrated lower strength and clustering coefficients (CC) and higher path lengths compared to those with SI. At the nodal level, these patients showed lower high-alpha-band CCs in most brain regions. This analysis achieved a classification accuracy of 73.39% for distinguishing between SA and SI groups using high-alpha-band network features.⁸ Building on these single-modality findings, additional research examining youth and young adults with mood disorders utilized EEG with source localization alongside functional magnetic resonance imaging (fMRI) data. This multimodal approach found consistent default mode network (DMN) dysfunction across multiple EEG frequency bands (theta, alpha, and beta), which was associated with SI.⁹

These spectral- and connectivity-based approaches have advanced the understanding of the neurophysiological correlates of suicidal behavior; however, they primarily capture sustained neural states over seconds to minutes. Such methods may fail to capture the dynamic, millisecond-scale fluctuations in brain activity that underlie rapidly changing cognitive and affective processes,¹⁰ a limitation the present study aims to address through microstate analysis and microstate-based functional connectivity (FC) analysis. Microstate analysis segments the continuous EEG signal into transient and quasi-stable states characterized by distinct scalp topographies. These states, or microstates, are thought to represent fundamental units of cognition, with different topographies linked to distinct large-scale neural networks. For instance, based on source localization studies, microstate A is associated with the auditory/language network, microstate B with the visual network (VN), and microstates C and E are linked to different components of the DMN.¹¹ Each microstate lasts approximately 60–120 ms, thus enabling a more detailed examination of moment-to-moment brain dynamics.¹² In addition, microstate-based FC analysis facilitates the investigation of connectivity patterns specific to these transient brain states, offering a richer and more nuanced understanding of the underlying neural network dynamics.¹³

The present study employs microstate and microstate-based FC analyses of resting-state EEG data to investigate the neurobiological distinctions between patients with SA and those with SI. This methodological approach offers several key advantages: it captures the dynamic nature of brain activity, provides a data-driven framework for identifying recurring neural states, and enables the detection of state-specific connectivity patterns. Considering previous findings linking alpha-band activity to suicidal behavior, it was hypothesized that microstate-based FC measures would reveal significant differences between the SA and SI groups, particularly within the alpha band. Additionally, the study examines the correlation between these EEG-derived markers and established psychological indicators of suicide risk. This comprehensive analysis aims to advance the understanding of the rapid neural dynamics underlying suicidal behavior and to contribute

to the development of more sensitive and objective measures for suicide risk assessment in clinical settings.

Materials and methods

Participants

Between September 2017 and March 2020, 130 medication-naïve patients with MDD were enrolled and allocated to either an SA group ($n = 68$) or an SI group ($n = 62$). Diagnoses were established by a board-certified psychiatrist according to the criteria of the Diagnostic and Statistical Manual of Mental Disorders, 4th edition (DSM-IV), using the Structured Clinical Interview for DSM-IV Axis I Disorders (SCID-I).¹⁴

General exclusion criteria comprised neurological disorders, severe medical illnesses, intellectual disability, history of electroconvulsive therapy, alcohol abuse, and significant head injury. Furthermore, individuals with a history of non-suicidal self-injury (NSSI) were excluded to isolate neurobiological markers specifically associated with the transition from SI to SA and to minimize confounding from different underlying psychopathologies.

The SA group was recruited through referrals from the medical or emergency departments to the psychiatry department of Soonchunhyang University Cheonan Hospital. Attempts determined to have lethal intent through clinical assessment included drug overdose ($n = 28$, 41.2%), pesticide poisoning ($n = 28$, 41.2%), cutting ($n = 7$, 10.3%), hanging ($n = 3$, 4.4%), and falling ($n = 2$, 2.9%). Admission to the Medical Intensive Care Unit (MICU) or Emergency Intensive Care Unit (EICU) following the attempt served as a primary inclusion criterion.

Enrollment proceeded only after medical stabilization in the MICU or EICU and transfer to the psychiatric ward. At this point, treating physicians confirmed capacity to provide informed consent and the absence of medical conditions that could confound EEG recordings. A standardized protocol, which included detoxification procedures (e.g., dialysis, intravenous hydration) for intoxication-related attempts, was subsequently implemented to minimize potential confounds. Furthermore, no new medications known to affect EEG outcomes were administered during this stabilization period.

The SI group was recruited from the psychiatric outpatient clinic and comprised patients with MDD without a lifetime history of SA or NSSI. Inclusion in this group required a score of 1 or greater on the initial five items and a total score of 9 or higher on the Beck Scale for Suicide Ideation (BSI).^{15,16}

For the SI group, psychological and EEG assessments were conducted at recruitment. For the SA group, assessments occurred after stabilization, with EEG recordings scheduled either immediately prior to discharge or at the earliest feasible outpatient visit if emotional instability was a concern; all such recordings were obtained within 7 days post-attempt. To ensure that all participants remained medication-naïve during assessment and to prevent pharmacological interference, psychiatric medication, when clinically indicated, was initiated only after EEG completion.

Psychological measures

Psychological constructs were assessed using the following self-report instruments: the BSI, Beck Depression Inventory (BDI), Beck Anxiety Inventory (BAI), Barratt Impulsiveness Scale (BIS-11), and Difficulties in Emotion Regulation Scale (DERS).

Current suicidal ideation was measured using the Korean version of the BSI.¹⁷ This self-administered questionnaire consists of 19 items evaluating suicidal ideation and preparatory behaviors during the week prior to its administration, and two additional items assessing previous suicidal behaviors. Each item is scored on a 0–2 scale, yielding a total possible score ranging from 0 to 38.¹⁸ Participants initially completed the first five items. If the fifth item received a score of 1 or 2, participants continued with the remaining items; otherwise, the assessment was discontinued.¹⁹

The Korean versions of the BDI and BAI were administered to assess depressive and anxiety symptoms, respectively.^{20,21} Both the BDI and BAI consist of 21 items; each item is rated on a 0–3 Likert scale. Total scores for each inventory range from 0 to 63, with higher scores indicating more severe symptoms in each domain.

The BIS-11 was used to measure impulsivity.²² This instrument consists of 30 items that assess impulsive personality and behavioral constructs across three second-order factors: attentional, motor, and non-planning subtypes. Each item is rated on a 1–4 Likert scale, producing a total score ranging from 30 to 120, with higher scores indicating greater impulsivity.

Additionally, the DERS was used to assess emotion regulation. This instrument consists of 36 self-report items; each item is rated on a 1–5 Likert scale. Total scores range from 36 to 180, with higher scores indicating greater difficulties in emotion regulation.²³

EEG acquisition

Prior to the recording, participants were instructed to abstain from substances known to affect the EEG, such as caffeine and nicotine. Resting-state EEG data were recorded for 5 min in a sound-attenuated room, and participants were instructed to keep their eyes open. This condition was chosen to minimize drowsiness and prevent the intrusion of sleep-related brain activity, which can significantly alter alpha rhythms and thus confound the analysis.²⁴ EEG signals were recorded using a NeuroScan SynAmps2 amplifier (Compumedics USA, Charlotte, NC, USA) with a Quik-Cap equipped with 62 Ag/AgCl electrodes arranged according to the extended 10–20 system. The Cz electrode served as the reference electrode, and the ground electrode was placed on the forehead. Horizontal electrooculogram (EOG) electrodes were placed at the outer canthi of both eyes, and vertical EOG electrodes were positioned above and below the left eye to monitor eye movements. Electrode impedances were kept below 5 k Ω throughout the recording. The EEG signals were band-pass filtered (0.1–100 Hz) and digitized at a sampling rate of 1000 Hz.

EEG preprocessing

EEG preprocessing consisted of several steps designed to ensure optimal data quality. Initially, EEG data were down-sampled to 128 Hz and then filtered using a finite impulse response (FIR) band-pass filter with a passband of 1–40 Hz. Following this, the signal was decomposed into eight levels using the discrete wavelet transform with a biorthogonal 4.4 basis to facilitate artifact removal. Subsequently, Bayesian estimation was applied to compute level-specific thresholds for artifact detection. Wavelet coefficients exceeding these thresholds were classified as artifacts, and the inverse wavelet transform was then applied to reconstruct the corresponding time-domain artifact signals. The reconstructed artifact signals were subtracted from the original EEG data.²⁵ Independent component analysis was performed to identify and remove residual artifacts, thereby further refining the EEG data. Finally, a common average reference was applied to all channels to standardize the reference and minimize potential bias.

For microstate analysis, a continuous 40 s segment of artifact-free EEG data with a maximum absolute voltage not exceeding 90 μ V was selected for each participant. This segment length was chosen based on previous research demonstrating its effectiveness for microstate analysis.^{26,27} For instance, one study found that 40 s epochs showed greater temporal stability, with a non-stationarity of 44%, compared with 60% for 20 s epochs and 80% for 10 s epochs.²⁸ Therefore, selecting a 40 s epoch optimized temporal stability by significantly reducing non-stationarity and provided a segment of sufficient length to robustly characterize the underlying EEG dynamics. To complement this analysis of temporal dynamics, a supplementary power spectral density analysis was conducted to characterize the overall spectral properties of the EEG in each group (see Supplementary Fig. S1 and supplementary material for methods and results). All preprocessing steps described in this section were executed using MATLAB R2021b (MathWorks, Natick, MA, USA).

Microstate analysis

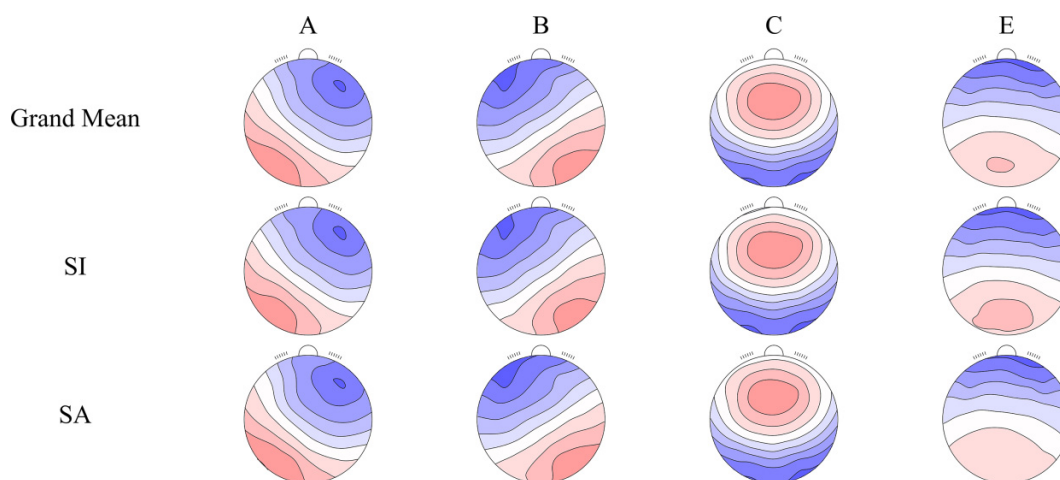
The analysis was performed using the MICROSTATELAB toolbox integrated with EEGLAB.²⁹ Initially, microstate maps were generated from the EEG data of each participant using the atomize-agglomerate hierarchical clustering algorithm.³⁰ This clustering was performed on the global field power (GFP) peaks of the EEG data, with polarity disregarded, as topographies with opposite polarities reflect the same underlying brain activity.

The GFP at each time point was computed using the following equation:³¹

$$\text{GFP}(t) = \sqrt{\frac{\sum_{i=1}^K (V_i(t) - V_{\text{mean}}(t))^2}{K}}$$

In the equation, K denotes the number of EEG electrodes, $V_i(t)$ is the potential at electrode i at time t , and $V_{\text{mean}}(t)$ represents the mean potential across all electrodes at time t . GFP peaks were defined as time points where the GFP value was greater than the values at the immediately preceding and fol-

Fig. 1. Comparison of topographic maps for four electroencephalography (EEG) microstate classes (A, B, C, and E) across different groups. The rows display the characteristic scalp potential distribution for the Grand Mean (average of all participants), the Suicidal Ideation (SI) group, and the Suicide Attempt (SA) group.



lowing time points (i.e., local maxima). Following GFP computation, the optimal number of microstate clusters was determined primarily to ensure comparability with findings in the broader literature.^{32,33} Therefore, the four-class solution was chosen, as it represents the most widely reported solution in resting-state EEG microstate research. The selected four-class solution explained an average of 51.83% of the global explained variance across all participants (standard deviation, $SD = 11.43\%$; SI group: 51.25%, $SD = 10.79\%$; SA group: 52.36%, $SD = 12.03\%$).

A hierarchical, multilevel clustering approach was used to compute the mean and Grand Mean maps. First, individual microstate maps were generated for each participant. These participant-level maps were then used as input for a second-level clustering to create group-mean maps for the SI and SA groups separately. Finally, these two group-mean maps were clustered together to produce the final Grand Mean map. This Grand Mean map was then sorted and labeled based on the highest spatial correlation with the normative seven-class template proposed by Custo et al.¹¹ The resulting four maps corresponded to microstates A, B, C, and E, and achieved high spatial correlations with the template maps of 72.43%, 74.13%, 95.04%, and 85.84%, respectively (Fig. 1). To ensure topographical consistency, individual microstate maps were visualized in a multidimensional scaling plot to identify any topographical outliers; however, no topographical outliers were identified in this dataset.³⁴

The sorted Grand Mean map was then back-fitted to the continuous EEG data, assigning the microstate class with the highest spatial correlation to each GFP peak. The time points between these peaks were then labeled using temporal interpolation, which assigned each non-peak time point the same label as the temporally nearest GFP peak. Subsequently, temporal parameters—including average duration, frequency of occurrence, and percentage of time coverage—were extracted for each microstate based on the assigned labels.

Microstate-based functional connectivity analysis

For each microstate class, FC was quantified using the phase lag index (PLI) across all channel pairs within three frequency bands: theta (4–8 Hz), alpha (8–12 Hz), and beta (12–30 Hz). EEG signals were band-pass filtered for these frequency ranges using an FIR filter. To precisely estimate the phase and amplitude of the time-domain signals, the Hilbert transform was applied using boundary extension techniques (detailed procedures are provided in the supplementary materials).

The analysis was conducted in sensor space. While source-space analysis would offer enhanced anatomical localization, it would introduce unique methodological challenges, such as addressing dipole flipping in source space, which typically requires discarding polarity (via absolute value or amplitude envelope transforms), thereby forfeiting polarity information.³⁵ The primary objective was to identify robust, comparable biomarkers rather than their precise anatomical origins. Therefore, the well-established sensor-space approach was employed to prevent the introduction of novel interpretative biases and to ensure consistency with the broader microstate literature.

Following the Hilbert transform, the analytic signal segments corresponding to each microstate class were concatenated to form a continuous time series. Although discontinuities occurred at microstate transitions, the phase and amplitude information was preserved because the Hilbert transform was applied to the continuous data prior to segmentation.³⁶ Subsequently, to standardize the data volume for analysis and ensure methodological consistency across participants and microstate classes, a random sampling approach was employed. For each participant and microstate class, 50 random starting points were selected from the concatenated time series, from which a continuous 2 s epoch was extracted.

Table 1. Demographic, clinical, and psychological characteristics of study participants.

Variable	Suicidal ideation (<i>n</i> = 62)	Suicide attempt (<i>n</i> = 68)	<i>p</i>
Sex (male/female)	25/37	27/41	0.942
Age (years)	40.48 ± 14.85	41.75 ± 14.74	0.627
Education (years)	11.87 ± 3.50	10.97 ± 3.21	0.130
Beck Scale for Suicide Ideation	20.12 ± 3.16	20.23 ± 3.55	0.857
Beck Depression Inventory	53.58 ± 9.29	51.86 ± 13.14	0.389
Beck Anxiety Inventory	31.22 ± 13.85	26.48 ± 14.34	0.057
Barratt Impulsiveness Scale	73.79 ± 11.27	71.95 ± 9.91	0.328
Attentional Impulsiveness	19.75 ± 3.77	18.76 ± 3.60	0.128
Motor Impulsiveness	24.87 ± 5.15	24.50 ± 4.45	0.663
Non-Planning Impulsiveness	29.16 ± 4.76	28.69 ± 4.26	0.555
Difficulties in Emotion Regulation Scale	111.04 ± 23.77	105.80 ± 23.32	0.207

For each epoch and channel pair, the PLI was calculated using the following formula:

$$PLI = |< \text{sign}[\sin(\Delta\phi(t))] >|$$

In this formula, $\Delta\phi(t)$ is the instantaneous phase difference between two channels at time t , $\text{sign}[\cdot]$ represents the signum function, and $\langle \cdot \rangle$ denotes averaging over time points. The resulting PLI values range from 0 (no phase coupling) to 1 (perfect phase locking). A key advantage of this measure is its relative insensitivity to volume conduction compared to other phase synchronization measures.³⁷ The PLI values from the 50 epochs were then averaged to yield a connectivity matrix for each microstate class and participant. This approach was chosen to mitigate potential bias from variable microstate durations and provide a consistent basis for comparison across the dataset.

Statistical analysis

Statistical analyses were conducted to compare demographic variables, psychological measures, and EEG microstate parameters between groups. Initially, demographic variables and psychological measures were compared using Welch's t tests because Levene's test indicated a violation of the homogeneity of variance assumption. Additionally, sex differences were evaluated using a χ^2 test. The normality assumption was satisfied for all variables, with absolute skewness not exceeding 2 and absolute kurtosis remaining below 7.³⁸

Welch's t tests were also applied to microstate-derived parameters, including average duration, frequency of occurrence, and time coverage. The resulting p values were subsequently adjusted using the false discovery rate (FDR) correction method to account for multiple comparisons.³⁹ Following this, microstate-based FC measures were examined. Because microstate-based FC measures constitute an inherently interconnected set in which each connection may influence the interpretation of others, a permutation-based T-max procedure was employed to account for such interdependencies and control the family-wise error rate.⁴⁰

For this procedure, data from both groups were pooled, and 5000 permutations were performed. In each iteration,

participants were randomly reassigned to two groups matching the original sample sizes. Subsequently, Welch's t tests were conducted on each microstate-based FC measure, and the maximum absolute t value (T-max) from each permutation was recorded to construct an empirical null distribution. This distribution established the critical threshold for statistical significance at $\alpha = 0.05$, thereby controlling the family-wise error rate. Any connectivity measure with an observed t value exceeding this threshold was deemed statistically significant.

To investigate associations between EEG features and psychological measures, Pearson's correlation analysis was performed. Specifically, EEG features that showed significant group differences (corrected $p < 0.05$) were correlated with scores from the BSI, BDI, BAI, BIS-11, and DERS. These analyses were conducted separately within each group (SA and SI). The p values from these correlations were then adjusted using the FDR method to correct for multiple comparisons. For all statistical tests, a significance threshold of $p < 0.05$ was adopted, and p values between 0.05 and 0.10 were regarded as marginally significant. All statistical procedures were performed using MATLAB R2021b.

Ethics approval

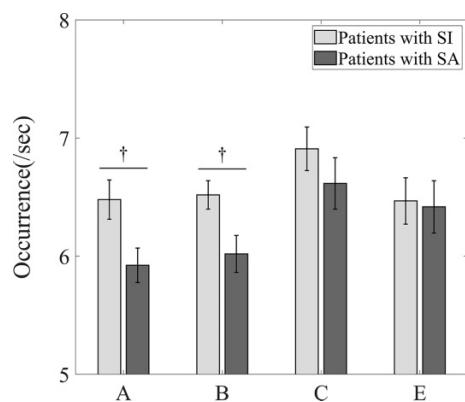
This study was approved by the Soonchunhyang University Cheonan Hospital Institutional Review Board (IRB No. 2017-06-035). All procedures conformed to the Declaration of Helsinki and applicable institutional and national research ethics regulations. Written informed consent was obtained from all participants after treating physicians verified decisional capacity. As specified in the IRB-approved protocol, participants were required to be medication-naïve at the time of assessment, and assessments for the SA group were conducted within 7 days after the attempt.

Results

Characteristics of suicidal ideation and suicide attempt groups

Table 1 presents the demographic and psychological characteristics of the study participants. No statistically signifi-

Fig. 2. Temporal characteristics of microstate classes in patients with suicidal ideation (SI) and suicide attempt (SA). This bar graph displays the frequency of occurrence (per second) for four microstate classes (A, B, C, and E) in patients with SI (light gray) and those with SA (dark gray). Error bars indicate standard errors. Marginally significant differences (false discovery rate (FDR)-corrected; $\dagger p = 0.078$) were observed for microstate classes A and B, with the SA group exhibiting a lower frequency than the SI group.



cant differences were detected between the SI and SA groups regarding demographic variables (sex, age, and education) or psychological measures (including suicidal ideation, depression, anxiety, impulsivity, and emotion regulation).

Microstate temporal characteristics

Marginally significant differences in the frequency of occurrence of microstate classes A and B ($p = 0.078$ for both classes, FDR-corrected) were identified between the SA and SI groups. The SA group exhibited a lower frequency of occurrence in both microstate classes compared to the SI group (Fig. 2). Additionally, no significant differences were observed in the average duration or the percentage of time coverage for any microstate class.

Microstate-based functional connectivity

The microstate-based PLI analysis revealed several significant group differences in alpha-band FC. Across all electrode pairs with statistically significant differences, the SA group consistently demonstrated higher PLI values than the SI group. In the alpha band during microstate E, the SA group showed significantly higher FC for the following electrode pairs: F5–F6 ($p = 0.043$), F7–C5 ($p = 0.009$), FC5–C5 ($p = 0.005$), F7–P3 ($p = 0.020$), and CP2–CB1 ($p = 0.041$) (Fig. 3). Additionally, marginally significant differences were observed. In the alpha band, the SA group showed marginally higher FC for the electrode pair AF3–F4 ($p = 0.055$) in microstate B and for the pair AF3–F5 ($p = 0.064$) in microstate C. In the theta band, the SA group showed marginally higher FC for the electrode pair Cz–TP7 in microstate E ($p = 0.078$). All reported p values for these connectivity analyses were corrected for multiple comparisons using the T-max procedure. Detailed results and PLI matrices for all significant and marginally significant

findings are provided in the supplementary materials (Supplementary Figs. S2–S8).

Correlations between EEG features and psychological measures

To investigate the clinical relevance of EEG features that showed significant group differences (corrected $p < 0.05$), correlation analyses were performed. Specifically, the FC values in the alpha band during microstate E were examined against all collected psychological measures (BSI, BDI, BAI, BIS-11, and DERS) for the SI and SA groups separately. Following an FDR correction for multiple comparisons, a single significant positive correlation emerged: in the SI group, alpha-band PLI values for the CP2–CB1 electrode pair during microstate E were positively correlated with DERS scores ($r = 0.433$, $p = 0.017$, FDR-corrected) (Fig. 4).

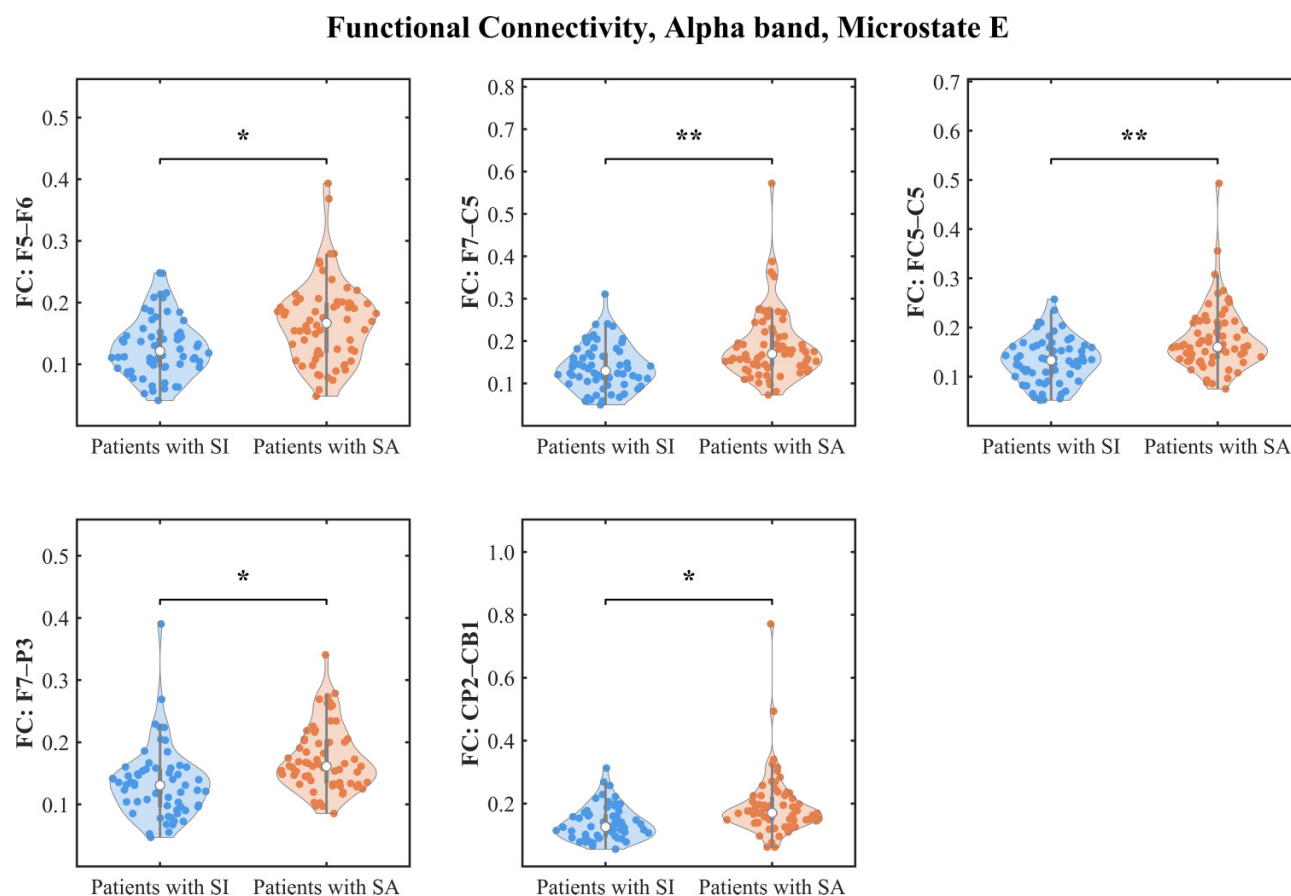
Discussion

This study investigated neurophysiological differences that distinguish SA from SI in patients with MDD using EEG microstate and FC analyses. The SA group exhibited a marginally lower frequency of occurrence for microstates A and B compared to the SI group. Furthermore, microstate-based FC analysis demonstrated significantly higher alpha-band connectivity during microstate E in the SA group, with marginally significant increases also observed in the alpha band during microstates B and C, and in the theta band during microstate E. In the SI group, a significant positive correlation was identified between alpha-band FC during microstate E and scores on the DERS.

The SA group exhibited significantly higher alpha-band FC during microstate E. Microstate E is associated with activation of key nodes within the DMN, including the anterior cingulate cortex (ACC), posterior cingulate cortex (PCC), and precuneus.¹¹ This result aligns with previous fMRI studies implicating DMN dysfunction in suicidal behavior. Recent research has indicated that patients with SA show greater activity in the precuneus of the posterior DMN and the medial prefrontal region of the dorsomedial DMN compared to controls, with neural activity in the posterior DMN also correlating positively with recent suicidal activity.⁴¹ Such increased DMN activity and connectivity may reflect heightened self-referential processing and rumination, both of which are associated with suicidal behavior.⁴² This interpretation is further supported by a meta-analysis of fMRI studies, which demonstrated that rumination is robustly associated with increased activation in core regions of the DMN, including the PCC. This research also identified co-activation of the subgenual prefrontal cortex.⁴³ Consequently, alpha-band connectivity during microstate E may serve as a key neurophysiological indicator differentiating SA from SI.

The functional characteristics of alpha oscillations help explain the pronounced differences observed in this frequency band. Alpha rhythms play a crucial role in internal attention and inhibitory processes and are closely linked to emotion regulation and rumination.⁴⁴ The increased alpha-band connectivity during microstate E in the SA group could reflect a

Fig. 3. Functional connectivity (FC) in the alpha band for microstate E. This violin plot illustrates the differences in FC in the alpha band for microstate E between patients with suicidal ideation (SI) and patients with suicide attempt (SA). Data are presented for five electrode pairs: F5–F6, F7–C5, FC5–C5, F7–P3, and CP2–CB1. In each plot, the distribution of connectivity values is shown, with patients with SI represented in blue and patients with SA in orange. Each dot represents the FC value for an individual patient. The gray bar within each violin plot indicates the interquartile range, and the white dot denotes the median value. Statistical significance is indicated by asterisks above each plot, reflecting T-max-corrected p values (* $p < 0.05$, ** $p < 0.01$).



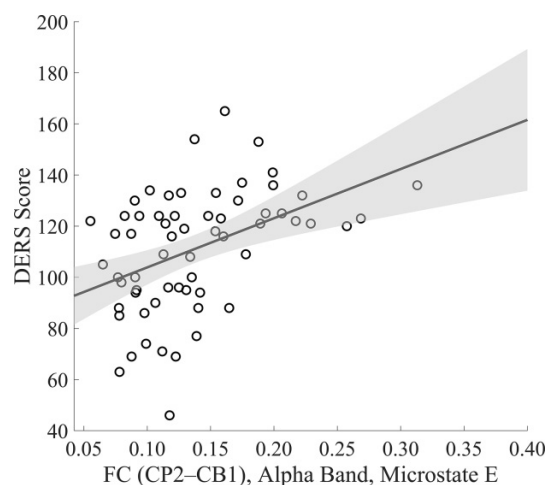
bias in these regulatory and attentional functions, characterized by a narrowed attentional scope that impairs cognitive flexibility and potentially leads to a fixation on negative information or thoughts.^{45,46} Previous research has shown that patients with SA exhibit significantly higher levels of rumination than those without SA.⁴⁷ Given that the DMN is involved in self-referential processing and rumination,⁴⁸ the observed alpha-band differences provide a physiologically plausible basis for the distinct patterns of rumination, attentional control, and negative information processing that appear to differentiate between the SA and SI groups.

A notable divergence exists between the neurophysiological data and the self-reported psychological measures. While the SA and SI groups did not differ significantly in the severity of depression (BDI) or anxiety (BAI), distinct differences were observed in EEG microstate and FC patterns. This suggests that the identified EEG markers may represent a neurobiological predisposition toward suicidal acts rather than merely reflecting the current state of depressive symptom severity. These markers could, therefore, represent the underlying neural mechanisms that facilitate the transition

from ideation to attempt—a distinction not always captured by standard clinical scales. This distinction underscores the incremental value of EEG-derived markers beyond conventional rating scales. This interpretation is further substantiated by the specificity of the correlation results. In the SI group, the only correlation that remained significant was between alpha-band FC during microstate E (for the electrode pair CP2–CB1) and DERS scores. The DMN is central to self-referential processing and rumination,⁴⁸ and the DERS measures difficulties in emotion regulation. This construct is strongly linked to the ruminative, self-focused thought patterns that can be difficult to disengage from.⁴⁹ In contrast, broad measures like the BDI and BAI encompass a wider spectrum of symptoms, such as sleep and appetite disturbances, which may be less directly related to the core functions of the DMN.⁵⁰ Therefore, altered DMN FC appears more mechanistically linked to emotion dysregulation than to overall depression severity.

Meanwhile, the absence of a DMN–DERS correlation in the SA group, despite stronger DMN connectivity, complicates the interpretation. The psychological state following a sui-

Fig. 4. Correlation between functional connectivity (FC) and Difficulties in Emotion Regulation Scale (DERS) scores in patients with suicidal ideation (SI). This scatter plot illustrates the relationship between FC and DERS scores in patients with SI. The x-axis displays the FC values for the electrode pair CP2–CB1 in the alpha band during microstate E, while the y-axis represents the DERS scores. Each point corresponds to an individual patient. The gray line shows the linear regression fit, with the shaded area indicating the 95% confidence interval. A significant positive correlation was observed (Pearson's $r = 0.433$, false discovery rate (FDR)-corrected $p = 0.017$).



cide attempt can be highly heterogeneous; some patients may experience relief, while others continue to have high levels of suicidal ideation. In this context, the lack of correlation in the SA group suggests an alternative interpretation: the heightened DMN coupling could reflect a post-attempt compensatory or state-dependent response rather than a stable, trait-level vulnerability. This possibility is strengthened by the potential for residual physiological effects post-attempt, as acknowledged in the **Limitations** section. The observed between-group difference should thus be cautiously interpreted as a neurophysiological indicator proximal to a crisis, specifically indicating acute neural patterns associated with recent suicidal events. Disentangling vulnerability from compensation will require prospective studies that track individuals from ideation through post-attempt recovery.

Temporal microstate metrics indicated a marginally lower frequency of occurrence of microstates A and B in the SA group compared to the SI group. Both microstates are associated with activation of the insula; microstate A is linked to the auditory/language network, and microstate B is linked to the VN. Specifically, microstate A corresponds to activity in the left temporal lobe and the left insula, regions involved in auditory and language processing, whereas microstate B is associated with activation in the occipital cortex, right insula, right frontal eye field, and other regions involved in visual processing.¹¹ These findings are consistent with neuroimaging studies that have reported reduced insular activity. For instance, reduced insular activity has been observed during decision-making tasks, such as the Iowa Gambling Task, in-

dicating impaired risk-reward evaluation. Reduced activity has also been noted during social exclusion tasks in individuals with a recent suicide attempt, suggesting distorted social perception.⁵¹ Additionally, decreased connectivity between the ventral anterior insula and the superior frontal gyrus has been observed, and this decrease was negatively correlated with psychological pain avoidance.⁵² Given the insula's critical role in interoceptive processing and emotion regulation,⁵³ the reduced occurrence of insula-linked microstates may indicate attenuated insular recruitment and altered coupling with frontal control regions, which could potentially impair interoceptive awareness and lead to emotional dysregulation. This finding suggests a complementary neurophysiological pathway that may operate alongside DMN-centered mechanisms.

The marginally significant differences observed in other microstates also have important implications. The increased connectivity during microstate C could suggest that DMN-related dysfunction manifests across multiple transient brain states; this interpretation is consistent with the topographical labeling adopted in this study.¹¹ However, the functional interpretation of microstates remains a topic of active debate. For instance, some research associates microstate C with salience or cognitive control networks that regulate attention allocation and error monitoring.^{54,55} From this perspective, the finding might reflect dysregulated attentional processes or impaired cognitive control in the SA group, which implies a potential disruption in large-scale network dynamics. Other observed alterations provide further insight. Increased alpha-band connectivity during microstate B, for example, implicates functional alterations in visual-attentional circuitry, consistent with fMRI findings linking VN-dorsal attention network coupling with affective somatization in depression.⁵⁶ This heightened connectivity may reflect an excessive focus on or biased processing of negative visual information, which could contribute to emotional distress in patients with SA. Similarly, in the theta band, the SA group exhibited marginally higher connectivity during microstate E. This finding aligns with magnetoencephalography studies reporting that theta-band connectivity and interactions among major brain networks, including the DMN, central executive network, and salience network, are associated with the severity of suicidal thoughts and attempts.^{57,58} Such patterns suggest that large-scale network dysregulation, potentially linked to maladaptive self-referential processes and ruminative thinking, is associated with the progression from ideation to attempt. In this context, the theta-band elevation may further indicate enhanced interaction between midline and temporoparietal regions, potentially representing a biomarker of DMN dysregulation that exacerbates suicidal risk.

In conclusion, EEG microstate dynamics and state-specific FC show promise as objective markers for differentiating between patients with SA and those with SI. Specifically, enhanced alpha-band connectivity during microstate E appears to be a core neurophysiological indicator reflecting DMN dysfunction, while the reduced occurrence of microstates A and B suggests a complementary mechanism involving insula-based emotional and interoceptive regulation. These EEG-

based measures could complement existing clinical suicide risk assessments and inform the development of early intervention strategies.

Limitations

Several limitations should be considered when interpreting the findings. First, although participants in the SA group were enrolled only after being deemed medically stable and free of confounding variables, the potential for residual physiological effects from their recent medical crisis cannot be entirely excluded. Distinguishing the neurobiological markers of a suicidal predisposition from the subtle aftereffects of the attempt itself remains a challenge. Additionally, the FC analysis was performed in sensor space. Although this approach was selected to avoid certain methodological issues and maintain consistency with the broader microstate literature, it limits the spatial precision in identifying the anatomical origins of EEG signals. Therefore, linking scalp-level activity to specific underlying neural networks requires cautious interpretation. Finally, the findings are situated within the conceptual framework of the microstate model. This model simplifies continuous neural dynamics into discrete states. A key aspect of this simplification is the selection of the number of classes, which was set to four for comparability with established resting-state EEG microstate research, a methodological choice that can influence the final results.

Conclusion

This study provides new insights into clinical neurophysiology and suicide research, representing the first application of microstate and microstate-based FC analysis to resting-state EEG data for differentiating SI from SA. The analysis revealed that increased alpha-band connectivity during microstate E—a state associated with the DMN—in patients with SA suggests potential neural mechanisms underlying the progression from SI to SA. These findings advance the understanding of the complex neurobiology of suicide and hold promise for developing more objective biomarkers for suicide risk assessment.

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Data availability

The datasets generated and analyzed during the current study are not publicly available due to privacy and consent restrictions concerning the research participants. De-identified versions of these datasets may be made available to qualified researchers for scientific inquiries upon reasonable request to the corresponding authors: Se-Hoon Shim, MD, PhD (shshim2k@daum.net) or Ji Sun Kim, MD, PhD (ideal91@hanmail.net). In accordance with recommendations to promote data comparability in the field, the grand mean microstate maps from this study will be uploaded to the “meta-microstates” database (<https://doi.org/10.1007/s10548-023-00993-6>) upon publication of the manuscript.

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Competing interests

None declared.

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Supplementary material

Supplementary data are available with the article at <https://doi.org/10.1139/jpn-2025-0078>.

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