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Decreased beta 1 (12–15 Hertz) power modulates the transfer of suicidal ideation to suicide in major depressive disorder

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Original Article

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Abstract

Background: Suicide prevention for major depressive disorder (MDD) is a worldwide challenge, especially for suicide attempt (SA). Viewing suicide as a state rather than a lifetime event provided new perspectives on suicide research. *Objective:* This study aimed to verify and complement SAs biomarkers of MDD with a recent SA sample. *Methods:* This study included 189 participants (60 healthy controls; 47 MDD patients with non-suicide (MDD-NSs), 40 MDD patients with suicide ideation (MDD-SIs) and 42 MDD patients with SA (MDD-SAs)). MDD patients with an acute SA time was determined to be within 1 week since the last SA. SUICIDALITY Part in MINI was applied to evaluate suicidality. Absolute powers in 14 frequency bands were extracted from subject's resting-state electroencephalography data and compared within four groups. The relationship among suicidality, the number of SA and powers in significant frequency bands were investigated. *Results:* MDD-SIs had increased powers in delta, theta, alpha and beta band on the right frontocentral channels compared to MDD-NSs, while MDD-SAs had decreased powers in delta, beta and gamma bands on widely the right frontocentral and parietooccipital channels compared to MDD-SIs. Beta 1 power was the lowest in MDD-SAs and was modulated by the number of SA. The correlation between suicidality and beta 1 power was negative in MDD-SAs and positive in MDD-SIs. *Conclusion:* Reduced beta 1 (12–15 Hz) power could be essential in promoting suicidal behaviour in MDD. Research on recent SA samples contributes to a better understanding of suicide mechanisms and preventing suicidal behaviour in MDD.

Summations

- Reduced beta 1 (12–15 Hertz) power could be essential in promoting suicidal behaviour in MDD.
- Research on recent suicide attempt samples contributes to a better understanding of suicide mechanisms and preventing suicidal behaviour in MDD.

Considerations

- This study could only explain high-impulsive SA in MDD, but not suit to explain well-planned SA in other psychiatric disorders.
- Although considerable neuroimaging data were collected, further follow-up data still lacked to test the results in this study.
- The study only demonstrated that SAs were associated with the reduced beta 1 power but could not explore the causal relationship between beta 1 power and SA.

Introduction

Major depressive disorder (MDD) is a highly prevalent mood disorder worldwide and has been rising rapidly alongside the fluctuations of social economy in recent years (Smith, 2014; Mazza *et al.*, 2020; Farooq *et al.*, 2021; Sher, 2021). Suicide is the most serious of all MDD outcomes, contributing to the deaths of more than one million patients each year (Chesney *et al.*, 2014). Suicide attempt (SA) was one of the strongest predictors of suicide (Hill *et al.*, 2020). Approximately 31 per cent of MDD patients have made at least one SA with the intention of death during their lifetime, and the toll each SA takes is devastating and disastrous (Dong *et al.*, 2019;

Marlow *et al*., 2021). Therefore, the search for reliable and effective biomarkers of SA in MDD is pressing and essential.

Non-invasive neuroimaging techniques have provided abundant empirical attempts on neuropathological mechanisms underlying suicide. A narrative review incorporating 131 neuroimaging studies from the last 20 years suggested that the impaired dorsal prefrontal cortex system was connected to the dysfunctional inferiorfrontal gyrus system via the dorsal anterior cingulate cortex and insula, facilitating the switch from suicide thoughts to behaviours (Schmaal *et al*., 2020). These functional brain connectivities were involved in reduced cognitive inhibition (Zhang *et al*., 2017; Lukito *et al*., 2020), inflexible decision-making and planning (Levy & Glimcher, 2012; Olié *et al*., 2015), and emotion dysregulation (Urry *et al*., 2006), which were widely reported in psychiatric disorders (Giakoumatos *et al*., 2013; Chesney *et al*., 2014; Norman *et al*., 2016; Johnston *et al*., 2017; Yu *et al*., 2021). Suicide, however, including suicide ideation (SI), SA and complete suicide (SC) (Klonsky *et al*., 2016), is a complex, paroxysmal and multiple-ending event (Volow *et al*., 1979; Struve, 1986; Deisenhammer *et al*., 2009; Kleiman *et al*., 2017). Furthermore, suicide in different psychiatric disorders involves different cognitive function impairments. For example, suicide in MDD was considered a highly impulsive event that was more unplanned, transient and dramatically fluctuating compared to other mental illnesses. Many studies investigated the relationship between the highly impulsive events and suicide in MDD. For example, a previous study confirmed that SAs may differ between subjects with MD, alcoholism or both disorders in terms of impulsiveness and suicide intent (Suominen *et al*., 1997). Another study probed the relationships between impulsiveness and irritability in young MDD patients with and without persistent depressive disorder, and it concluded that inattention and irritable mood both made independent significant contributions to impulsiveness (Vance & Winther, 2021). A recent study explored the effects of MDD and impulsivity on lifetime SAs among suicide survivors, and results indicated that surviving suicide by family members is an important risk factor for SAs. In particular, MDD with insomnia and impulsivity are associated with SAs among suicide survivors (Jang *et al*., 2020). While suicide in obsessive-compulsive disorder and some chronic diseases tend to be determined and well planned (Vanyukov *et al*., 2015; Dombrovski & Hallquist, 2017). Therefore, suicide in different mental illnesses needs to be discussed separately.

A critical view is that SA resulted from the transient dynamic transition in the functional brain states, which was mediated by abnormal neuronal activity (Cáceda *et al*., 2014). Neural oscillations were generated from synchronous firing patterns of brain neurons and viewed as causal drivers of consciousness (Young *et al*., 2021), which could reflect the rapidly changing functional brain states. Previous studies suggested that MDD-SAs have elevated frequency power in delta, theta and gamma bands on right frontoparietal sites and decreased power in beta band on occipital sites (Lee *et al*., 2017b; Benschop *et al*., 2019; Rakús *et al*., 2021). These frequencies were associated with heightened arousal (Liu & Dan, 2019), increased impulsivity (Lee *et al*., 2017b), blunt psychological pain perception (Meerwijk *et al*., 2015; Meerwijk & Weiss, 2018) and rumination (Dell'Acqua et al., 2021), which were also essential predictors of suicide risk (Rogers *et al*., 2021). Among them, a large clinical trial with 533 subjects reported that elevated absolute power in high gamma band (40–50 Hz (Hz)) might be a SA biomarker in depression (Arikan *et al*., 2019). In this research, the power in delta, theta and beta bands did not differ. Soon after, however, another study showed the female MDD-SAs had hypoactivity in beta and gamma bands (Benschop *et al*., 2019). Additionally, a study including 402 female MDD subjects attempted to replicate the results in previous experiments but frustratingly found no difference (Krepel *et al*., 2021).

The primary factor contributing to the inconsistent previous experimental results is the rapidly changing suicide risk (Ballard *et al*., 2021). The progression from suicide thoughts to action could take as little as a few minutes (Deisenhammer *et al*., 2009), which made it challenging to identify the level of suicide risk in different experimental subjects. Cáceda and colleagues did many valuable studies to find significant transient abnormalities in cognition and inflammation after a SA and would recover within a week (Cáceda *et al*., 2014; Gibbs *et al*., 2016; Cáceda *et al*., 2017; Cáceda *et al*., 2018). It indicated that classifying SA as a stable lifetime trait would overlook some transient, highly suicide-relevant neurophysiological indicators that were even more important for the rapid interruption of a suicide crisis. Neural frequency oscillations underlie the neural activity of the changes in functional brain states and could give a more objective process to identify individuals at imminent risk. However, until now, only a few works studied acute suicide samples, and none of them studied neuron oscillations.

Therefore, in the current experiment, we investigated the neural frequency oscillations power of resting-state electroencephalography (EEG) data in MDD patients with an acute SA (within 1 week since the last SA) to verify and further enrich the biomarkers of SA. We hypothesised that, as reported in previous studies, MDD-SAs had enhanced delta, theta and gamma frequency power on right frontal sites and decreased beta frequency power on occipital sites. Additionally, we could detect some paradoxical frequency-specific powers that have never been reported before, as these powers could only be detected within 1 week after SA. Ultimately, we speculated that the frequency-specific power is relevant to the generation of SA in MDD patients and could predict suicide behaviour.

Materials and methods

Participants

Two hundred and one Han Chinese subjects initially participated in this study, including 141 MDD patients (47 MDD patients with non-suicide (MDD-NSs); 40 MDD patients with suicide ideation (MDD-SIs); 42 MDD patients with SA (MDD-SAs)) and 60 healthy controls (HCs). All participants were right-handed. Patients were recruited from the Department of Psychiatry, The Affiliated Mental Health Center of Jiangnan University, China, between June 2018 and June 2020. The HCs matched for age, gender and education were enrolled from the local advertisements.

MDD-SAs were those who had at least two failed suicide behaviour with the intent to die during their lifetime, and one of these attempts was documented within a week (Cáceda *et al*., 2018). MDD-SIs were those with no history of suicide but current SI. The time since the last suicide averaged 2.43 days in MDD-SAs. Thus, of the initial 201 subjects, 12 subjects, including 8 MDD-SIs (had at last one documented self-injurious behaviour with the intent to die in their lifetime) and 4 MDD-SAs (over a week since the previous SA), were excluded from the study. Then, MDD group was divided into the non-suicide group (NS group, $n = 47$), the SI group (SI group, $n = 40$), and the SA group (SA group, $n = 42$). Cohen's f was used to determine the minimum sample size. With large effect size (Cohens' $f = 0.7$), the minimum total sample size was 148 subjects, which suggested that the sample size of 189

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subjects is adequate for our study. The estimates were conducted by G*Power software, version 3.1.9.7 (https://download.freedownloadmanager. org/Mac-OS/G-Power/FREE.html).

In this study, MDD patients were in a depressive episode and diagnosed according to the Diagnostic and Statistical Manual of Mental Disorders, 4th edition (DSM-IV). The inclusion criteria for MDD were as follows: (1) age range from 18 years to 65 years, and 17-item Hamilton Depression Scale (HAMD-17) scores ≥20 (Hamilton, 1960); (2) no comorbidity with other DSM-IV disorders; (3) no severe medical illness; (4) no repetitive transcranial stimulation or electroconvulsive over the past 6 months; (5) no use of antidepressants, mood stabilisers and antipsychotics in the past 2 weeks; and (6) no alcohol, tobacco or drug abuse history. The inclusion criteria for HCs were as follows: (1) no lifetime DSM-IV axis-I psychiatric disorders; (2) no family history of any mental disorders in the first-degree relatives evaluated by family history screen; (3) severe medical illness; (4) no history of neurological disorders; (5) no brain injury, alcohol, tobacco or drug abuse history, and (6) pregnancy.

Clinical assessment

In this study, subjects were interviewed with the Chinese version of the MINI International Neuropsychiatric Interview evaluated by two experienced psychiatrists before the experiment. HAMD-17 was applied to evaluate the severity of the disorder. A previous study reported that the interrater and test–retest reliabilities of the Chinese version of the Mini International Neuropsychiatric Interview were 0.9429 and 0.971–1.0, respectively (Si *et al.*, 2009). Based on the large study of psychiatric outpatients with MDD, HAMD-17 is reliable in evaluating the severity of MDD (Zimmerman *et al.*, 2013). Hamilton Anxiety Scale (HAMA) was applied to evaluate the severity of the anxious emotion (Hamilton, 1959). Suicide behaviour was determined based on answers to Part C (SUICIDALITY) in MINI, including 'Attempt suicide within the past month' and 'Attempt suicide in the lifetime'. Only subjects within 7 days of their last suicide were included in the research. SI was evaluated by the total scores of the items C1–C7 in MINI Part C, which could assess SI within the past month. MDD-SAs reported their SI after the last suicide.

EEG single recording and analysis

All EEG data sets were recorded by a 68-channel EEG set-up with EEG caps matched to the individual head size. Electrodes were placed on the scalp based on the International 10/20 electrode system. Subjects sat calmly with eyes closed in a quiet, dimly lit room during the 5-min recording time. The initial sampling rate was 1000 Hz, and the data were re-referenced to FCz electrode.

The acquired signals were band-pass filter at 1–100 Hz and notch filter at 50 Hz. Then, data artefacts were manually eliminated for each participant. Independent component analysis (ICA) was conducted on each subject's data to further remove eye movements, blinks and the cardiac field artefact. The removed ICA components were no more than 4. Clean, continuous EEG signals were segmented into 2 s epochs. The absolute power was computed by averaging across epochs for the following bands: delta (1–4 Hz), theta (4–7 Hz), alpha 1 (8–10 Hz), alpha 2 (10–12 Hz), beta 1 (12–15 Hz), beta 2 (15–18 Hz), beta 3 (18–25 Hz), high beta (25–30 Hz), gamma (30–50 Hz), gamma 1 (30–35 Hz), gamma 2 (35–40 Hz), gamma 3 (40–48 Hz), gamma 4 (52–70 Hz) and gamma 5 (70–100 Hz) as previous studies (Arikan *et al.*, 2019). EEGLAB (EEGLAB 9.0.3, University of San Diego, San Diego, CA) performed all EEG data analysis.

Finally, the power was averaged across significant channels in significant band to locate the brain region, such as the average beta power of F2, F4 and F6 represented beta power on right frontal sites. The averaged powers were applied to study the relationship between brain spectral power and clinical assessments.

Statistical analysis

The demographic data among the four groups (HC, NS, SI and SA group) were compared by chi-square *t*-test (gender) and one-way analysis of variance (ANOVA) (age, BMI and education). Disease duration, HAMD-17 and the suicidality scores of MINI were compared with one-way ANOVA within MDD groups (NS, SI and SA group). Differences were considered significant at $p < 0.05$.

The electrophysiological data were compared by one-way ANOVA in all channels among four groups (HC, NS, SI and SA group) under 14 frequency bands. Then *post hoc* analysis was conducted among the significant EEG channels under significant frequency bands by the Bonferroni test. *P* value was corrected by false discovery rate (FDR). In addition, this study was conducted on acute suicidal states, so time since the last SA was an important control variable. Suicide was also found to be associated with gender, age, disease duration and education (Knipe *et al.*, 2022; Turecki & Brent, 2016), which also need to be controlled for. Therefore, a partial correlation was conducted among the number of SA, SI and the average power after controlling for gender, age, disease duration, education and time since the last SA. All statistical analyses were performed with the SPSS version 17.0 (SPSS Inc., Chicago, IL, USA).

Results

Demographic and clinical assessments

Table 1 summarised the demographic and clinical assessments of all participants. Demographic variables were all statistically matched among the four groups (HC, NS, SI and SA group). There was no significant difference in the total scores of HAMD-17 and HAMA in three groups (NS, SI and SA group) (HAMD-17: $F_{(2,\ 126)} = 2.340$, $p > 0.05$; HAMA: $F_{(2,\ 126)} = 2.211$, $p > 0.05$). C-scores in SA group was higher than that in SI group ($t = 4.372$, $p = 0.000$). Although SI scores ($t = -1.704$, $p = 0.093$) was no difference in SA group versus SI group, the SI scores were higher in SI group than SA group. In the SA group, the resting-state EEG was performed on average 2.43 (standard deviation (SD) 0.56) days since the last SA, and the SA history averaged 2.45 (SD 0.68) days. Table 2 showed the suicide methods in SA group. Seven overdosed subjects underwent an EEG examination on average 4.57 (SD 1.2) days after the last SA.

Comparisons of absolute powers among four groups (HC, NS, SI and SA group)

Quantitative EEG (qEEG) analysis, as shown in *Supplement 1*, demonstrated four groups (HC, NS, SI and SA group) had significant differences in delta (AF4, F4, F6, F8, FC2, FC4, FC6, C2, C4, C6, T8, CP4, CP6), theta (F6, FC2, FC4, FC6, C2, C4, C6, T8, CP6), alpha 2 (C2, C4, C6, T8, CP6, TP8, PO8), beta 1 (FC2, FC4, C2, C4, C6, T8, CP2, CP4, CP6, TP8, P7, P1, P2, P4, P6, P8, PO7, PO3, PO4, PO8, O1, O2), beta 2 (FPZ, FP2, AF3, AF4, F1, FZ, F2,

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Table 1. Demographic features of all participants

Demographic	NS	SI	SA	HC	Statistical	*P* value
Numbers	47	40	42	60	–	–
Gender (female/male)	31/16	18/22	31/16	33/27	$^{2} = 7.269$	0.064
Age (years)	25.62(8.13)	26.23(8.93)	22.36(5.78)	25.33(4.84)	$F_{(3,185)} = 2.610$	0.053
Education (years)	14.45(1.95)	14.73(1.96)	13.88(2.19)	14.82(1.95)	$F_{(3,185)} = 1.668$	0.175
Disease duration (months)	45.85(66.25)	58.88(72.80)	45.05(43.77)	–	$F_{(2,126)} = 0.643$	0.527
Family history of mental disorder (Y/N)	20/27	19/21	20/22	0/60	–	–
Family history of suicide (Y/N)	2/45	2/38	9/33	0/60	–	–
HAMD scores	30.60(3.42)	31.60(3.85)	32.33(4.03)	–	$F_{(2,126)} = 2.340$	0.101
HAMA scores	7.17(3.22)	8.23(3.14)	8.45(2.86)	–	$F_{(2,126)} = 2.211$	0.114
C-scores	–	15.45(12.50)	25.52(7.67)	–	$t = 4.372$	0.000
Suicide ideation	–	15.45(12.50)	11.52(7.67)	–	$t = -1.704$	0.093
Numbers of suicide attempts	–	–	3.26(1.08)	–	–	–
Time since suicide attempt	–	–	2.43(1.31)	–	–	–

NS: major depressive disorder patients with non-suicide; SI: major depressive disorder patients with suicide ideation; SA: major depressive disorder patients with suicide attempt; HC: healthy controls; HAMD: 17-item Hamilton Depression Scale; HAMA: Hamilton Anxiety Scale; Y: yes; N: no.

Table 2. Suicide methods in suicide attempt group

Suicide method	*N*
Hanging	3
Slitting a wrist	13
Jumping off buildings	16
Overdose on medicine	7
Crash	1
Bang head against the wall	2

F4, F6, FC2, C2, C4), beta 3 (FPZ, FP2, AF3, AF4, F3, F1, FZ, F2, F4, F6, C2), beta 4 (FP1, FPZ, FP2, AF3, AF4, F7, F5, F3, F1, F2, F4, F6, F8, FC5, FC3, FC1, FC2, FC4, FC6, C5, CZ, C2, C4, C6, CP2, CP4, CP6, TP8), gamma 1 (FPZ, FP2, AF3, AF4, F7, F5, F3, F1, F2, F4, F6, F8, FC5, FC3, FC1, FC2, FC4, FC6, C5, C3, CZ, C2, C4, C6, TP7, CP5, CP3, CP1, CP2), gamma 2 (AF3, AF4, F3, F1, FZ, F2, F4, F6), gamma 3 (AF4, F3, F1, FZ, F2, F4, F6), gamma 4 (AF4, F1, FZ, F2, F4) and gamma 5 (AF3, AF4, F3, F1, F2, F4, CP5, CP3, CP1).

Post hoc comparisons, as shown in *Supplement*, revealed increased powers in delta, theta, alpha 2 and beta 2 on the right frontal-central sites of SI group compared to NS group. While decreased powers in delta, beta 1, beta 2, beta 4, and gamma 1 on the right frontal-central sites and parietal-occipital sites of SA group compared to SI group. There was no difference between SA group and NS group. Compared to HC group, SA group had a decreased absolute power in beta 1 (12–15 Hz) on the right central sites and the parietal-occipital sites; NS group had an increased absolute power in beta (beta 2, beta 3 and beta 4) on left frontal-central sites and gamma (gamma 1–gamma 5) on frontal sites; and SI group had an increased absolute power in beta and gamma on widely frontal-central sites. HC group had higher absolute power in alpha 2 than NS group. The above results demonstrated that frequency powers appeared to be 'increased' from NS group to SI group and then 'recover' after a SA (Fig. 1).

The correlation analysis between beta 1 power, suicidality and the number of SA

As shown in Fig. 2, the reduced beta 1 power was negatively related to the number of SA ($r = -0.332$, $p = 0.045$) and suicidality ($r = -0.330$, $p = 0.046$) after controlling for age, gender, education, disease duration and time since SA; however, we did not find the relationship between suicidality and the number of SA ($r = 0.287$, $p = 0.085$). Furthermore, the increased beta 1 power was positively related to suicidality ($r = 0.339$, $p = 0.043$) in SI group. It indicated that the decreased beta 1 power was a SA biomarker modulated by the number of SA, which was different from that in SI.

Discussion

The current study examined neuronal oscillatory activity following a recent SA with resting-state EEG data to validate and refine the biomarker of SA in MDD. Here, we successfully replicated partial results in previous studies that MDD-SAs had lower power in the beta and gamma band than MDD-SIs in the right hemisphere, and MDD-SIs had the highest power in the theta band (Lee *et al.*, 2017; Benschop *et al.*, 2019; Iznak *et al.*, 2021a; Thompson & Ong, 2018). Moreover, we observed that powers in delta, theta and beta band were elevated from MDD-NSs to MDD-SIs and decreased significantly after acute SA. Eventually, decreased beta 1 power modulated by the number of SA was negatively correlated with suicidality in MDD-SAs.

In recent years, a great controversy has developed regarding neurophysiological biomarkers of SA with resting-state EEG, especially in beta frequency. Beta frequency was a highly state-dependent endogenous oscillation and could be classified as low- (12–15 Hz, beta 1) and high-beta (15–30 Hz, beta 2 – beta 4) (Engel & Fries, 2010; Kober *et al.*, 2015). Low-beta was usually detected in the waking state during motion suppression over the motor cortex and corresponded to cognitive control (Jenkinson & Brown, 2011; Wagner *et al.*, 2016), while high-beta was involved in activating the reward network related to high arousal, agitation, anxiety and depression (Andreou *et al.*, 2017; Chen & Lin, 2020). Benschop and his colleagues found the lower beta power in female

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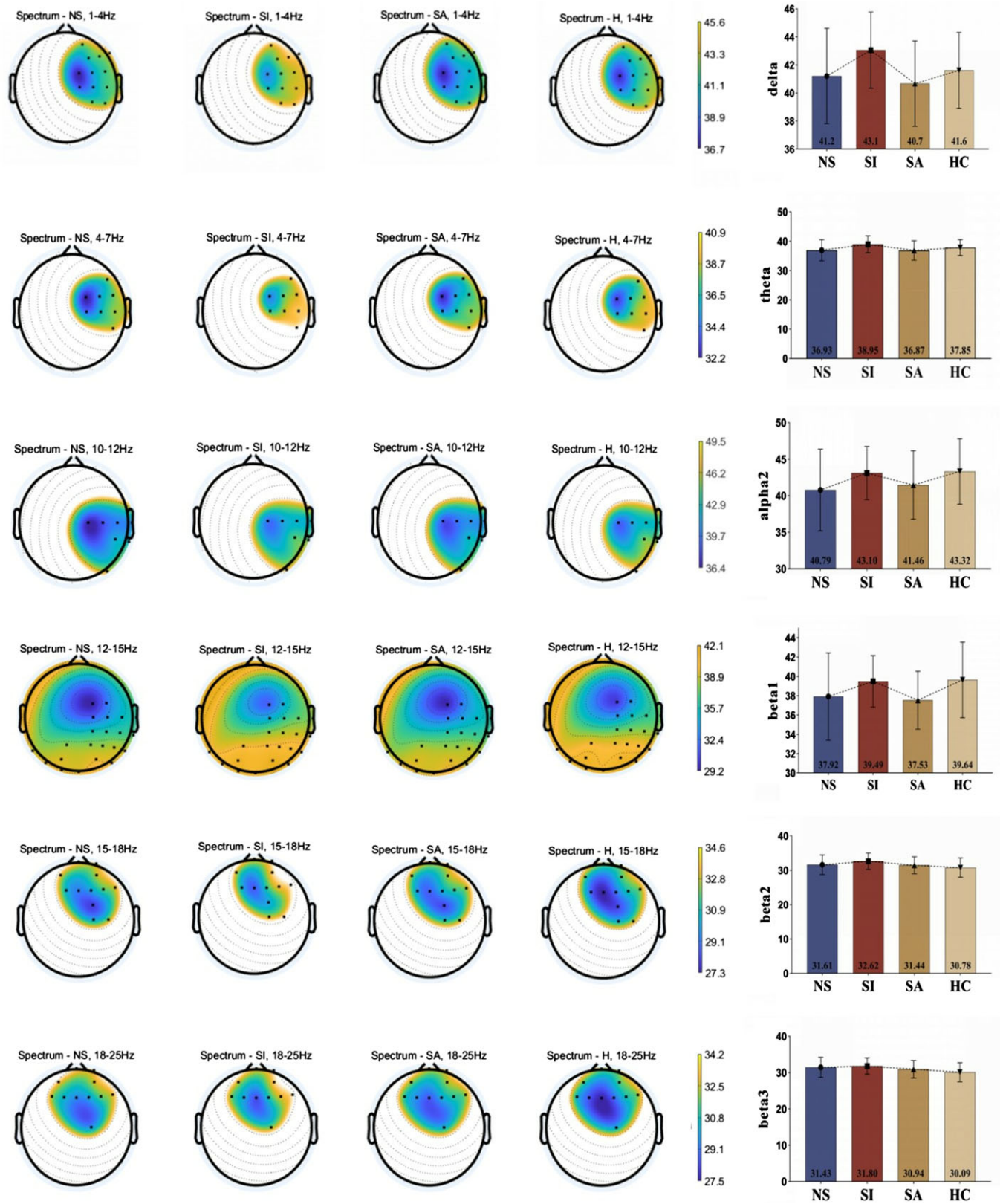

Figure 1. Top plot of power between groups and colour bar of the average power in frequency bands. The picture showed that power differences mainly existed in the right hemisphere. Moreover, the power increased from NS to SI and then decreased from SI to SA.

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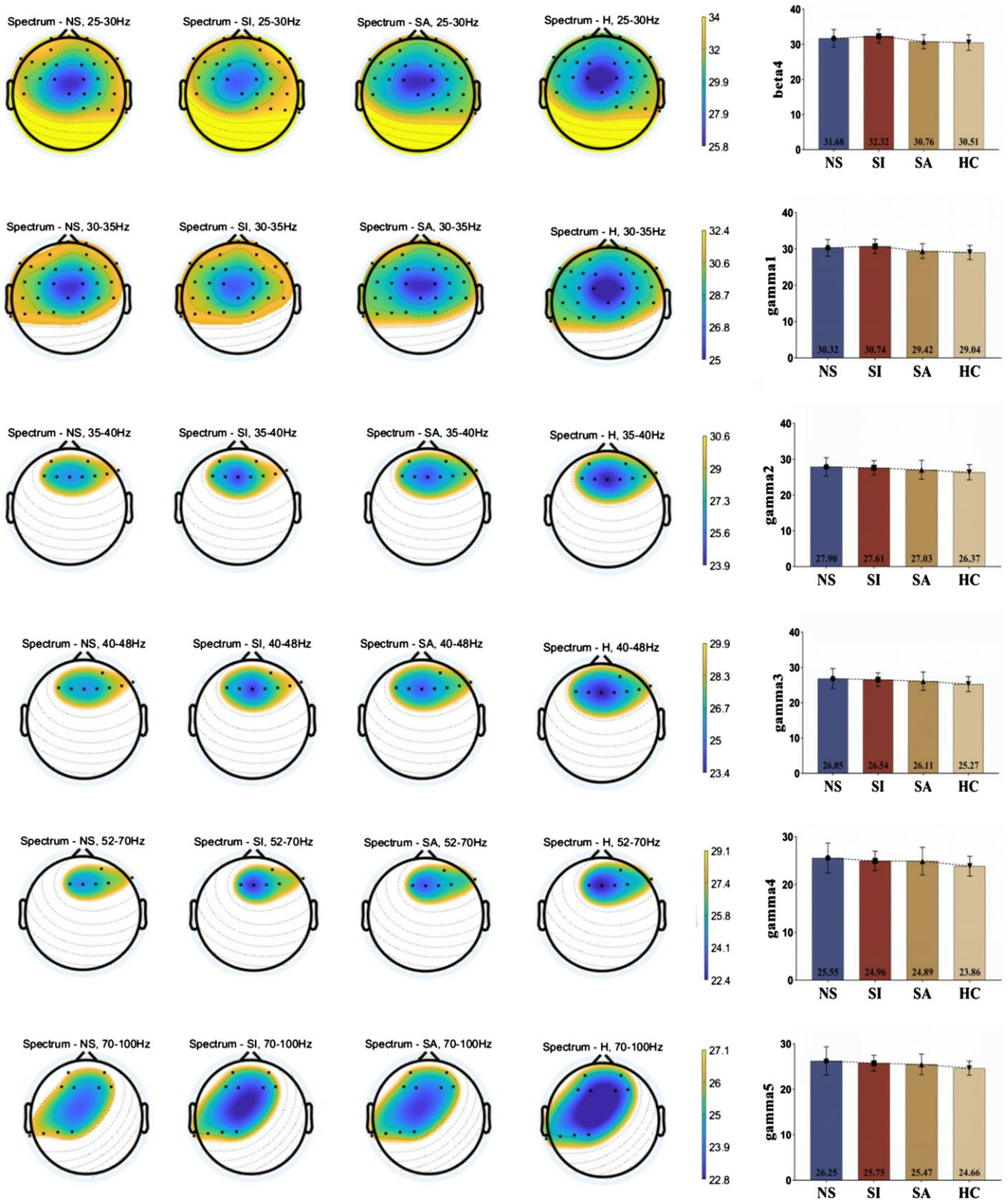

Figure 1. (Continued).

MDD-SAs with a small sample while they failed to replicate previous findings with a large sample without SA. The paradox could result from beta 1 power being strongly dependent on suicidal behaviour. There were three points in the present experiment that linked low- and high-beta to suicide. First, MDD-SAs demonstrated the lowest low-beta among groups,

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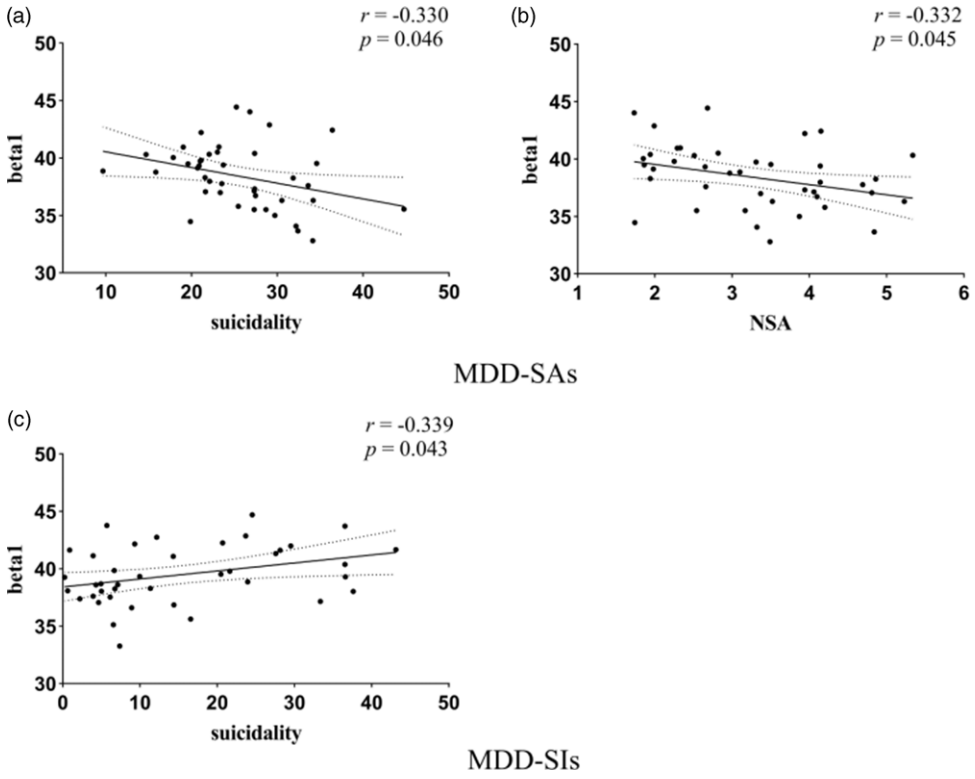

Figure 2. (a and b) Beta 1 power was negatively correlated with the number of SA and suicidality in MDD-SAs, indicating that subjects with lower beta 1 power tended to perform suicide behaviour. (c) Beta 1 power was positively correlated with suicidality in MDD-SIs. The opposite direction of correlation in MDD-SIs and MDD-SAs suggested that beta 1 power which related to cognitive control could mediate the transformation from suicide ideation to suicide behaviour.

indicating poorer inhibitory control function in MDD-SAs. It was in line with Yoon SH's report that inhibition-related P3 amplitude decreased in MDD-SAs who within 7 days after the SA. P3 amplitude was generally related to beta power (Karch *et al.*, 2016; Yoon *et al.*, 2022). Second, MDD-SIs had a higher low-beta power similar to HCs and the highest high-beta power of all groups. 'Controlling impulses and states and stopping action' was critical to transforming from SI to suicide behaviour. The results indicated that enhanced cognitive control mediated by elevated low-beta, which could be the critical factor in blocking the transition from SI to SA. Finally, although high-beta power increased in both MDD-SIs and MDD-NSs than HCs, high power in MDD-SIs was significantly higher on the right frontoparietal sites. It was consistent with previous study that elevated right-brain beta power was associated with impulsivity and aggression (Hofman & Schutter, 2012; Neal & Gable, 2017; De Pascalis *et al.*, 2018), suggesting that enhanced asymmetric resting-state beta oscillations may have a role in impulsive suicidal ideation. In summary, these results suggested that beta-frequency characteristics could identify suicide risk and that reduced low-beta power facilitated the transition from SI to SA. It also explained the absence of reduced beta power in samples without SA, as poor low-beta power marking the suicidality with suicide capacity rather than simply synonymous with high suicide risk.

Furthermore, many studies reported the higher gamma frequency power in MDD-SAs. A large of clinical studies had proposed that the gamma band is the highest in MDD-SAs than other groups (SI, NS and HC group) and could work as a biomarker for SAs (Arikan *et al.*, 2019). And a small sample study of the Chinese Han population suggests that MDD-SAs had higher power in delta, beta and gamma frequency bands than patients without SA history (Duan *et al.*, 2021). Although our results were contrary, it was interesting to note that all of the above results were similar to MDD-SIs in the current study. The study that reported increased gamma power in MDD-SAs classified suicide as a lifetime event and recruited subjects who had a history of SAs in the last month and were currently at SI. Since there was no suitable tool for predicting suicide behaviour, these experiments used scales related to SI to assess suicide risk and validate the obtained neurophysiological indicators, which would confound SI biomarkers with SA biomarkers. A randomised, double-blind longitudinal study of antidepressant efficacy reported that 8 of 35 depressed patients in the placebo group developed SI with their brain spectral power increasing over 48 h, suggesting that SI was associated with a rise in frequency power (Hunter *et al.*, 2010). Other studies in a large sample indicated that SI was related to agitation, which heightened arousal and provided the necessary energy to push people who were immediately before lethal suicide behaviour forward (Ribeiro *et al.*, 2015; Lieberman *et al.*, 2021). We, therefore, speculated that the 'SA biomarker' of many previous studies might be the 'suicide ideation biomarker'. In fact, SI was lower in acute SA than in SI (Cáceda *et al.*, 2018; Yoon *et al.*, 2022). Psychiatrists would also observe that depressed patients would show apathy for a short time after a SA and did not commit the subsequent suicide in the immediate future (Dombrovski & Hallquist, 2017). This clinical phenomenon was consistent with our finding of lower gamma power in MDD-SAs because increased gamma power was always associated with positive cognitive activity (Buzsáki & Wang, 2012; Adaikkan & Tsai, 2020). Furthermore, MDD-SAs also experienced an overall decrease in other frequency bands, which indicated that global brain activity tended to 'calm down'.

Ultimately, we attempted to further explore the relationship of beta 1 power on SI by correlating it with the suicidality score in MINI. Consistent with the neurophysiological observations, the results suggested that the correlation between suicidality and beta 1 power was negative in MDD-SA while positive in MDD-SI. The physiological significance of beta 1 corresponds to cognitive

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control. The decreased inhibitory function is a risk factor for MDD-SAs, while the increased inhibitory function is a protective factor for MDD-SIs. Therefore, the fluctuations of beta 1 power were critical in the conversion of suicidal ideation to SAs. We also detected a negative correlation between the number of lifetime SAs and beta 1 power, suggesting that the impairment of beta 1 power worsened with the increasing number of SAs. Beta 1 power seemed to be an electrophysiological scarring produced by suicidal behaviour rather than a trait marker. More importantly, the reduced beta 1 power was likely to recover after the SA, as beta 1 was a highly state-dependent neurophysiological indicator and the poor control ability in MDD was more paroxysmal and dynamically fluctuating (Dombrovski & Hallquist, 2017). Considering suicide as a transient state rather than a lifelong trait would facilitate further exploration of suicide mechanisms.

Three limitations should be further considered in the experiment. First, this study could only explain high-impulsive SA in MDD but not suit to explain well-planned SA in other psychiatric disorders such as obsessive-compulsive disorder. Second, although considerable neuroimaging data were collected, further follow-up data still lacked to test the results in this study. The reduced beta 1 power in the SA group was weakly associated with suicide in the study, possibly due to the inability of suicidality assessment scales to reflect suicide behaviour accurately. Almost all suicidality assessment scales focus on the assessments of suicidal ideation, including the scale used in this study. For this reason, the result of a weak correlation between suicidality and reduced beta 1 power after controlling for demographic characteristics could be explained. To verify this result, a follow-up study assessing the acute suicide state in MDD-SAs is necessary. Third, the study only demonstrated that SAs were associated with the reduced beta 1 power but could not explore the causal relationship between beta 1 power and SA. Whether the decrease in beta 1 power appeared prior to the suicide behaviour or induced subsequent suicide behaviour after a SA required a longitudinal study with a large sample to explore further.

Overall, the present study validated the results of previous experiments by an acute SA sample, demonstrating that beta 1 power dependent on suicide behaviour was a more reliable neurophysiological marker of SA. Specifically, compared with other groups, beta 1 power corresponding to cognitive control was lowest in SA. Notably, beta 1 power was negatively correlated with the number of SA and suicidality in MDD-SAs and was positively correlated with suicidality in MDD-SIs. It was crucial since beta 1 power linked suicidal ideation with SAs and thus allows for effective intervention. In addition, our study identified a reduction in global brain power in MDD-SAs, contrary to the results in previous studies that considered suicide as a lifelong event, suggesting a significantly different brain activity in the short and long term after SA. Investigating suicide as an acute state would help to deepen our understanding of depressive suicide. Longitudinal follow-up studies with larger samples are needed in the future to understand the mechanisms of suicide better.

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Statement of interest. The authors declare that they have no competing interests.

Ethical statement. All experimental protocols were approved by the Ethics Committee of the Affiliated Mental Health Center of Jiangnan University, China, according to the Declaration of Helsinki; and all methods were carried out in accordance with relevant guidelines and regulations according to the Declaration of Helsinki. All participants in this study signed the informed consent before the experiment.

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