Characteristics of Saccadic Dysmetria and the Lesion Analysis in Isolated Cerebellar Infarction 김 소 현 2022년 2월

석 사 학 위 논 문

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이 논문을 석사학위 논문으로 제출함

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김소현의 석사학위 논문을 인준함

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Acknowledgement

본 논문을 완성할 때까지 바쁘고 어려운 와중에도 불구하고 내용을 꼼꼼히 살펴주시고 많은 조언과 교열의 노고를 아끼지 않으신 이형 지도교수님, 김현아 교수님, 홍정호 교수님께 감사의 말씀을 드립니다. 학문적으로 뿐만 아니라 깊은 정으로 제자로 이끌어 주신 이형 교수님을 지도교수로 모시고 논문을 완성하게 되어 기쁩니다. 또한 이는 저를 위하여 항상 마음 쓰시는 존경하는 부모님과 모든 은사님, 동료들과 함께하는 기쁨입니다.

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김 소 현

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1. Introduction

Saccades are rapid movements of the eyes required for directing fovea toward the target of interest. These eye movements play an important role in perception and responding to the visual environment.[1] The cerebellum in the human brain is in charge of optimizing and modulating motor functions including ocular motor performance and lesions of cerebellum can cause inaccurate, inconsistent and slow saccades.[2] Saccade circuitry has been studied in multiple animal studies. The oculomotor vermis (OMV) and caudal fastigial nucleus (CFN) are found to be the critical structures for the accuracy of saccades. The fastigial nucleus is one of the deep nuclei located in the rostral part of cerebellum and OMV settles in the most dorsal part on lobules VI and VII, projecting perkinje fiber to the posterior part of fastigial nucleus.[3] Results from animal studies using microstimulation, injections, or cooling of focal cerebellar areas revealed that isolated lesions of OMV lead to contraversive saccades while CFN lesions give rise to ipsiversive saccades.[4-8] Impairment of saccadic gain, the ratio of actual and intended size of saccades, is referred to as saccadic dysmetria.

There is uncertainty about applying the outcomes of animal studies directly to humans and yet corresponding areas of human brains are not clearly revealed. Few studies about saccadic control of the human cerebellum showed that not only the posterior vermis but also the cerebellar hemisphere can affect saccadic accuracy[9,10] and demonstrated the possibility that broader portion of the cerebellum could play a role in saccadic control. In fact, stroke physicians occasionally encounter patients presenting with saccadic dysmetria but lacking lesions in CFN or OMV.

We conducted the present study to explore cerebellar regions in charge of horizontal saccadic accuracy in humans by utilizing magnetic resonance image (MRI) lesion mapping technique with diffusion weighted image (DWI) of isolated cerebellar stroke patients. Results of electrophysiologic tests for saccades are also compared in groups of different lesional vascular territories.

2. Materials and Methods

2.1. Study participants:

The patients with cerebellar infarction were recruited from the acute stroke registry of Keimyung University Dongsan Hospital between July 2016 and October 2020. Among these patients, the ones (1) who have concurrent lesions in the brainstem or cerebral hemisphere, (2) who are unable to cooperate during video-oculography (VOG) test due to disease severity or cognitive dysfunction, and (3) who has history of other neurologic diseases which can induce saccadic abnormality were excluded. Forty-three patients were finally enrolled for the study. Clinical profiles including date of birth, age at onset, neurologic examination findings at the time of admission, electrophysiologic test results and neuroimaging studies including DWI were reviewed retrospectively in selected patients. Patients were divided into 2 groups, with saccadic dysmetria and without dysmetria to be compared. Then, they were classified again into groups for further analysis according to the cerebellar vascular territory supplying main lesions.[11] This study was approved by the institutional review board of Dongsan Hospital (IRB no. 2021-12-055).

2.2. Lesion analysis:

Lesions were identified based on DWI scan displaying high signals and drawn by a trained image analyst manually on the T1 scans of each patient using the MRIcron software. Volume-of interest images of right-sided lesions were flipped onto the corresponding portion of the opposite side for analysis. Lesions were mapped in the stereotaxic space on T1-weighted MRI atlas of Spatially unbiased infratentorial template (SUIT) space by applying the segmentation and normalization method[12] provided by the SPM8 software. The Talairach Daemon software was used for anatomical labelling in the created overlap images.[13] Voxel-based lesion symptom mapping (VLSM) was then performed with nonparametric mapping (NPM) software provided with MRIcron. Voxel-by-voxel analysis was undergone between patients with or without saccadic dysmetria using the nonparametric Liebermeister test for binary data.[14] Only voxels that exhibited lesions in at least 5% ($n = 2$) of all patients were included for analysis and $p < 0.05$ was considered significant.

2.3. Electrophysiologic assessment:

Video-oculography (VOG) (SMI, Teltow, Germany, resolution of 0.1 °, sampling rate of 60 Hz) was used to record horizontal saccade, spontaneous nystagmus (SN), gaze-evoked nystagmus (GEN), head-shaking nystagmus (HSN) and caloric responses. Detailed testing techniques have been previously published.[15] Saccadic dysmetria was determined by target fixation task using ± 15 ° target steps to evoke 30 ° alternate horizontal saccades. The gain of each saccade, that is, the ratio of amplitude of implemented saccade divided by the expected amplitude of the target step, was marked as hypometric when the value is < 0.85 and hypermetric when > 1.0.[16-19]

2.4. Statistical analysis:

Statistical analysis was performed using SPSS statistics V.26.0. Data were expressed as mean with standard deviations, medians with interquartile ranges or as proportions. Student's t-test, Mann-Whitney U test, analysis of variance and Fisher's exact or χ^2 test were performed as appropriate and p-value < 0.05 was considered to be significant. To determine statistical power using the lesion image data, voxel-by-voxel analysis with a nonparametric Liebermeister test was used as mentioned above.

3. Results

3.1. Comparison of clinical characteristics between patients with and without saccadic dysmetria:

In total, 43 patients with isolated cerebellar infarction were included in the present study. Of these, 30 patients (69.8%) demonstrated either hypometria or hypermetria in horizontal saccade and were labeled as 'with dysmetria' group. On the other hand, 'without dysmetria' group consisted of 13 patients (30.2%). Clinical characteristics and VOG results were compared between the groups (Table 1). Age was significantly higher in patients with saccadic dysmetria compared to those without dysmetria (66.87 ± 12.82 vs 53.54 ± 14.09, $p < 0.01$). There was no definite gender predominance. All superior cerebellar artery (SCA) territory infarction patients were included in the with dysmetria group, albeit the proportion of lesion territory did not show significant difference between groups. Time interval from the onset of symptoms to the VOG test was collected in each patient. The median interval was 5.0 days in the with dysmetria group and 6.0 days in the without dysmetria group. There was no significant difference in SN, GEN, HSN and caloric response results.

3.2. Difference in saccadic features according to vascular territory of cerebellar lesion:

Saccadic features of 8 patients with SCA territory infarction and 32 patients with posterior inferior cerebellar artery (PICA) territory infarction are analyzed in Table 2. Accuracy of saccades in percentage was similar between both groups in ipsilesional and contralesional directions. The proportion of patients with saccadic dysmetria did not differ significantly in both groups. All SCA infarction patients had saccadic dysmetria while 21 (65.6%) patients with PICA infarction did. Types of dysmetria were assessed based on the dominant direction of saccades in relation to the side of brain lesions and showed significant differences between groups. Ipsilesional hypometria was more frequent in the SCA infarction group compared to the PICA group (87.5% vs 15.6%). On the other hand, the opposite tendency was observed for ipsilesional hypermetria (0% vs 25.0%) ($p < 0.01$). Contralateral hypometria was significantly more frequent in the PICA infarction group compared to the SCA group (59.4% vs 25.0%) and contralateral hypermetria was not observed in the PICA infarction (0% vs 37.5%) ($p < 0.01$). As directional preponderance was found from the above findings, we classified saccadic dysmetria again as ipsiversive and contraversive. A significant difference was observed that the PICA infarction group was apt to have ipsiversive saccadic dysmetria while the SCA group tended to show contraversive saccadic dysmetria ($p < 0.001$).

3.3. Lesion analysis of patients with saccadic dysmetria:

The overlapped lesion image of patients with saccadic dysmetria was created for SCA and PICA cerebellar infarction groups. Images of 8 patients with SCA infarction and 21 patients with PICA infarction were included for analysis. The frequency of overlap was demonstrated with rainbow color from blue to red, the red representing the most often shared region in common. In the SCA infarction group, culmen, fastigium and dentate were the frequently damaged regions (Figure 1) while cerebellar tonsil and inferior semilunar lobule were in PICA infarction patients (Figure 2). However, the VLSM method with nonparametric mapping found no voxels to be statistically significant in relation to saccadic dysmetria or ipsi/contraversive saccades in either group.

Table 1. Clinical Characteristics and Video-oculography Result of Isolated Cerebellar Infarction Patients with and without Saccadic Dysmetria

	With dysmetria (n=30)	Without dysmetria (n=13)	p-Value
Age at diagnosis, years	66.87 ± 12.82	53.54 ± 14.09	$p < 0.01^{*}$
Sex			NS
Male	24 (80.0)	10 (76.9)	
Female	6 (20.0)	3 (23.1)	
Lesion territory			NS
SCA	8 (26.7)	0 (0)	
AICA	1 (3.3)	2 (15.4)	
PICA	21 (70.0)	11 (84.6)	
Interval from symptom onset to electrophysiologic evaluation, days	5.0 [2.0-8.0]	6.0 [4.0-9.0]	NS
VOG findings			
Presence of spontaneous nystagmus	8 (26.7)	2 (16.7)	NS
Presence of gaze evoked nystagmus	2 (8.3)	1 (9.1)	NS
Abnormal caloric paresis	4 (19.6)	3 (27.3)	NS
Abnormal head shaking nystagmus	8 (32.0)	3 (27.3)	NS

Data are represented as mean ± standard deviation, median [interquartile range] or number (%).

AICA: anterior inferior cerebellar artery; NS: not significant; SCA: superior cerebellar artery; PICA: posterior inferior cerebellar artery; VOG: video-oculography; *: $p < 0.01$

Table 2. Comparison of Saccadic Features of Cerebellar Infarction Patients with Superior Cerebellar Artery Territory Lesion and Posterior Inferior Cerebellar Artery Territory Lesion

	SCA lesion (n=8)	PICA lesion (n=32)	p-Value
Saccadic accuracy (%)			
Ipsilesional	71.77 ± 16.21	82.85 ± 12.88	NS
Contralesional	82.36 ± 6.97	83.70 ± 10.62	NS
Saccadic dysmetria	8 (100)	21 (65.6)	NS
Type of saccadic dysmetria			
Ipsilesional saccade			$p < 0.01^{*}$
Hypometria	7 (87.5)	5 (15.6)	
Hypermetria	0 (0)	8 (25.0)	
Contralesional saccade			$p < 0.01^{*}$
Hypometria	2 (25.0)	19 (59.4)	
Hypermetria	3 (37.5)	0 (0)	
Directional preference of dysmetria			$p < 0.001^{**}$
Ipsiversive	0 (0)	16 (50.0)	
Contraversive	6 (75.0)	2 (6.3)	

Data are represented as mean ± standard deviation or number (%).

NS: not significant; SCA: superior cerebellar artery; PICA: posterior inferior cerebellar artery; *: $p < 0.01$; **: $p < 0.001$

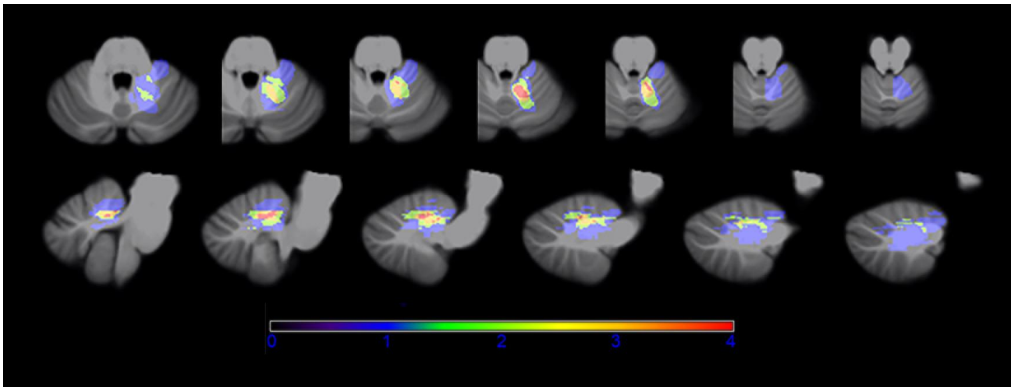

Figure 1. The overlapped lesion image of patients with superior cerebellar artery territory infarction with saccadic dysmetria. Culmen, fastigium and dentate were the most frequently damaged regions.

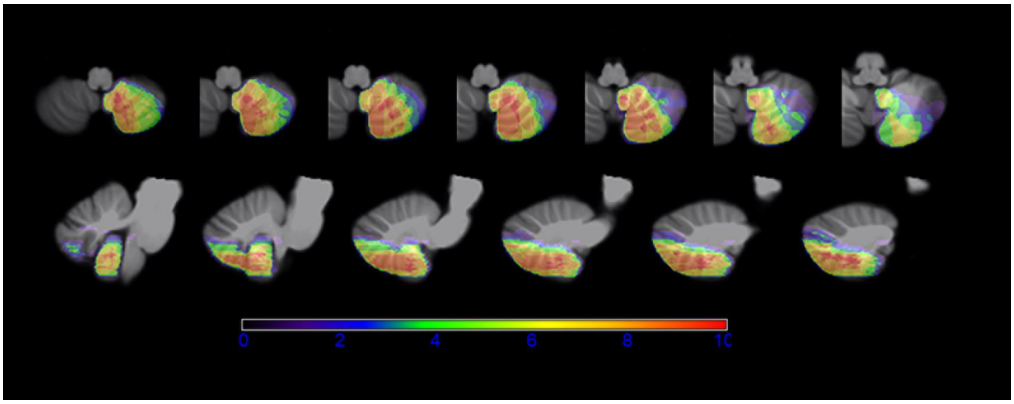

Figure 2. The overlapped lesion image of patients with posterior inferior cerebellar artery territory infarction with saccadic dysmetria. Cerebellar tonsil and inferior semilunar lobule were the most frequently damaged regions.

4. Discussion

Accurate saccade is a fundamental and critical ocular motor function required in humans for perception of visual environments. We found in this study that saccadic dysmetria is quite a common manifestation in SCA and PICA infarction patients and interestingly, opposite directional preference of dysmetria was observed according to vascular territory of the lesion. SCA infarction tends to provoke contraversive saccades, while PICA infarction likely causes ipsiversive saccades. Overlapping lesion images revealed that in comparison with the findings of classic animal studies, rather broader area of cerebellum can attribute to saccadic dysmetria in humans.

In our study, clinical characteristics of isolated cerebellar infarction patients with and without saccadic dysmetria were compared. Age was significantly higher in the with dysmetria group. Normal saccade in humans is known to be slightly hypometric and this tendency intensifies in the elderly.[20)] In addition, aging might negatively affect immediate saccadic adaptation in older patients.[21)] Vascular territory of the lesion did not make significant difference in proportion of patients with dysmetria. It was not surprising because of the well-known highly variable vessel branching and blood supply of posterior circulations and our initial assumption that broad area of cerebellum would involve in saccadic accuracy.[22,23)]

Until now, a number of experimental animal studies have proved that the fastigial nucleus and dorsal cerebellar vermis, also known as oculomotor vermis, are primarily in charge of maintaining saccadic accuracy.[6,7,24)] However, there are other reports suggesting the potential role of the cerebellar hemisphere in saccadic control. Superior and inferior semilunar lobules have been proven to evoke saccades in stimulation studies of monkeys.[25,26] Possible relationship between saccades and the cerebellar hemisphere is further emphasized in human studies. Functional MRI studies showed increased activation in the vermis as well as in cerebellar hemispheres on the horizontal saccade task.[10,27,28] Lesion study with structural MRI also supported the findings.[9] In line with previous publications, our study showed that PICA infarction patients with saccadic dysmetria most frequently shared lesions in cerebellar hemispheres. However, in VLSM with nonparametric statistical analysis, there was no specific region in the cerebellum that could be localized as the focus of saccadic dysmetria with sufficient statistical significance.

The association between cerebellar structure and the direction of saccadic dysmetria has also been studied in various experiments. It is generally accepted that OMV elicits ipsiversive saccades and CFN promotes contraversive saccades on activation. In other words, OMV lesions sparing CFN can cause contraversive saccadic dysmetria when CFN lesions lead to ipsiversive dysmetria.[4,29] Saccadic features of circumambient lesions could be inferred from understanding saccade circuitry. Brainstem and cerebellar portion of the horizontal saccade circuitry are composed of the inferior olivary nucleus, oculomotor vermis, fastigial nucleus, excitatory burst neurons, inhibitory burst neurons and the connecting fiber between these principal structures. Connecting fiber traverses from side to side by passing through superior and inferior cerebellar peduncles.[2-4] We found that patients with SCA infarction have a tendency of contraversive saccadic dysmetria with ipsilateral hypometria and contralateral hypermetria. Anatomical structures the most frequently damaged were fastigium, culmen and dentate. Lesions in this area could disrupt the inhibitory connections of the vermis to the ipsilateral fastigial nucleus or could interfere with the projection from the contralateral fastigial nucleus into the superior cerebellar peduncle, thereby resulting in contraversive saccades. Previously published case reports in cerebellar infarction and demyelinating disease depicted this behavior.[30, 31] On the other hand, PICA infarction patients frequently had ipsiversive saccadic dysmetria with ipsilateral hypermetria and contralateral hypometria. The most overlapped site of lesion was in part of the cerebellar tonsil and a wide portion of inferior semilunar lobules. In this case, damage to the inhibitory climbing fiber from the inferior olivary nucleus to the contralateral OMV could explain the ipsiversive dysmetria. Similar findings with impairment of the olivocerebellar pathway have been well studied in medullary infarction.[32-34]

Several limitations exist in the present study. First, it was a retrospective study with a single-center source of patients. The number of participants in the SCA and AICA infarction groups was so small that the results may not be generalized into larger population. Also, on the standard MRI scan, a very small lesion in the brainstem could be missed and this might have influenced the results. The VOG testing as well bears controversies. Since testing largely depends on patients' cooperation, careful patient selection cannot completely exclude possible errors. The inconsistent extent of saccadic adaptation in the individuals may have played role as a confounding factor, albeit there was no significant difference in the time interval from symptom onset to saccadic investigation between patient groups. In addition, there is no universally accepted testing method or reference value for defining saccadic dysmetria.

5. Summary

Saccadic dysmetria was observed in a large proportion of cerebellar stroke patients. Also, directional preference of saccadic dysmetria was distinctive according to vascular territory of the lesion. In real-world practice, stroke lesions are rarely focal insult as in experimental animal study designs. Instead, broad involvement of cerebellar structures and injury in connecting fibers of saccade circuitry seems more common in humans. The present study emphasizes that understanding the anatomy of the saccadic circuitry and the respective saccadic abnormalities would help physicians in diagnosing and localizing cerebellar infarction.

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Characteristics of Saccadic Dysmetria and the Lesion Analysis in Isolated Cerebellar Infarction

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(Abstract)

Saccade is a critical function for percepting visual environments. So far, oculomotor vermis and caudal fastigial nucleus in the cerebellum have been known as the crucial structures for saccadic accuracy in animal studies. We sought to assess the responsible area in humans and conducted the lesional image analysis in cerebellar infarction patients. We also compared saccadic features in patients with different vascular territory lesions.

Forty-three patients from the acute stroke registry of Keimyung University Dongsan Hospital between July 2016 and October 2020 were enrolled. Saccadic dysmetria was observed in 69.8% of isolated cerebellar infarction. 75.0% of patients with superior cerebellar artery (SCA)

territory infarction showed contraversive saccadic dysmetria, while 50.0 % of patients with posterior inferior cerebellar artery (PICA) territory infarction presented ipsiversive saccades. Unlike animal studies, MRI analysis showed the most frequently damaged structures were fastigium, culmen and dentate in the SCA group while part of cerebellar tonsil and inferior semilunar lobule in the PICA group.

Two thirds of patients presented saccadic dysmetria. Midline cerebellar structures and hemisphere were associated area. The present study emphasizes that knowledge in anatomy of saccade circuitry and understanding the respective saccadic abnormalities would help physicians in diagnosing and localizing cerebellar infarction.

소뇌경색에서의 신속보기 정확도 이상의 양상 및 연관부위에 대한 연구

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(초록)

신속보기는 특정 시각적 대상을 시야에 정확히 위치시켜 주위 환경을 인지하게 하는데 중요한 기능을 한다. 현재까지 실험적 동물연구에서 뇌간의 중심결다리뇌그물체에서 시작하여 상소뇌교를 지나 반대편 꼭지핵, 안구운동을 담당하는 소뇌충부, 하소뇌교를 지나 반대편 하올리브핵까지 이르는 경로 중 이상이 있는 경우 신속보기의 정확도 이상이 발생하는 것으로 확인되었다. 따라서 상소뇌동맥이나 후하소뇌동맥 영역의 뇌경색으로 상소뇌교가 손상되었거나 소뇌충부에 이상이 발생한 경우 신속보기의 정확도 이상이 보고되어 있으나 실제로 소뇌경색 환자에서 유병률이나 양상, 연관부위에 대한 연구는 명확히 없는 실정이다. 본 연구진은 소뇌경색 환자에서 신속보기 이상을 초래하는 해부학적 위치를 MRI 분석을 통하여 확인하고 병변의 혈관 영역에 따른 신속보기의 양상의

특징을 확인하여 진찰을 통해 병변 예측에 활용 가능할지 임상적 유용성을 평가하기 위하여 연구를 진행하였다.

2016년 7월부터 2020년 10월까지 계명대학교 동산병원 급성 뇌경색 레지스트리에 등록된 환자들 중에서 소뇌경색을 진단받은 환자들을 대상자로 등록하여 연구를 진행하였다. 신속보기 겨냥이상은 이 중 69.8%의 환자에서 관찰되었다. 상소뇌동맥 영역의 뇌경색 환자 중 75.0%는 병변과 이향성(contraversive) 방향의 신속보기 겨냥이상을 보였으며, 후하소뇌동맥 영역 뇌경색 환자의 50.0%에서 병변과 동향성(ipsiversive) 방향의 겨냥이상이 확인되었다. MRI 분석을 통하여 확인하였을 때 신속보기 겨냥이상을 보이는 환자에서 가장 자주 손상된 해부학적 부위는 상소뇌동맥 영역 뇌경색의 경우 꼭지핵, 소뇌정상 및 치상핵 부위였고 후하소뇌동맥 영역 뇌경색의 경우 소뇌 편도의 일부와 하반월소엽 부위로 확인되어 동물연구에서 확인된 것과는 다소 차이가 있었다.

전체 분석한 소뇌경색 환자 중 약 2/3에서 신속보기 겨냥이상이 발생하였으며 소뇌 정중부 구조물 뿐만 아니라 소뇌반구도 연관된 부위로 확인되었다. 본 연구를 통하여 신속보기 안구운동의 신경회로에 대한 지식을 갖고 해부학적으로 손상 부위에 따라 나타날 수 있는 특징적인

신속보기 이상의 양상을 이해하는 것이 소뇌경색 환자를 진단하고 병변을 예측하는데에 도움이 될 수 있음을 확인할 수 있었다.