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Different Patterns of Functional Connectivity Alterations Within the Default-Mode Network and Sensorimotor Network in Basal Ganglia and Pontine Stroke

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Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
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Background: The aim of this study was to investigate whether patients with basal ganglia stroke and patients with pontine stroke have different types of functional connectivity (FC) alterations in the early chronic phase.

Material/Methods: We included 14 patients with pontine stroke, 17 patients with basal ganglia stroke, and 20 well-matched healthy controls (HCs). All of them underwent resting-state functional magnetic resonance imaging (rs-fMRI) scanning. The independent component analysis (ICA) approach was applied to extract information regarding the default-mode network (DMN), including anterior DMN (aDMN) and posterior DMN (pDMN) components and the sensorimotor network (SMN).

Results: Compared with HCs, patients with basal ganglia stroke exhibited significantly reduced FC in the left precuneus of the pDMN, right supplementary motor area (SMA), and right superior frontal gyrus (SFG) of the SMN. Additionally, FC in the left medial prefrontal gyrus (MFG) of the aDMN, right precuneus and right posterior cingulate cortex (PCC) of the pDMN, and left middle cingulate gyrus (mid-CC) of the SMN decreased in patients with pontine stroke.

Conclusions: The different patterns of FC damage in patients with basal ganglia stroke and patients with pontine stroke in the early chronic phase may provide a new method for investigating lesion-induced network plasticity.

MeSH Keywords: Functional Neuroimaging • Magnetic Resonance Imaging • Stroke

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Background

The lesion location of ischemic stroke is variable, and location is associated with functional outcome [1]. A brain lesion may affect functions that are not directly related to the damaged brain area, suggesting that a complex system underlies functional brain organization, consisting of broader functional networks rather than simple structure-function relationships [2,3].

Numerous neuroimaging techniques have been used to detect functional changes following stroke [4]. Diffusion tensor imaging (DTI) is widely used to detect white matter integrity after stroke, and numerous studies have demonstrated that white matter integrity is associated with functional deficits, including motor recovery after stroke [5,6]. In addition, diffusion kurtosis imaging (DKI) is a novel technology that has demonstrated that pontine stroke can lead to microstructural changes of the corticospinal tract in the early phase [7]. Recently, increasing attention has focused on the structural or functional changes of the gray matter. Resting-state functional magnetic resonance imaging (rs-fMRI) has the advantage of not requiring the performance of any specific tasks during functional neuroimaging acquisition [8]. Functional neuroimaging allows us to compute how activity in one region is related to activity in another region. This relationship is referred to as functional connectivity (FC) [9]. It has been suggested that infarctions located anywhere in the brain can induce widespread effects, disrupting functional networks [10].

Complex network approaches have been used to characterize relationships between different brain areas [11]. As a multivariate data-driven analysis method, independent component analysis (ICA) has been increasingly applied to rs-fMRI data. ICA can identify multiple resting-state networks (RSNs) and investigate intra- and internetwork FC *in vivo* [12]. Rather than identifying areas of activation that correlate with a region of interest, ICA identifies independent profiles of spatial activation throughout the brain. Wang et al. first reported the altered FC of subcortical stroke patients in both intra- and internetwork between multiple networks using ICA [13]. Recently, Zhao and colleagues revealed the intra- and internetwork FC alterations involved multiple brain networks in the subcortical chronic stroke patients by applying ICA [14]. Another study used ICA to demonstrate default-mode network (DMN) changes of patients with acute brainstem stroke and found that FC within the DMN decreased [15].

The basal ganglia and pontine regions are the most common sites for subcortical stroke [16]. A structural MRI study by Jiang et al. suggested that capsular and pontine stroke patients exhibit different patterns of secondary damage. Structural damage in capsular stroke is noted in the sensorimotor area, but patients with pontine stroke exhibited cerebellar atrophy [17]. Primary sensorimotor areas are the most frequently reported regions involved in the reorganization of motor function, and DMN connectivity impairment has been observed in patients with lesions at various locations [14,18]. Numerous rs-fMRI studies have accordingly demonstrated altered FC of both sensorimotor and higher order cognitive control regions. However, no studies have revealed different patterns of FC alterations in basal ganglia and pontine ischemic stroke patients in the early chronic phase.

In this study, we aimed to apply the ICA method to investigate the FC changes of patients with basal ganglia stroke and patients with pontine stroke 1 month after acute stroke onset. We hypothesized that these 2 groups would exhibit specific types of FC damage in motor and cognitive areas, respectively.

Material and Methods

Subjects and clinical data

This study was approved by the Research Ethics Committee of the Nanjing Medical University and all participants gave written informed consent.

A total of 14 patients with pontine stroke (9 males and 5 females, 65.07±9.56 years) and 17 patients with basal ganglia stroke (12 males and 5 females, 62.29±11.26 years) were enrolled in this study. The inclusion criteria for the stroke patients were as follows: (1) age 40–80 years, (2) right-handedness, (3) first-onset ischemic stroke, (4) 1 month had passed since acute stroke onset. Exclusion criteria for all subjects were: (a) a contraindication for MRI, (b) severe quadriplegia, (c) a history of neurological and psychiatric disorders. We included 20 well-matched HCs (13 males and 7 females, age 58.70±5.88 years) in the final analysis.

Fugl-Meyer assessment was used to assess the motor function of patients with stroke. The general cognitive function of the participants was established using the Montreal Cognitive Assessment (MoCA).

MRI acquisition

All MR images were acquired from a 3.0 Tesla MRI scanner (Ingenia, Philips Medical Systems, Netherlands) with an 8-channel head coil. For rs-fMRI, all subjects were required to stay awake and not think of anything, relax with their eyes closed, and avoid any head motion. The rs-fMRI parameters were: 2000 ms/30 ms repetition time/echo time, 36 slices, 4 mm section thickness, 0 mm gap, 240×240 mm field of view, 64×64 acquisition matrix, and 90° flip angle. The fMRI sequence was obtained in 8 min 8 s.

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Table 1. Demographic and clinical characteristics of all subjects.

	Pontine stroke (n=14)	Basal ganglia stroke (n=17)	Healthy controls (n=20)	P
Age (years)	65.07±9.56	62.29±11.26	58.70±5.89	0.072
Sex (Male/Female)	9/5	12/5	13/7	0.923
Education (years)	8.36±1.50	8.45±1.32	8.30±1.98	0.958
NHISS	3.29±1.49	2.50±1.42	–	0.140
Fugl-Meyer assenssment	89.14±3.39	91.00±2.40	–	0.008
Superficial sense deficits	5	3	–	0.252
Time of imaging (d)	29.50±1.51	29.64±1.50	–	0.803
MoCA	22.21±1.89	21.50±2.09	27.25±1.25	0.000
Hypertension (%)	11 (78)	14 (82)	8 (40)	0.045
Diabetes (%)	4 (29)	7 (41)	6 (30)	0.967
Smoking (%)	3 (21)	4 (24)	4 (20)	0.170
Alcohol (%)	5 (36)	3 (18)	5 (25)	0.562

fMRI Data Preprocessing

The rs-fMRI data preprocessing steps were conducted using Data Processing Assistant for Resting-State fMRI (*http://www.restfmri.net/forum/DPARSF*) based on statistical parametric mapping (SPM8; *http://www.fil.ion.ucl.ac.uk/spm*) on MATLAB 7.12.0 (R2013a). The first 10 volumes were removed from each time series. We excluded any data involving a head motion of greater than 2.0 mm maximum displacement in any of the x, y, or z directions or 2.0° of any angular motion throughout the scan. Four patients with pontine stroke and 5 patients with basal ganglia stroke were excluded for head motion. A total of 14 patients with pontine stroke (9 males and 5 females, 65.07±9.56 years) and 17 patients with basal ganglia stroke (12 males and 5 females, 62.29±11.26 years) were enrolled. Then, we spatially normalized the remaining dataset to the Montreal Neurological Institute template with the resampling voxel size of 3×3×3 mm^3. The normalized fMRI data were smoothed with 6-mm full width at half-maximum (FWHM) Gaussian kernel.

Group Independent Component Analysis (GICA)

After preprocessing the data, Group ICA of fMRI Toolbox (GIFT; *http://mialab.mrn.org/software/gift/*) was used to decompose the data into functional networks using group spatial ICA. The number of components was estimated using the minimum description length criteria tool in GIFT, which suggested that 30 was the optimal number of independent components (ICs). The ICs were then estimated using the Infomax algorithm. Following group ICA, the anterior DMN (aDMN), posterior DMN (pDMN), and sensorimotor network (SMN) components were identified by visual inspection as previously described. Group statistical maps of subject IC patterns representing aDMN, pDMN, and SMN were entered into one- and two-sample *t* tests in SPM8.

Statistical analyses

Statistical analysis of demographics between patients with stroke and healthy controls were performed using the SPSS software package (SPSS, Inc., Chicago, IL, USA). Differences were tested using one-way ANOVA for quantitative continuous variables and a χ^2 test for proportions variables. Statistical significance was set to $p<0.05$.

For within-group analyses, the aDMN, pDMN, and SMN spatial maps were performed by one-sample *t* tests using SPM8 for each group. The threshold was set to $p<0.001$ (FDR-corrected).

Two-sample *t* tests were performed to explore the aDMN, pDMN, and SMN differences between the 2 group of stroke patients and the HCs. The statistical significance threshold was set as $p<0.001$ and a minimum cluster size of 5 voxels.

A region of interest (ROI)-wise manner was adopted to investigate the relationship between DMN connectivity and MoCA by Pearson's correlation analyses. We used REST software to extract mean z values of each brain region that showed significant group differences of FC, and then used the SPSS statistics software for Pearson's correlation coefficients between

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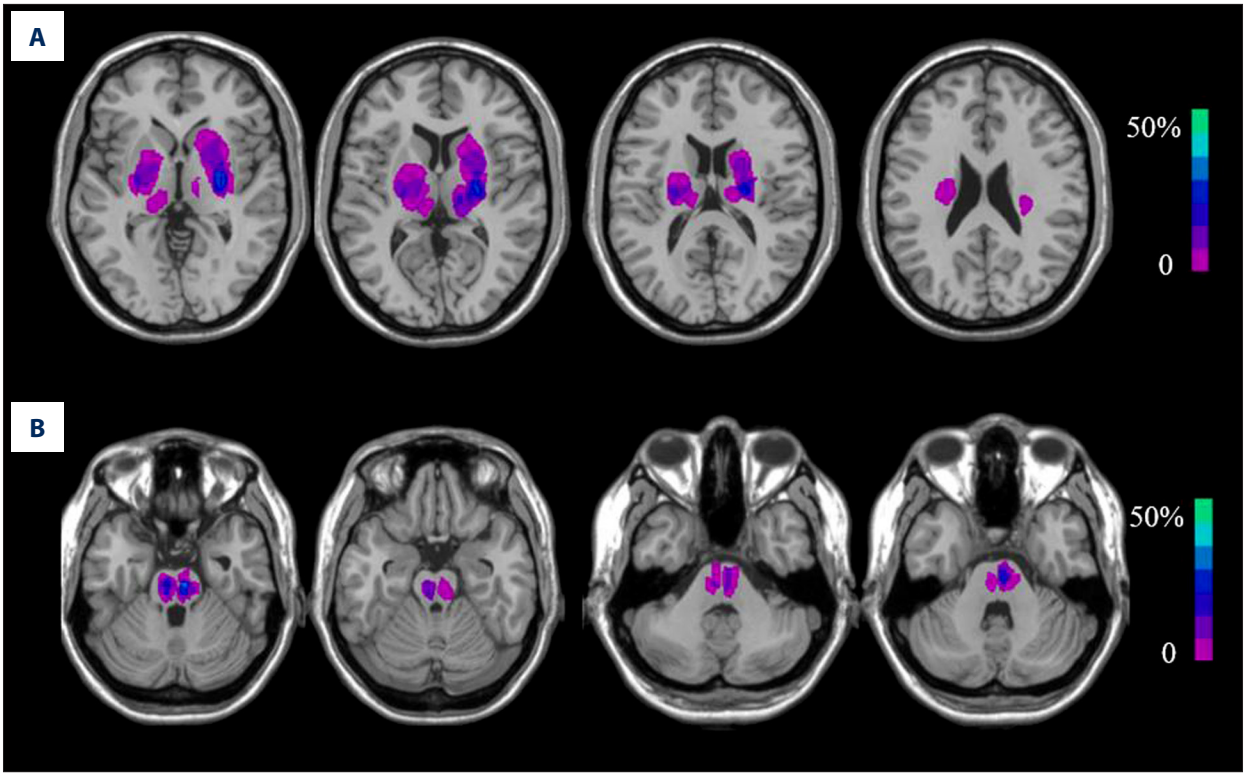

Figure 1. Probability maps of lesion distribution in patients with basal ganglia stroke (**A**) and pontine stroke (**B**). Color bars denote the probability of lesion distribution.

the changes in FC strength and MoCA. Age, sex, and education were set as covariates in these analyses. P value <0.05 was considered as statistically significant.

Results

The characteristics of pontine stroke patients, basal ganglia stroke patients, and HCs are summarized in Table 1. The 3 groups were well-matched with regard to age, sex, and education. There were no significant differences on NHISS, Fugl-Meyer assessment, superficial sense deficits, lesion side, or time after stroke between the pontine stroke patients and the basal ganglia stroke patients (all P>0.05). The MoCA was different in the 3 groups (P<0.05), while after the post hoc test, there was no difference between the pontine stroke patients and basal ganglia stroke patients (P>0.05). Lesion probability maps of patients with basal ganglia stroke and pontine stroke are depicted in Figure 1.

Two components were considered as DMN sub-networks – the aDMN and pDMN – and 1 component was considered as an SMN sub-network among the selected 30 ICs. Figure 2 displays the results of these 3 sub-networks by one-sample *t* test (P<0.001, FDR-corrected).

Compared with HCs, patients with basal ganglia stroke exhibited significantly reduced FC in the left precuneus of the pDMN, right supplementary motor area (SMA), and right superior frontal gyrus (SFG) of the SMN (Figure 3). The brain regions are listed in Table 2. Compared with HCs, patients with pontine stroke exhibited significantly less FC in the left medial prefrontal gyrus (MFG) of the aDMN, right precuneus, right posterior cingulate cortex (PCC) of the pDMN, and left middle cingulate gyrus (mid-CC) (Figure 4). The brain regions are listed in Table 3. A detailed list of brain regions with decreased FC in each sub-network is presented in Table 3. After correcting for age, sex, and education, we found that the strength of FC in the DMN had no correlation with MoCA score (P>0.05).

Discussion

By applying unbiased whole-brain analysis to investigate FC changes in patients with basal ganglia stroke and patients with pontine stroke, we found that both groups of patients exhibited FC reduction in the SMN and DMN. Our findings suggest that patients with basal ganglia stroke and patients with pontine stroke exhibit specific types of FC damage in sensorimotor and cognitive areas. The differences between the 2 groups emphasize the importance of lesion location-specific studies of stroke patients.

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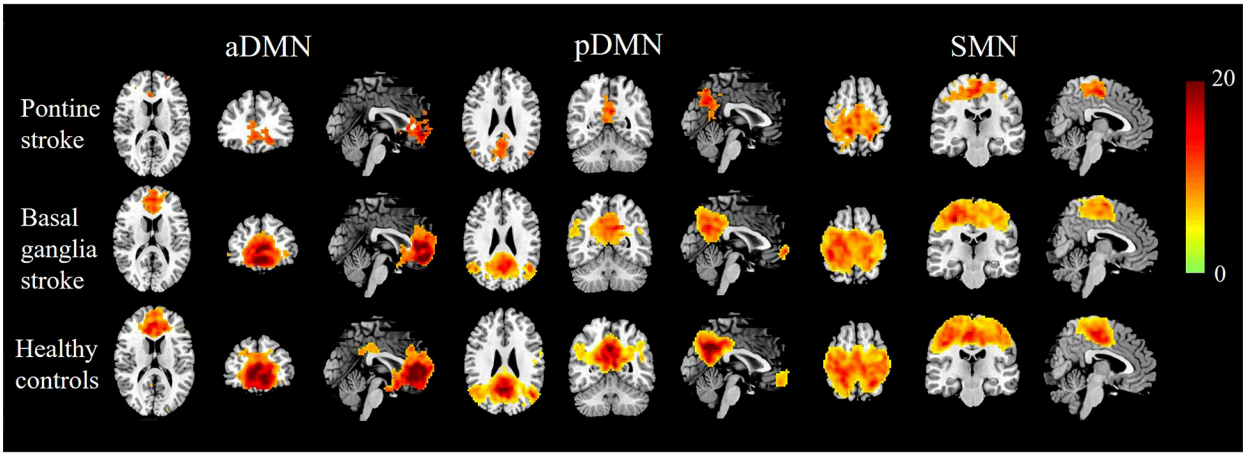

Figure 2. Results of the 3 components representing the aDMN, pDMN, and SMN using one-sample *t* test in patients with subcortical infarctions in the basal ganglia compared with pontine stroke and healthy groups (P<0.001, FDR-corrected). All the components are displayed from multiple sectional, coronal, and sagittal views. Color bar represents T values in each component (P<0.001, FDR-corrected).

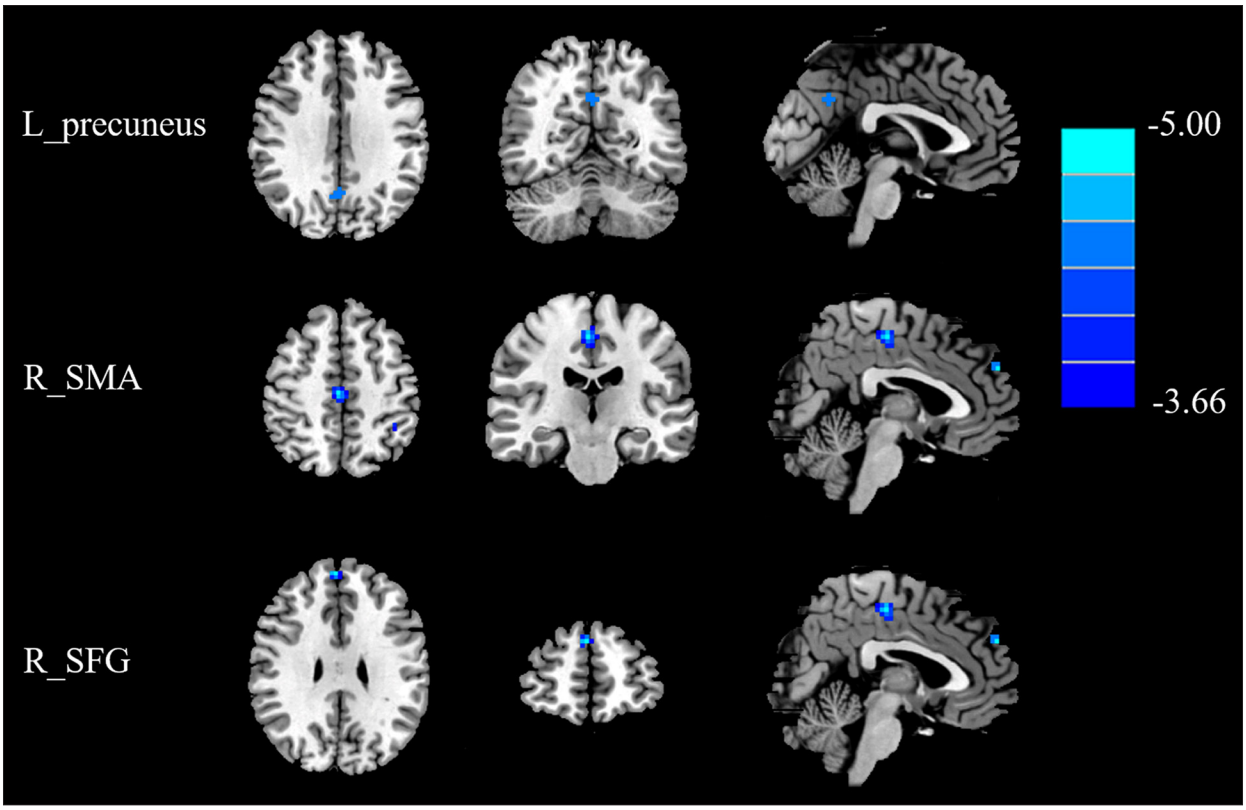

Figure 3. FC differences in networks between patients with basal ganglia stroke and healthy controls. Color bar denotes T values (P<0.001). SMA – right supplementary motor area; SFG – superior Frontal Gyrus; L – left; R – right.

The DMN includes the medial frontal gyrus; posterior cingulate cortex (PCC); angular gyrus (ANG); the medial, lateral, and inferior parietal cortices; the hippocampal formation; and the thalamus [19,20]. The DMN have been regarded as a brain region associated with cognitive and emotional processing by prior studies [21]. A study found that the FC dysfunction of DMN can be detected by resting-state functional MRI 10 days after stroke [22]. Our study revealed FC changes in different areas of both the DMN in the 2 groups in the early chronic phase. The precuneus is an associated area that connects multiple regions and is involved in various functions, especially cognitive function [23,24]. One study indicated that the strength

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Table 2. Decreased FC in patients with basal ganglia stroke compared with healthy patients.

Brain regions	BA	MNI Coordinates x, y, z (mm)	Peak T value	Voxels
pDMN				
L precuneus	7	–1, 60, 33	–4.342	11
SMN				
R supplementary motor area	6	3, –21, 51	–4.857	15
R superior frontal gyrus	9	3, 54, 30	–4.865	7

BA – Brodmann area; MNI – Montreal Neurological Institute; L – left; R – right.

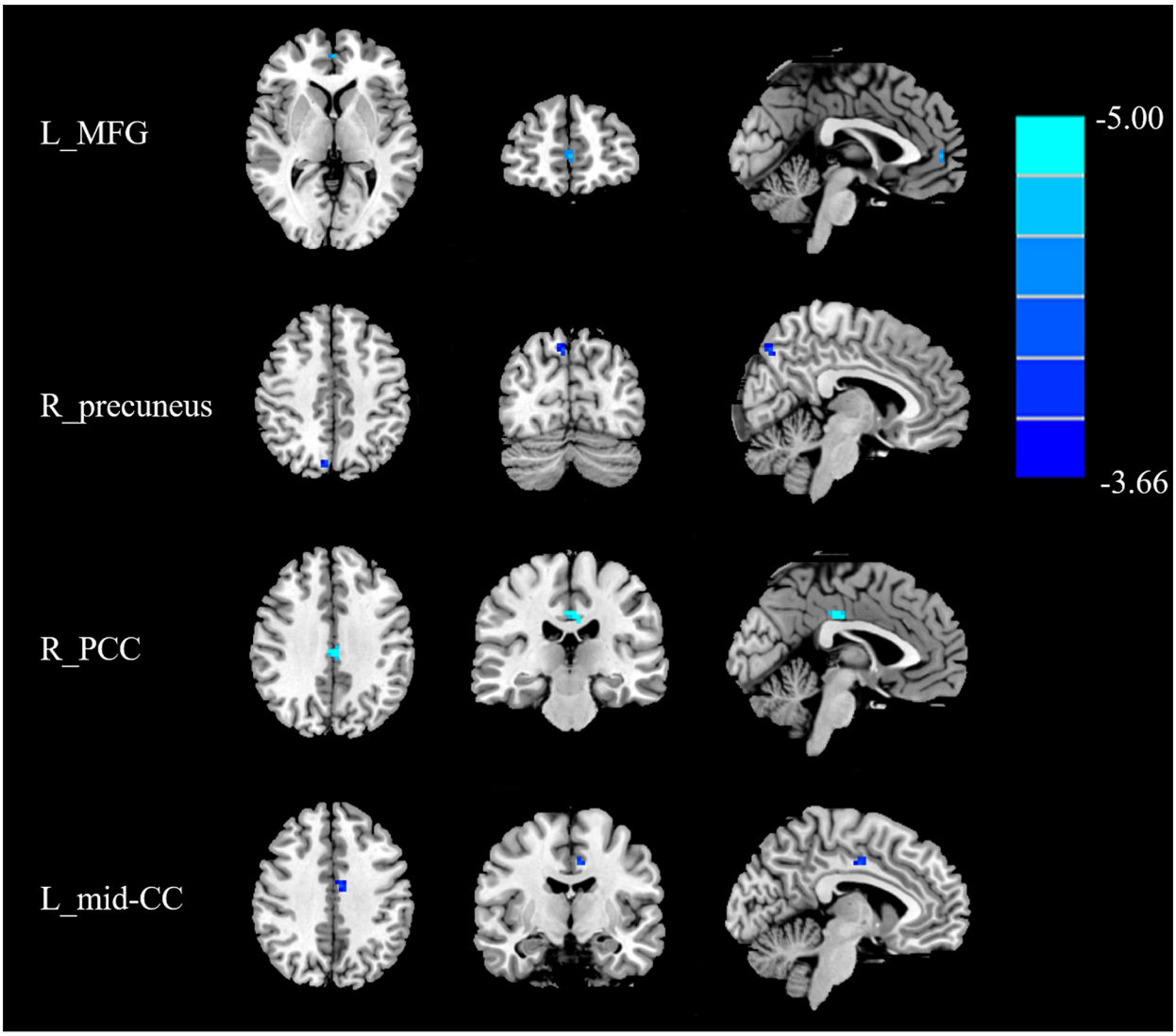

Figure 4. FC differences of networks between pontine stroke and healthy controls. Color bar denotes T values (P<0.001). MFG – medial frontal Gyrus; PCC – posterior cingulate cortex; mid-CC – middle cingulate cortex; L – left; R – right.

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Table 3. Decreased FC in patients with pontine stroke compared with healthy patients.

Brain regions	BA	MNI Coordinates x, y, z (mm)	Peak T value	Voxels
aDMN				
L medial prefrontal gyrus	10	–1, 51, 3	–4.582	5
pDMN				
R precuneus	7	6, –75, 45	–4.119	21
R posterior cingulate cortex	23	1, –24, 36	–4.897	13
SMN				
L middle cingulate cortex	24	–6, –9, 36	–4.191	9

BA – Brodmann area; MNI – Montreal Neurological Institute; L – left; R – right.

of DMN connectivity was significantly decreased in the precuneus in acute stroke patients with impaired consciousness [25]. A study by Ding et al. reported that patients exhibited significantly less FC in the precuneus compared with healthy controls depending on whether they had post-stroke cognitive impairment [26]. Similar to the above-mentioned studies, the 2 groups in our study exhibited reduced FC in the precuneus. The MFG is the region that exhibits the most extensive reorganization as it has undergone considerable cortical expansion across primate evolution [19]. The FC of the MFG area in pontine stroke patients was decreased, whereas FC in basal ganglia stroke patients was normal. As part of the dorsolateral prefrontal cortex, the MFG is a putative cognitive area [27]. The FC of the MFG area in the aDMN of pontine stroke patients decreased, whereas FC in the aDMN of the basal ganglia stroke patients were normal and the pontine stroke patients showed a lower MoCA score than the healthy controls. Roe et al. showed that the rate of brain MRI change was positively correlated with the conversion from cognitively normal to Clinical Dementia Rating (CDR) >0 [28]. Role of brain deficits in predicting disease progression suggested that MRI changes may precede the onset of cognitive impairment. This result may suggest that pontine stroke patients may exhibit more severe cognitive damage, especially memory processing [29]. The PCC, which projects to and receives input from the anterior cingulate, prefrontal, lateral parietal, and parahippocampal regions, is the principal node of the network [30]. The localization of lesion is important in cognitive impairment after stroke. If a lesion is situated in the PCC or disrupts the connectivity of this node, the consequences of the lesion would be of significant relevance in both the short term and long term [31]. This finding reflects that the pontine stroke patients may have cognitive impairment for a long time.

Sensorimotor deficits after stroke are common and may lead to a global functional impairment [32]. The SMN includes somatosensory and motor regions and extends to the supplementary motor areas [33]. Both pontine and hemispheric lesions after stroke can lead to motor or sensory deficits [34]. In the present study, although both basal ganglia stroke and patients with pontine stroke exhibited involvement of the motor pathway, FC was weakened in different sensorimotor regions. Patients with basal ganglia stroke exhibited reduced FC in SMA and SFG. Functionally, SMA is involved in the performance of difficult tasks [35,36]. A number of previous studies consistently found that, compared with controls, the FC between sensory and motor areas decreased and the FC have a correlation with the degree of behavioral impairments in the acute phase of the stroke patients [37–39]. With the transition to the chronic post-stroke phase, the motor connectivity gradually recovers to normal [9]. Recently, a meta-analysis using movement tasks reported that the activity of the SMA was associated with good outcome [32]. The FC in SMA still decreased in the patients with early chronic basal ganglia stroke, indicating that they may have a poor motor function outcome. Basal ganglia are involved in higher-order motor control such as movement planning and execution [40]. The SFG is located at the superior part of the prefrontal cortex and is involved in a variety of cognitive and motor control tasks [41]. The dysfunction of the basal ganglia has an effect on the balance of facilitatory and inhibitory aspects of frontal cortex function [42]. Axonal degeneration secondary to lesions might be a reasonable explanation for these changes [43]. Nevertheless, patients with pontine stroke exhibited reduced FC only in the mid-CC of the SMN. The mid-CC serves as a functional circuit via fiber connection to the SMA in rhesus monkey [44]. The CC is a major constituent of the limbic brain, and cutaneous nociceptive neurons are most abundant [45,46]. A case has been reported showing hypoperfusion presenting in the mid-CC ipsilateral to the infarction with heat anesthesia and deep sensory disturbance in the right half of the body [47]. This indicates that the pontine stroke patients may have a more serious sensory

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deficit than motor function deficit. These results may aid clinicians to design measures to monitor sensorimotor damage in these 2 subgroups.

Several limitations in the present study should be noted. First, the cross-sectional experimental design could not reveal the evolution of FC changes in stroke patients. Longitudinal studies with a large sample size may provide more useful information. Second, we did not eliminate the effect of the lesion side. Future studies with large sample sizes should be performed to analyze patients with left and right lesions separately. Finally, the longitudinal data of the fMRI and neuropsychological assessments should be assessed to explore the dynamic relationship between the FC and cognitive function.

Conclusions

The different patterns of FC damage in patients with basal ganglia stroke and patients with pontine stroke expand the understanding of the changes occurring in the brain after stroke in the early chronic phase and may provide a new method for investigating lesion-induced network plasticity.

Conflict of interests

None.

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