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RESEARCH

Heterogeneous Brain Dynamics Between Acute Cerebellar and Brainstem Infarction

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Abstract

To evaluate the alterations in brain dynamics in patients suffering from brainstem or cerebellar infarctions and their potential associations with cognitive function. In this study, 37 patients were recruited who had acute cerebellar infarction (CI), 32 patients who had acute brainstem infarction (BsI), and 40 healthy controls (HC). Every participant had their resting-state electroencephalogram (EEG) data captured, and the EEG microstates were analyzed. The cognitive function was measured by the Neuropsychological Cognitive Scale including the Mini-Mental State Examination (MMSE), the Montreal Cognitive Assessment (MoCA), the Boston Naming Test (BNT), the Digit Span Test (Digitspan), and the Symbol Digit Modalities Test (SDMT). Compared with the HC group, the transition probabilities from Microstate A(MsA) and MsD to MsC significantly decreased while the transition probabilities from MsA to MsD and from MsD to MsB significantly increased in the BsI group. By contrast, the CI group showed a significant increase in transition probabilities from MsA and MsD to MsC, whereas the transitions from MsD to MsB significantly decreased. Subgroup analysis within the CI group demonstrated that the CI patients with dizziness showed increased coverage and duration in MsB but decreased MsD occurrence than those of CI patients with vertigo. In addition, the BsI patients with pons infarction performed a decreased transition probability between MsA and MsD than those of BsI patients with medulla oblongata infarctions. Moreover, the changes in Microstate (Ms) were significantly correlated with cognitive scales in patients with CI or BsI. Altered brain dynamics in patients with CI or BsI suggested that disturbances in resting brain networks might play a functional role in the cognitive impairment of the CI or BsI patients. Through the use of microstate analysis, the dizziness or vertigo following CI could be differentiated. These findings may serve as a powerful tool in our future clinical practices.

Keywords Cerebellar infarction · Brainstem infarction · EEG microstate · Dizziness · Vertigo

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Introduction

Posterior circulation infarctions, which predominantly affect the brainstem and cerebellum, account for approximately 20% of all ischemic strokes. These infarctions are more commonly observed in older individuals and can significantly impair both daily functioning and cognitive abilities [1–3]. Recent research utilizing diffusion tensor imaging (DTI) and resting-state functional magnetic resonance imaging (rs-fMRI) has shed light on how these infarctions disrupt node efficiency within structural networks and compromise brain network integration. Specifically, cerebellar infarction (CI) and/or brainstem infarction (BsI) have been shown to lead to reduced amplitudes of low-frequency fluctuations, which are closely linked to cognitive deficits observed in the post-stroke period [4–7].

The cerebellum and brainstem are involved in various cognitive functions, including attention, executive function, language, and visuospatial abilities [5, 8]. Recent evidence has demonstrated that ischemic lesions in regions, such as the frontal lobe and temporal lobe, are associated with post-cognitive dysfunction in patients with brainstem infarction [9, 10]. This may be because brainstem infarction may damage the corticocerebellar loop and limbic system, leading to impaired cognitive function [8]. At the same time, the reticular ascending activating system of the brainstem is an important nervous system located in the brainstem. It plays an important role in maintaining wakefulness and consciousness [11]. After brainstem stroke, the ascending pathway of the brainstem may be damaged, which may lead to abnormal production and transmission of neurotransmitters such as dopamine, glutamate, and acetylcholine, and then trigger abnormal functional connections in distal brain regions, resulting in cognitive dysfunction associated with the brainstem and advanced cortical or limbic regions [12]. For the cerebellum, a prior study demonstrated that language function is linked to lesions of the right Crus I and II extending to the IX and that these lesions cause Cerebellar Cognitive-Affective Syndrome (CCAS) [13], which may be partly expressed by the existing of extensive interconnection between the cerebellum and the cerebral hemisphere, forming a complex neural network such as "frontal cortex-pons-cerebellar cortex-dentate nucleus-thalamus-frontal cortex" [14, 15]. Damage to these loops will affect the cognitivedomain function [16].

Furthermore, recent research indicates that nearly 75% of individuals with CI experience dizziness or vertigo [17]. After a cerebellar infarction, injury to the posterior inferior cerebellar artery (PICA), which supplies the tubercle, uvula, and tonsils, or the anterior inferior cerebellar artery (AICA), which supplies the pontine bulb, is a common cause of dizziness or vertigo [18–20]. Vertigo is typically defined as a sensation of spinning or movement that is perceived as an illusion or distortion of one's spatial orientation [21],whereas dizziness refers to confusion or a loss of spatial orientation that does not involve an illusion of movement or a distortion of sensation, but is frequently accompanied by confusion of thought or a feeling of pressure in the head [22]. Dizziness and vertigo can potentially contribute to negative impacts on an individual's everyday functioning and cognitive performance by increasing the risk of falls, disrupting daily tasks, and limiting social interactions [23]. However, there is currently a lack of research investigating the relationship between factors leading to vertigo and dizziness after CI and brain network activity.

Notably, EEG microstate (Ms) analysis is a well-established technique for studying neuronal activity in the spontaneous resting state, which has been used to gain insight into brain dynamics [24]. Microstate analysis can convert electrical signals into multiple topographical maps that reflect different brain activities and indicate different ongoing functions [25]. It has been widely used in the field of neurological and psychiatric disorders such as schizophrenia [26–28], autism spectrum disorders [29–31], Alzheimer's disease and Parkinson's disease [32–34], multiple sclerosis [35], and stroke [36]. One of our previous retrospective studies has found microstate changes in cerebellar infarction [37]. However, a prospective design study on the brain dynamics of CI and BsI and their relationships with cognition deficits is still lacking.

Therefore, the purpose of this study was to investigate the differences of brain networks in resting-state using EEG microstate analysis between patients with CI and BsI and to explore their relationships with abnormal cognitive performance and motor sensations (i.e., dizziness and vertigo).

Materials and Methods

Participants

Patients with acute infarction limited to the cerebellum and brainstem treated at the Department of Neurology of the affiliated hospital of Southwest Medical University were recruited. The presence of cerebellar or brainstem infarction and no infarction in other brain regions were verified by magnetic resonance images (MRI) based on the documented radiologist's report. Healthy subjects with gender and age-matched were recruited as the healthy control (HC) group.

The inclusion criteria for all subjects were: (1) aged between 20 and 85 years; (2) right-handed; and (3) no usage of psychoactive substances, such as tobacco, heroin, and cocaine. The exclusion criteria included (1) any history of other brain abnormalities that impact neurological function, such as Parkinson's disease, seizure disorder, or brain tumor; (2) any history of alcohol or drug addiction; and (3) comorbidities that potentially affect cognitive function, such as hematological system diseases, serious liver or kidney dysfunction. Consequently, a total of 37 patients with CI (13 females and 24 males, 62.38±12.58 years), 32 patients with BsI (9 females and 23 males, 61.34±11.80 years), and 40 HC (10 females and 30 males, 60.03±13.04 years) were enrolled in this study. The demographic characteristics were analyzed using ANOVA for the age difference and the chi-square test for the sex distribution.

Neuropsychologic Testing

Patients with acute CI and BsI underwent a battery of scales to evaluate their neuropsychology. The Chinese version of the Mini-Mental State Examination (MMSE), and the Montreal Cognitive Assessment (MoCA) [38] were employed

to evaluate overall cognitive well-being. The Chinese version of the 30-item Boston Naming Test (BNT) was used to evaluate language proficiency. The attentional function was measured by using the Symbol Digit Modalities Test (SDMT) [39]. The executive function was assessed through the Digit Span Test (Digitspan). All participants finished the MMSE, MoCA, BNT, and Digitspam questionnaires, whereas the SDMT scores of 1 participants in the CI group and 10 participants in the BsI group were not available. The executive function was assessed through the Digit Span Test (Digitspan). Patients with acute CI also finished the Vertigo Related Scale (VAS) to assess the effects of vertigo severity and the Chinese version of the dizziness handicap inventory (DHI). Eight CI participants failed to finish the assessments of dizziness and vertigo

EEG Recording

The EEG data of all patients were collected using a 19-channel recorder (EB Neuro, Italy) with electrodes used according to the international 10–20 system (Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, T6, Pz, Cz, Fz). The sampling rate of recording was set as 500 Hz. The impedance was less than 10 kΩ, and the recording duration was at least 30 minutes. During the EEG resting-state recordings, participants were required to keep their eyes closed while remaining awake and relaxed in a room with low lighting.

EEG Processing

The EEG data was recorded and analyzed in the local database of the Department of Neurology at Southwest Medical University Affiliated Hospital. All raw data were preprocessed by using the EEGLAB toolbox in MATLAB (R2014a, The MathWorks Inc.) [40]. Any bad electrodes that were not functioning or faulty were removed and interpolated by imported European Data Format EEG data. Data then were filtered by the bandpass filter between 1 and 30 Hz. Artifacts were identified using independent component analysis (ICA) and manually removed. Finally, five EEG segments lasting 10 seconds each were chosen for the microstate analysis.

Microstate Analysis

The preprocessed data were imported through the LORETA-Key tool and then subjected to microstate analysis. This was divided into three main steps: first the Global Field Potential (GFP) of each time sample point [41], the GFP can then be computed as:

$$GFP(t) = \sqrt{\frac{\sum_{i=1}^{n} \left[vi(t) - \bar{v}(t)\right]^2}{n}}$$

where N represents the total number of electrodes, $vi(t)$ is the potential of the i-th electrode at time t. $v^{-}(t)$ is the mean of the instantaneous potentials across the electrodes.

Then, the EEG topographies at the peak of the GFP were selected for the cross-validation (CV) criterion and k-means clustering analysis [42]. We chose a group of optimal categories based on the largest global explained variance (GEV) and divided the original instantaneous maps of the three groups (CI group, BsI group, and HC group) into four microstate categories (MsA, MsB, MsC, and MsD). Finally, the subsequent parameters were derived for each microstate at various time intervals [43]: (1) Coverage: percentage of the analyzed time occupied by a specific Ms; (2) Duration: The average duration of each microstate; (3) Occurrence: i.e., the average number of times per second that the Ms occurs; and (4) Transition: the probability that one type of Ms transfers to another.

To investigate the group difference in microstate parameters, MANOVA was applied with the group variable as the fixed factor. Post-hoc pairwise comparisons were conducted for three groups by using independent t-tests.

Correlation Analysis

To understand the correlation between cognitive function, dizziness, and vertigo with the brain dynamic parameters, Pearson correlation coefficients were performed between EEG microstate parameters, cognitive-related scale scores (e.g., MMSE, MoCA, SDMT, BNT, and Digitspam), and dizziness scale-related scores (e.g., VAS and DHI). In addition, the correlation between the Ms parameters and the cognitive measures in the BsI group was also analyzed.

Subgroup Analysis

Considering that clinical symptoms may have an impact on functional brain networks, subgroups of CI patients were divided by clinical traits (vertigo or dizziness after CI). Furthermore, a subgroup comparison for the BsI groups was conducted, which was either divided by the anatomical localization in BsI (e.g., pons, midbrain, medulla oblongata.) or SDMT score (SDMT scales> 20 and SDMT scales ≤20). The difference in individual Ms parameters was compared among CI subgroups or BsI subgroups by independent t-tests.

Statistical Analyses

Clinical data were compared using two-sample *t-tests* based on the normal distribution test and homogeneity of variance test. All the tests were carried out using MATLAB (R2014a, The MathWorks Inc.). The statistical significance level (alpha level) was set to 0.05.

Results

Comparison of Clinical Data and Neuropsychological Scores Among the Three Groups of Subjects

This study comprised 37 CI patients (age = 62.38 ± 12.58 years, males: females = 24: 13), 32 BsI patients (age = 61.34 ± 11.80 years, males: females = 23: 9), and 32 sex-matched healthy participants (age = 62.47 ± 9.21 years, males: females = 30: 10). We observed no significant difference in the age ($F\ (2,106) = 0.342,\ p = 0.711$) and sex ($X^2 = 0.985,\ p = 0.611$).

For the neuropsychological scores, there were no significant differences in MMSE ($t = 0.784,\ p = 0.437$), MoCA ($t = 0.206,\ p = 0.837$), DST scores ($t = -0.149,\ p = 0.882$) between CI and BsI. SDMT scores in the CI group were significantly lower than those in the BsI group ($t = -3.986,\ p<0.001$); BNT scores were significantly higher, and the difference was statistically significant ($t = 3.267,\ p < 0.05$) (Table 1).

Temporal Dynamics of EEG Microstates

Four microstates were identified according to their potential distribution. In BsI patients, the transition probability from MsA ($t = -4.031,\ p <0.001$) and MsD ($t = -4.264,\ p <0.001$) to MsC decreased than HC, and the transition probability from MsA to MsD ($t = 3.798,\ p <0.001$) and MsD to MsB ($t = 3.228,\ p <0.001$) increased than HC. The CI group showed increased transition probabilities from MsA ($t = 3.483,\ p <0.001$) and MsD ($t = 3.619,\ p <0.001$) to MsC than the BsI group. By contrast, the transitions from MsD to MsB decreased in the CI group relative to the BsI group ($t = -4.304,\ p <0.001$) (Fig. 1).

Table 1 Demographic and clinical data results

Demographic and clinical data	CI ($n = 37$)	BsI ($n = 32$)	HC ($n = 40$)	p-Value
Age (mean ± SD)	62.38±12.58	61.34±11.80	60.03±13.04	0.711
Sex (F/M)	13\24	9\23	10\30	0.611
MMSE	23.84±2.79	23.06±4.95		0.437
MoCA	19.62±4.03	19.38±5.63		0.837
BNT	19.70±5.01	14.78±713		0.002
SDMT	8.00±6.36	21.05±14.52		<0.001
Digitspan	10.35±1.62	10.44±2.91		0.882
VAS	7.14±1.36			
DHI	27.72±8.22			
DHI-P	12.48±4.43			
DHI-E	4.07±1.73			
DHI-F	11.1±3.73			

This study comprised 37 CI patients (aged 62.38 ± 12.58 years),32 BsI patients (aged 61.34 ± 11.80 years), and 40 sex-matched healthy participants (aged 60.03±13.04 years). CI group was divided into 22 patients with vertigo and 12 patients with dizziness. There were no significant variations in age or gender. *CI* cerebellar infarction, *BsI* brainstem infarction, *HC* healthy control, *MMSE* Mini-mental State Examination, *MoCA* Montreal Cognitive Scale, *BNT* Boston Naming Test, *SDMT* symbol digit modalities test, *Digitspan* digit span test, *VAS* visual analog scale, *DHI* dizziness handicap inventory

Correlation Analysis Between Cognitive Function Scores and Ms Parameters

The correlation between cognitive function and Ms parameters was further analyzed in the CI group. BNT was negatively correlated with the coverage ($r = -0.356,\ p < 0.05$) and duration ($r = -0.415,\ p < 0.05$) of MsB in the CI patients. VAS was negatively correlated with the coverage ($r = -0.398,\ p < 0.05$) and duration ($r = -0.414,\ p < 0.05$) of MsB in the CI patients, positively correlated with the occurrence per second of MsD ($r = 0.427,\ p < 0.05$) and VAS is negatively correlated with the transfer probability of MsA ($r = -0.405,\ p < 0.05$) and MsC ($r = -0.387,\ p < 0.05$) to MsB, positively correlated with the transfer probability of MsC($r = 0.505,\ p < 0.05$) to MsD. DHI ($r = 0.505,\ p < 0.05$), DHI-F ($r = 0.390,\ p < 0.05$), and DHI-P ($r = 0.414,\ p < 0.05$) were positively correlated with the transfer of MsC to MsD. DHI-F was negatively correlated with the transfer of MsC ($r = -0.417,\ p < 0.05$) to MsB (Fig. 2).

Subgroup Microstate Comparisons

Comparisons Between CI Subgroups

The CI patients with dizziness showed increased coverage ($t = 2.203,\ p < 0.05$) and duration ($t = 3.079,\ p < 0.05$) in MsB and the transition probability from MsA to MsB ($t = 2.425,\ p < 0.05$), decreased MsD occurrence ($t = -2.589,\ p < 0.05$) and the transition probability from MsA ($t = -2.079,\ p < 0.05$) and MsC ($t = -2.179,\ p < 0.05$) to MsD than those of CI patients with vertigo (Fig. 3).

Comparisons Between BsI Subgroups

Subgroup comparisons (divided by the anatomical localization: pons (n =24), midbrain (n = 4), medulla oblongata (n =4)) were performed. Compared to medulla oblongata infarctions patients, the transition ratio from MsA to MsD decreased ($t = -3.508,\ p < 0.001$) in pons infarctions patients, while the transition probability from MsD to MsA increased ($t = 2.874,\ p < 0.05$) in pons infarctions patients. We further divided the BsI patients into two subgroups by using the SDMT (SDMT scales> 20 and SDMT scales

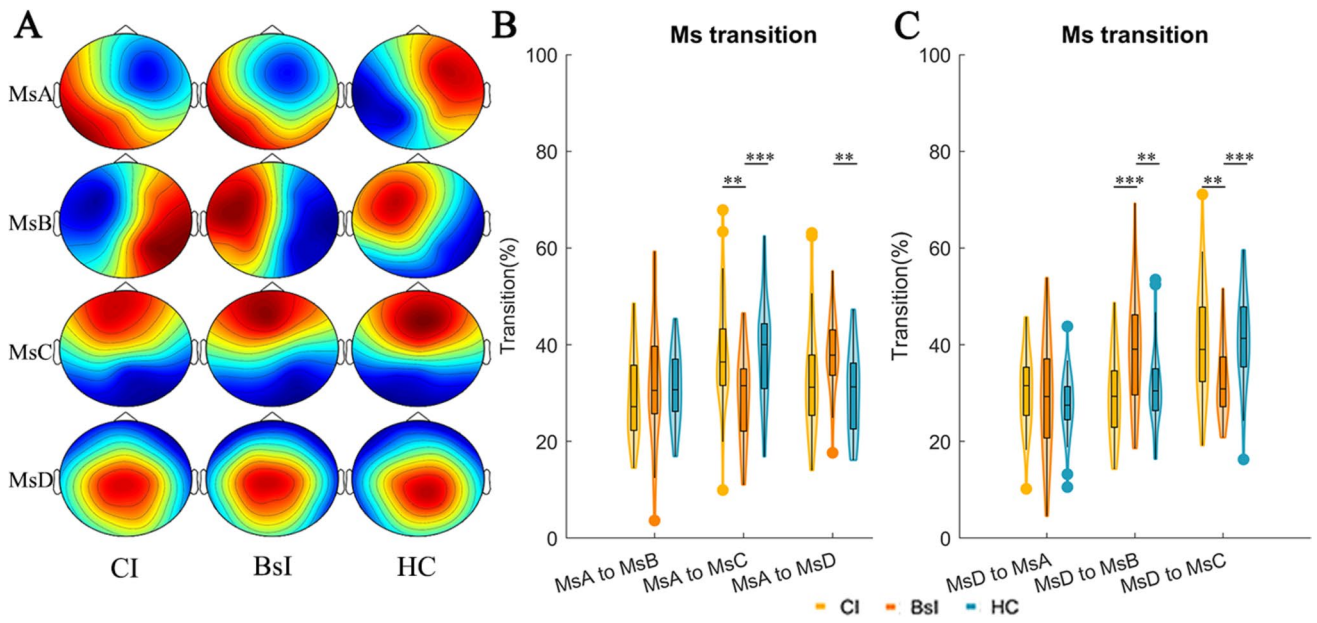

Fig. 1 Microstate temporal dynamics of CI, BsI, and HC groups in resting-state EEG. **A** The four microstates were recognized according to their potential distribution in the CI, BsI, and HC groups. **B** The transition probabilities from MsA to other Ms in the CI, BsI, and HC groups. **C** The transition probabilities from MsD to other Ms in the CI, BsI, and HC groups. A generalized linear model (GLM) with age and sex as covariates was used to eliminate the possible interferences of age and gender. The short horizontal bars in the figure indicate the pairs of groups being compared. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$ after FDR correction. CI, cerebellum infarction; BsI, brainstem infarction, HC, healthy control; Ms, microstate

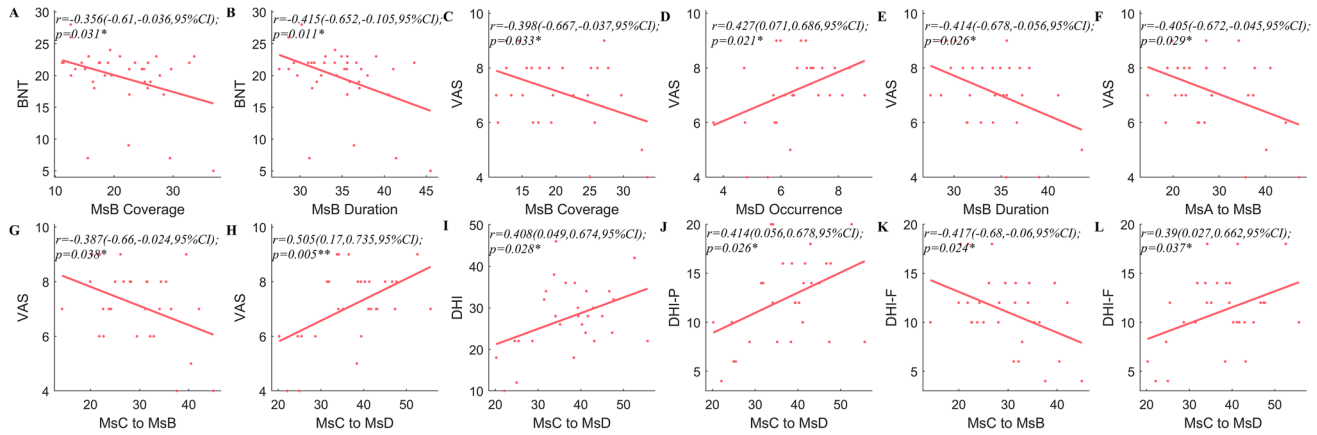

Fig. 2 The correlation between scale scoring and Ms parameters of CI. **A** The correlation between BNT scales and coverage of MsB. **B** The correlation between BNT scales and duration of MsB. **C** The correlation between VAS scales and coverage of MsB. **D** The correlation between VAS scales and the occurrence of MsD. **E** The correlation between VAS scales and duration of MsB. **F** The correlation between VAS scales and transition probability from MsA to MsB. **G** The correlation between VAS and transition probability from MsC to MsB. **H** The correlation between VAS scales and transition probability from MsC to MsD. **I** The correlation between DHI scales and transition probability from MsC to MsD. **J** The correlation between DHI-P scales and transition probability from MsC to MsD. **K** The correlation between DHI-F scales and transition probability from MsC to MsB. **L** The correlation between DHI-F and transition probability from MsC to MsD. The correlation was analyzed by the residuals of microstate parameters and CI with age and sex as covariates. Ms, microstate; BNT, the Boston Naming Test; VAS, Visual Analog Scale; DHI, the Dizziness Handicap Inventory; DHI-P, physical of DHI; DHI-F, functional of DHI; CI, cerebellum infarction; *$p < 0.05$

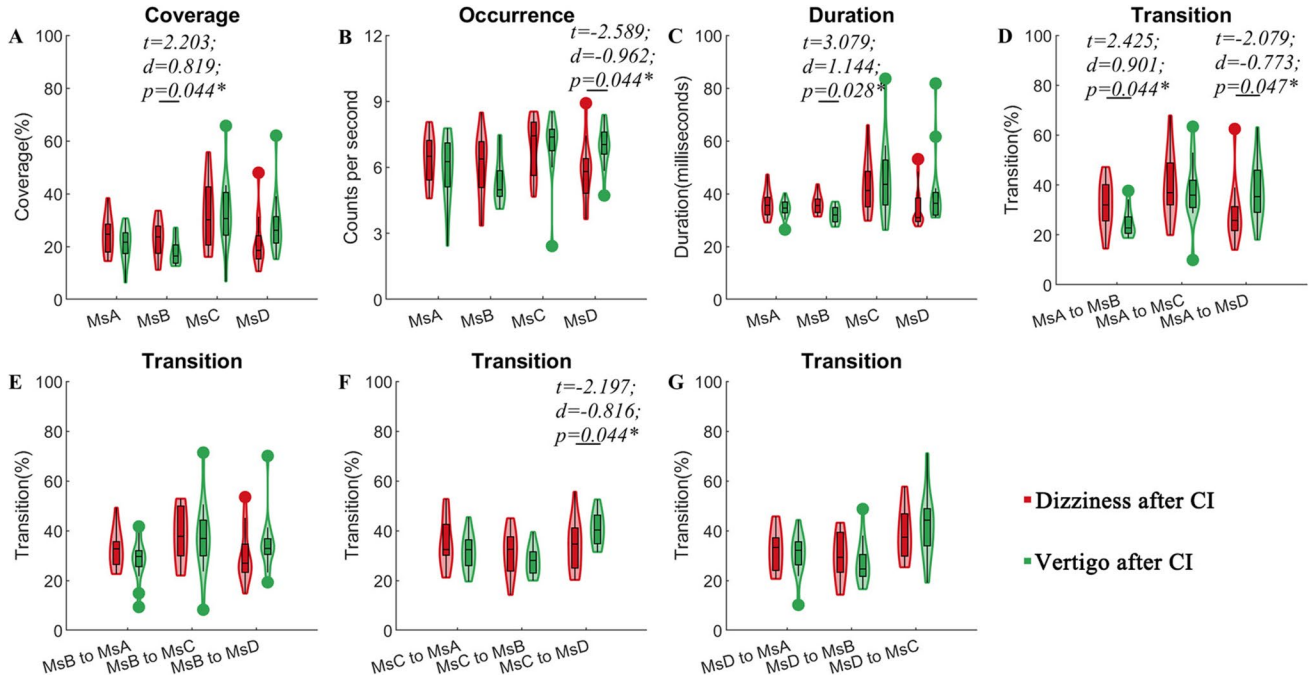

Fig.3 Comparisons of temporal dynamics between dizziness and vertigo after CI. The comparison results of coverage (**A**), occurrence (**B**), duration (**C**), and Markov chain transition probabilities (**D–G**) of the four Ms. Two sample t-tests,*$p < 0.05$, dizziness after CI compared with vertigo after CI . Ms, microstate; CI, cerebellar infarction; d, the effect size Cohen's d

≤20). Those BsI patients with SDMT larger than 20 showed increased MsC duration ($t = 2.961$, $p < 0.05$), compared with those BsI patients with SDMT less than or equal to 20. SDMT was positively correlated with MsC duration ($r = 0.493$, $p < 0.05$) in BsI patients (Fig. 4).

Discussion

The brain is a dynamic processing system that incorporates a complex distribution of information to support time-varying information dissemination among brain regions [36]. In this

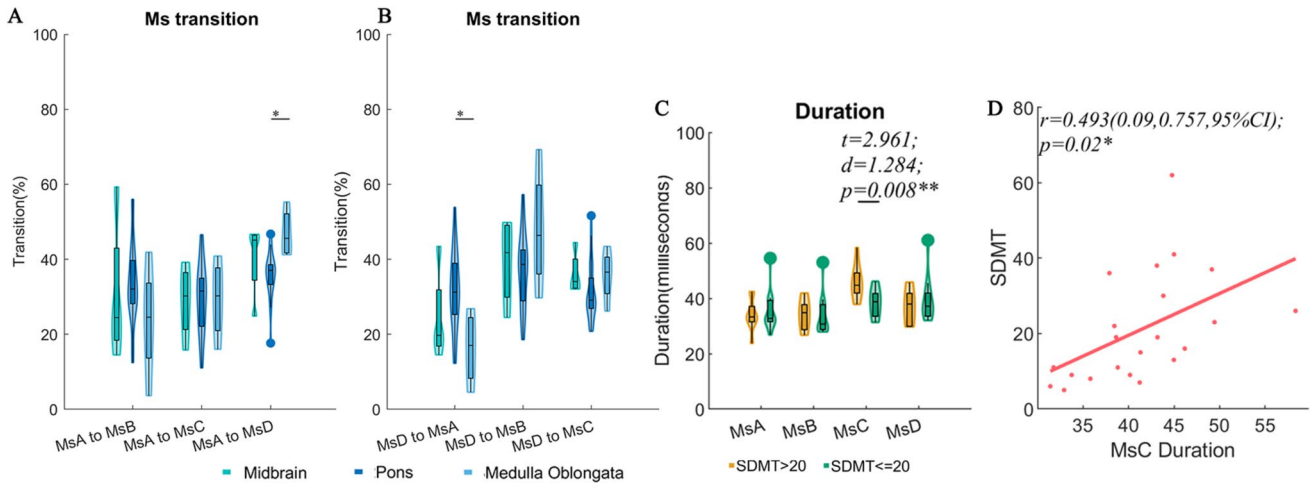

Fig. 4 Comparison of Markov chain transition probabilities of the four microstates and duration in BsI groups. **A** The transition probabilities from MsA to other Ms; **B**. The transition probabilities from MsD to other Ms. **C** The duration of the four Ms in each group when SDMT scale>20 or SDMT scale≤20. **D** The correlation between SDMT and duration of MsC. The transition probabilities from one Ms to another were calculated using Markov chains. The short horizontal bars in the figure indicate the pairs of groups being compared. SDMT, Symbol Digit Modalities Test; d, the effect size Cohen's d. **$p < 0.01$, *$p < 0.05$

study, we applied resting-state EEG microstate analysis to investigate distinguished characterization in microstate dynamics between CI, BsI, and HC. To assess the differences between CI, BsI, and HC, we performed group comparisons for each microstate parameter. We found that in patients with BsI, the probability of transition from MsA and MsD to MsC was significantly lower than in the CI and HC groups, whereas the probability of transition from MsD to MsB was significantly higher than in the CI and HC groups. We also examined the correlation between microstates and clinical scales. The results demonstrated that the SDMT scale showed a significantly positive correlation with the duration of MsC in patients with BsI, whereas the BNT was negatively correlated with the degree and duration of MsB in patients with CI. These findings contributed to a deeper understanding of posterior circulation infarction from a brain electrophysiological perspective and laid the foundation for exploring more effective treatment strategies.

Several studies have proposed that shifting between microstates might indicate the dynamic progress in network sequences within brain networks [25]. Specifically, MsA-D have been associated with the resting-state networks (RSNs) that are involved in speech processing, visual networks, and attention. Operational disruptions in this network configuration can cause maladaptive connections among brain networks, leading to abnormal changes in functionality [43], which was observed in patients with schizophrenia, and depressive disorder [44–46]. In the patients with BsI, we observed a higher probability of transition from MsA to MsD and MsD to MsB, suggesting an increased tendency to activate MsB and a corresponding rise in the extent of neural activity over time. Meanwhile, recent studies suggested altered functional connectivity in the visual cortex (VIS) after BsI, potentially reflecting disruption in the transmission of visual information [47]. As MsB has been related to the visual network in the resting state, our finding might also imply heightened excitability and activity in the visual cortex during visual impairment.

In addition, our findings suggested a difference in the probability of transition between patients with CI and BsI. In patients with CI, we found a higher probability of transition from MsA and MsD to MsC compared to BsI and HC. The decrease in MsC-related parameters was primarily related to task-negative activation of the default mode network (DMN) and reduced functional connectivity in previous studies [34, 48]. The DMN is actively involved in cognitive and emotional processing [48, 49] and MsC is recognized as a portion of the DMN [25]. A previous study suggested abnormal functional connectivity between the DMN nodes and the right cingulate gyrus in patients with cerebellar infarction [4]. Thus, our findings verified that the DMN is involved in abnormal dynamic processing during the resting state for patients with CI. In addition, we found the significant differences among different subgroups of the BsI. Specifically, the results showed a significantly decreased probability of MsA to MsD transition and a significantly increased probability of transferring from MsD to MsA after pontine infarcts compared with medulla oblongata infarcts. This suggested a trend toward increased activation of MsA and a trend toward decreased activation of MsD. MsA was reported to be correlated with the decreased BOLD activation in bilateral superior and middle temporal gyrus, which were involved in the auditory network and the multi-modal vestibular network [25], whereas MsD could reflect the dynamics of the dorsal attention network [25]. Based on this observation, we suggested that there may be a functional mechanism of mutual compensation between the auditory vestibular network and the attention network in patients with BsI.

Furthermore, the SDMT and BNT scales and the duration of the microstate were correlated in this study to find a link between cognitive function and brain networks. We observed a significant and positive correlation between the duration of MsC in patients with BsI and the SDMT scale. Conversely, there was a significant and negative correlation between the duration of MsB in patients with CI and the BNT scale. The SDMT is designed for assessing attention [50]. The results, thus, might suggest that BsI compromises the cognitive ability in the domains of attention. By contrast, in patients with CI, recent imaging studies have shown a link between damage to certain parts of the cerebellum and the development of cerebellar cognitive-affective syndrome (CCAS), which mainly affects their language ability [51]. This notion aligns with our finding that the language impairments observed in patients with CI were correlated with the alterations in MsB parameters. In addition, it has been shown that the probability of transition microstates can reflect the severity of cognitive impairment [33], indicating that patients with CI may experience more severe cognitive impairment. Meanwhile, this might also support that the cerebellum has an impact on specific microstate parameters that can regulate language and other cognitive functions [37]. The cerebellum-brainstem-cortical route is created through the positional relationship and functional contact between the brainstem and cerebellum, demonstrating their collaborative role in cognitive function [5, 9]. The cerebellum receives modulation from the cerebral cortex to refine the information and subsequently sends it back to the cerebral cortex and other brain regions. The cerebral cortex is actively involved in advanced cognitive functions and processes information from the sensory system for complex cognitive processing. This involves both the reception of incoming information and the processing and feedback of information at a higher level. Thus, the cerebellum performs both top-down processes in the information processing circuit and bottom-up processes that adjust and optimize sensory inputs.

Notably, patients with CI often present with symptoms such as dizziness and vertigo. To distinguish the difference in the brain dynamics between the dizziness group and the vertigo group, we divided the cerebellar infarction group into a vertigo

group and a dizziness group. We observed that the frequency of MsD and the probability of conversion of MsA and MsC to MsD were significantly higher in the CI vertigo group than in the dizziness group. Interestingly, our previous retrospective studies have suggested that increased MsD activity may be a candidate biomarker of vertigo [52], supporting that the MsD parameters may help to distinguish dizziness and vertigo after CI [37]. Here, we sought to further validate this idea. We correlated the microstates of the CI patients with the associated vertigo scales and found that the VAS scale and the DHI scale were positively correlated with the parameters of MsD. As MsD correlates with attention [53], it might suggest that when dizziness or vertigo is present it could result in an impaired balance system requiring more attention to postures and gaits that may lead to falls, and the higher demands on attention may increase vestibular dysfunction. These findings emphasized an increased need for prevention measures from falling for patients with severe abnormalities in DHI and their VAS scores.

Moreover, our study also found that for the CI patients DHI-F and DHI-P were positively correlated with the probability of conversion from MsC to MsD, and DHI-F was negatively correlated with the probability of conversion from MsC to MsB. DHI-F measures functional aspects of activity, whereas DHI-P, which reflects the severity of somatic vertigo, is used to rate activity function [54]. It has been shown that patients with dizziness and vertigo might experience cognitive dysfunction as a result of their condition, as well as higher mood changes such as depression, anxiety, and stress [23]. Over the course of disease progression, patients' social skills and mental health status might also be affected, which may lead to psychosomatic disorders. Therefore, when treating such patients in clinics, we should not only focus on the disease itself but also on the patient's physical and mental health.

Some limitations of this study should be taken into consideration. First, this study did not differentiate the subregions within the cerebellum. Different subdivisions, which may be responsible for different functions, contribute to a more precise understanding of the role of the cerebellum. Future research could analyze the cerebellum by dividing it into the anterior lobe, posterior lobe, and flocculonodular lobe. Also, a future longitudinal study is highly recommended to validate our findings in a large time course.

Conclusions

Our study confirmed the altered brain dynamics involving microstate transitions in patients with CI or BsI, suggesting that disturbances in resting brain networks may play a functional role in cognitive impairment. Additionally, the dizziness or vertigo after CI may be recognized by using microstate analysis. These findings may serve as a powerful tool in our future clinical practices such as neuromodulation therapy and provide strong support for the diagnosis and treatment of diseases.

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Data Availability EEG data supporting the findings of this study are available upon request from the corresponding authors.

Declarations

Competing Interest The authors declare no competing interests.

Ethical Approval This study was performed following the 2008 Helsinki Declaration. The study was approved by the Ethics Committee of the Affiliated Hospital of Southwest Medical University. Written informed consent was obtained from all participants.

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