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Original Article

A Comparative Study of Cerebrovascular Reactivity Using Transcranial Doppler Ultrasonography in Sports-Related Concussion Patients

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Abstract

Objective: This study aimed to investigate the relationship between changes in cerebrovascular resistance under hyperventilation stress and symptom induction in patients with sports-related concussions (SRCs).

Subjects and Methods: Thise study included 51 patients who visited our hospital between January 2020 and December 2023 (19 with a previous history of SRC, 20 without a previous history of SRC,) and 12 control subjects). Using transcranial Doppler (TCD), the resistance index (RI) was calculated from the blood flow in the right middle cerebral artery before and after 1min of hyperventilation stress, and the percentage change in RI (ΔRI rate) was determined. The presence or absence of symptoms before and after hyperventilation were assessed.

Results: The ΔRI rate before and after hyperventilation stress was 0.19 in the "Previous History group," 0.25 in the "No-Pprevious Hhistory group," and 0.29 in the "Ccontrol group." Symptom induction rates following hyperventilation stress were 52.6% (10/19) in the "Previous History group," 25% (5/20) in the No Previous History group," and 0% (0/12) in the Ccontrol group. Significant differences were observed in both RI and symptom induction rates between the Previous History and Control groups.

Conclusion: In patients with SRC, particularly those with a history of SRC, reduced cerebrovascular reactivity to hyperventilation stress and pronounced symptom induction were observed. These findings suggest that interventions that consider respiratory changes may be beneficial during stepwise return-to-play protocols following the SRC.

Keywords: cerebrovascular reactivity; return to sport; sports-related concussions; transcranial Doppler ultrasonography

Introduction

Sports-related concussion (SRC) is a form of mild traumatic brain injury (TBI) that results from either a direct impact on the head or an indirect force transmitted to the body that affects the head. The International Sports Concussion Conference defines SRC as "a complex pathophysiological process involving the brain." From an epidemiological perspective, concussions are highly prevalent, particularly in the context of sports-related trauma [1]. An estimated 1.1 to 1.9 million concussions are reported annually in the United States, approximately 20% of which are sports-related [2]. However, it is possible that a significant number of SRCs remain unreported, and the actual incidence may be higher.

In addition to its high prevalence, SRC is associated with prolonged and symptom exacerbation of symptoms due to re-injury. Effective management of SRC involves a stepwise approach, gradually increasing the exercise load upon return to competition [3]. However, this process may exacerbate symptoms and, potentially dela the athletes return to competition. Prior research has indicated that cerebral blood flow diminishes after concussion [4]. Moreover, fluctuations in carbon dioxide (CO_2) concentration due to respiratory changes during anaerobic exercise may alter cerebrovascular resistance and, contribute to symptom recurrence [5]. However, the precise relationship between respiratory changes and cerebrovascular resistance in SRC remains unclear [6,7].

Transcranial Doppler (TCD) ultrasonography is widely used to assess the cerebral blood flow and cerebrovascular resistance [8]. This method is particularly valuable for conditions such as cerebral vasospasm following subarachnoid hemorrhage. This study investigated symptom recurrence in patients with SRC by evaluating the changes in cerebrovascular resistance using (TCD) after induced hyperventilation.

Material and Methods

Data Sources and Study Population

This retrospective study analyzed the electronic medical records of patients diagnosed with (SRC). We searched the electronic medical records of patients who visited the Sports Head Trauma Outpatient Clinic of the Department of Neurosurgery at Toho University Medical Center Ohashi Hospital, located in Meguro Ward, Tokyo, between January 2020 and December 2023. Patients aged 13 years or older who were examined within 28 days of injury were included in the study. Patients with structural brain injuriesy identified usingby neuroimaging (braincomputed tomography [CT] or magnetic resonance imaging [MRI]) were excluded.

Previous research investigating the impact of SRC history has predominantly compared individuals who have experienced one or more SRCs to those without such experience. Some studies have compared multiple SRC experiences in participants with no prior concussions, which is the approach adopted in this research.

Patients with SRC were categorized into two groups based on their previous SRC history: "Previous History" and "No Previous History" groups. In addition, a Control group was selected from patients diagnosed with non-head trauma during the same period. This study was approved by the Ethics Committee of the Toho University Medical Center Ohashi Hospital (approval number H21095 and H24033).

Methods and Observational Items

The Sports Head Trauma Outpatient Clinic routinely performs medical interviews, physical examinations, Sports Concussion Assessment Tool (SCAT) 5, and (TCD) evaluations for all patients. Through a retrospective review of electronic medical records, we extracted four observational items::

1. Patient basic information (age, sex, height, weight, headache history, previous concussion history, sports type, position)
2. SCAT5 subjective symptom scores (total number and severity of symptoms)
3. Cerebral blood flow evaluation using TCD from the right middle cerebral artery (mean flow velocity, peak flow velocity, pulsation index [PI], and , resistance index [RI])
4. RI change rate (ΔRI) and symptom presence before and after hyperventilation.

Instrumentation

The SCAT5 symptom evaluation is an objective measure of symptoms following SRC. It has been found to be sensitive, reliable, and valid in concussed high school and collegiate athletes [25]. The checklist includes 22 symptoms that are graded on a Likert scale from 0 (not present) to 6 (severe). The total scores represents the total number of symptoms checked and the total severity score.

A TCD ultrasound (2 MHz probe, Nicolet® SONARA®Transcranial Doppler System,Natus Neurology, Middleton, Wisconsin, USA) was used to record blood flow velocity at the M1 segment of the right middle cerebral artery at a depth of 45-55 mm. After identifying the vessel and optimizing the signals based on depth, waveform, and velocity, the ultrasound probe was fixed using a head frame(Natus Neurology, Middleton, Wisconsin, USA).

Cerebrovascular reactivity can be measured using various methods. Although CO_2 inhalation methods have higher short and long-term reproducibility than breath-holding techniques, the latter are low-cost, portable, and minimally invasive. Following previously published protocols, cerebrovascular reactivity was measured using breath-holding and hyperventilation techniques.

After standard TCD measurements in the supine, resting state, the participants were instructed to hold their breath for 20s, followed by 40s of normal breathing. The breath-holding protocol was repeated five times. After a 2-minute recovery period, the participants were instructed to breathe at a rate of 36 breaths per minute using a metronome for 20s, followed by 40 s of normal breathing. This procedure was repeated five times.

The primary evaluation items for the cerebrovascular reactivity protocol were the RI before and after breath-holding and hyperventilation, and the RI change rate (ΔRI): ΔRI = (post-hyperventilation RI - resting RI) / resting RI(Fig . 1).

PI =(Peak flow velocity - Diastoric flow velocity)/Mean flow velocity)

RI =(Peak flow velocity - Diastoric flow velocity)/Peak flow velocity)

Δ RI= (Post-hyperventilation RI - Resting RI) / Resting RI

Figure . 1.Calculation Formula of PI, RI and ΔRI

Data Analysis

The analysis included age, sex, height, weight, headache history, previous concussion history, sports type, position, SCAT5 subjective symptom score cerebral blood flow evaluation, RI, ΔRI rate, and symptom presence. Comparisons were made among the three groups. Statistical analysis was performed using Welch'st-test or the Kruskal–-Wallistest, with significance set at $p<0.05$. The statistical software R(version 4.1.2) was used for all analyses.

Result

Patient and Injury Characteristics

We reviewed the electronic medical records of 425 patients during the observation period and extracted data from 51 patients (Tables 1 and 2). Patients were excluded if they had incomplete observation items, were under 13 years of age, or had an structural brain injury on head CT or MRI. The 51 patients were categorized into three groups: 19 in the "Previous History" group, 20 in the "No Previous History"group, and 12 in the "Control" group.

Table 1: Characteristics and result of SCAT5/TCD

	Patient group			P value
	Previous History	No Previous History	Control	
	(n=19)	(n=20)	(n=12)	
Age, mean (SD), year	21.9(4.3)	19.6(4.0)	17.0(3.3)	<0.05
Sex				
Male (%)	15(78.9)	12(60.0)	12(100.0)	<0.05
Female (%)	4(21.1)	8(40.0)	0(0.0)	
Height, mean (SD), cm	172.7(8.7)	167.1(9.2)	172.8(4.8)	0.132
Weight, mean (SD), kg	73.4(13.7)	63.3(17.9)	66.8(11.0)	0.059
Headache history (%)	5(26.3)	5(25.0)	2(16.7)	0.771
Numberof prior concussions, mean (SD), times	4.2(4.9)	0(0.0)	0.1(0.3)	<0.05
Sports				
Rugby (%)	6(31.6)	4(20.0)	0(0.0)	
American football (%)	4(21.1)	4(20.0)	11(92)	
Soccer (%)	4(21.1)	4(20.0)	0	
Lacrosse (%)	1(0.1)	4(20.0)	0	
Others (%)	4(21.1)	4(20.0)	1(0.1)	
Collision, Rugby+American football (%)	10(52.6)	8(40.0)	11(91.7)	<0.05
Positiona				
Offence (%)	7(36.8)	9(45.0)	7(58.3)	0.697
Defence (%)	8(42.1)	9(45.0)	4(33.3)	
Others (%)	4(21.1)	2(10.0)	1(0.8)	
SCAT5				
Number of symptoms, mean (SD)	7.8(7.3)	6.8(6.6)	1.1(1.4)	<0.05
Symptom severity, mean (SD)	23.6(32.0)	14.3(17.0)	1.3(1.6)	<0.05
TCD				
Mean flow velocity, mean (SD), cm/s	57.1(7.87)	64.1(10.14)	58.9(8.38)	<0.05
Peak flow velocity, mean (SD), cm/s	95.1(15.0)	99.9(15.3)	100.1(12.2)	0.428
PI, mean (SD)	0.98(0.15)	0.87(0.13)	1.02(0.14)	<0.05
RI, mean (SD)	0.59(0.05)	0.56(0.05)	0.60(0.04)	<0.05
ΔRI, mean (SD)	0.19(0.08)	0.25(0.11)	0.28(0.12)	<0.05
Patient of symptom induction (%)	10(52.6)	5(25.0)	0(0.0)	<0.05

Abbreviations: SD, standard deviation; SCAT5, sports concussion assessment tool 5; TCD, transcranial Doppler; PI, palsatility index; RI, resistance index
*a Rugby was not divided into offense and defense; therefore the FW was tentatively placed in offense and the BK in defense.

Table2: List of all cases

No.	Age (year)	Sex	Height (cm)	Weight (kg)	Sports	Position	Number of prior concussions	Headache history
1	21	Male	183	73	Soccer	GK	2	–
2	17	Male	180	66	Soccer	SB	0	–
3	21	Male	175	93	American football	OL	1	–

4	33	Female	152	46	Trainer	–	0	+
5	17	Male	160	50	Soccer	FW	0	–
6	20	Male	165	74	American football	RB	3	+
7	31	Male	183	93	Rugby	FB	2	–
8	13	Male	165	51	Rugby	WTB	0	–
9	20	Male	168	69	American football	WR	1	–
10	21	Male	174	72	Basketball	GK	1	–
11	20	Male	168	77	Rugby	FL	6	–
12	22	Female	163	51	Lacrosse	G	0	–
13	22	Female	158	50	Lacrosse	AT	0	–
14	19	Female	164	52	Lacrosse	MD	0	+
15	19	Female	160	52	Cheerleading	middle	0	–
16	17	Male	173	74	Baseball	inside	0	–
17	21	Male	177	75	American football	DB	0	–
18	21	Female	161	54	Lacrosse	DF	3	–
19	34	Male	183	91	Rugby	SO	14	–
20	21	Female	158	54	Karate	–	1	+
21	25	Male	175	84	Rugby	WTB	4	–
22	25	Female	169	58	BMX	freestyle	20	+
23	14	Male	165	42	Rugby	WTB	0	–
24	25	Male	188	87	Basketball	G	1	+
25	21	Male	174	85	Rugby	CTB	0	+
26	21	Male	171	85	Rugby	FL	5	–
27	17	Male	178	70	Soccer	CB	2	–
28	17	Male	177	71	Soccer	DF	0	–
29	20	Female	151	48	Soccer	MF	0	–
30	19	Male	165	60	American football	WR	0	–
31	19	Male	184	97	Rugby	LO	0	–
32	19	Male	172	70	Rugby	FL	8	–
33	22	Male	178	113	American football	C	0	+
34	21	Female	155	50	Soccer	SB	1	–
35	16	Male	175	55	Soccer	MF	3	+
36	18	Male	180	85	American football	DL	1	–
37	17	Male	174	66	American football	RB	0	+
38	20	Female	163	56	Baseball	Catcher	0	–
39	22	Female	159	60	Lacrosse	MF	0	–
40	19	Male	174	89	American football	OL	0	–
41	15	Male	170	49	American football	TE	0	–
42	15	Female	172	55	American football	OL	0	+

43	15	Male	170	56	American football	OL	0	–
44	15	Male	180	63	American football	WR	0	–
45	13	Male	170	70	American football	DB	0	–
46	18	Male	178	76	American football	DB	0	–
47	26	Male	168	68	Wrestling	–	1	–
48	16	Male	168	72	American football	DL	0	+
49	16	Male	183	70	American football	WR	0	–
50	16	Male	168	56	American football	TE	0	–
51	20	Male	173	78	American football	S	0	–

Abbreviations: GK, Goal keeper; SB, Side back; OL, Offensive line; FW, Forward; RB, Running back; FB, Full back; WTB, Wing three-quarter back; WR, Wide receiver; G, Guard; FL, Flanker; G, Golie; AT, Attack; MF, Midfielder; DB, Defensive back; DF, Defender; SO, Stand off; CTB, Center three-quarter back; CB, Center back; LO, Lock; C, Center; DL, Defensive line; TE, Tight end; S, Safety

Patient Demographic Information

No statistically significant differences were observed among the three groups in terms of patient characteristics (height, weight, and history of headache). Mean ages were 21.9 ± 4.3 years for the "Previous History group, 19.6 ± 4.0 years for the "No Previous History group, and 17.0 ± 3.3 years for the "Control group"($p<0.05$). Sex composition was as follows: the "Previous History group" consisted of 15 males, the "No Previous History group" had 12 males, and the "Control group" comprised 12 males($p<0.05$). The number of previous SRC was 4.2±4.9 in the "Previous History group" ($p<0.05$). The primary sports were rugby, American football, and soccer, in that order, within the "Previous History group. The "No Previous History " group exhibited a similar representations of rugby, American football, soccer, and lacrosse. American football was the most prevalent sport in the Control group. The percentage of each collision sport (rugby and American football) was 52.6% in the "Previous History established" group, 40.0% in the "No Previous History" group, and 91.7% in the Control group ($p<0.05$).

SCAT5 Symptom Score

SCAT5 symptom scores were 23.6 ± 32.0 for the "Previous History group" and 14.3 ± 17.0 for the "No Previous History group, significantly lower at 1.3 ± 1.6 for the "Control group" ($p<0.05$).

TCD Cerebral Blood Flow Evaluation

RI of the right middle cerebral artery was measured TCD and was 0.59±0.05 in the "Previous History" group and 0.56±0.05 in the "No Previous History" group, whereas it was 0.60±0.04 in the "Control" group ($p<0.05$).

RI Change Rate and Symptom Occurrence during Hyperventilation Challenge

The RI change rate (ΔRI) before and after hyperventilation was 0.19 for the "Previous History group, 0.25 for the "No Previous History group, and 0.29 for the "Control group(Fig. 2). Symptom provocation rates during hyperventilation were 52.6% (10/19) for the "Previous History group," 25% (5/20) for the "No Previous History group, and 0% (0/12) for the "Control group(Fig. 3).

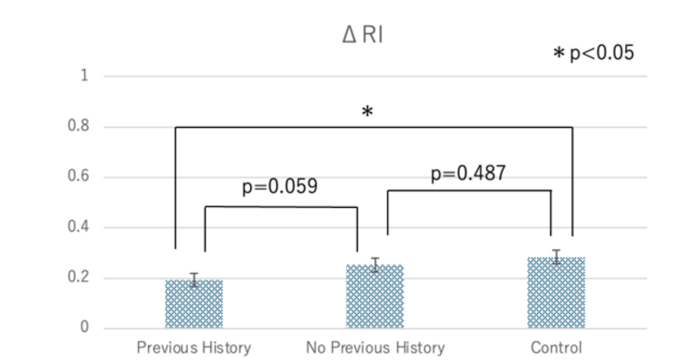

Figure 2. Result of ΔRI

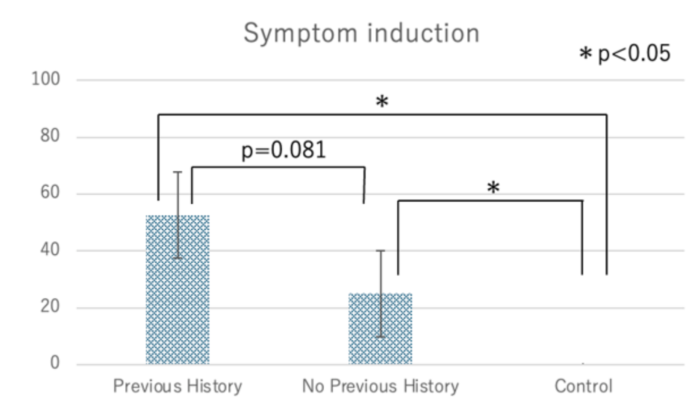

Figure 3. Result of symptom induction

Discussion

The present study employed a hyperventilation load in patients with SRC. This study aimed to examine the relationship between changes in cerebrovascular reactivity changes and symptom induction. The results demonstrated that in a cohort of patients with a history of SRC, hyperventilatory stress resulted in reducedt cerebrovascular reactivity and symptom exacerbation [9-11]. Transient cerebral blood flow changes associated with SRC have been shown to vary across studies, and the detailed pathophysiological mechanisms have remaineduncleear ([12)]. Recently, it has been reported that patients with SRC show differences in cerebrovascular reactivity rather than in cerebral blood flow [13]. In the present study, physiological changes were induced by a hyperventilation load, which allowed for a more detailed visualization of cerebrovascular dysfunction and symptom exacerbation in patients with SRC.

The results of this study revealed that patients with SRC exhibit reduced cerebrovascular responsiveness to arterial CO_2 reduction. Symptoms are elicited when patients are subjected to exercise, leading to ventilatory thresholds.

During mild-to-moderate exercise, hypercapnia causes a decrease in pH and, vasodilation, and an increase in CBF (Cerebral blood flow) [14, 15]. As exercise intensity approaches the ventilatory threshold, arterial blood CO_2 levels decrease due to ventilatory incompatibility [16-18].

Conventional angiographic studies have demonstrated that the diameters of the major cerebral vessels, including the internal carotid artery and the main trunk of the middle cerebral artery, remain unaltered [19]. It was previously thought that changes in contrast media or blood CO_2 concentrations did not cause significant changes unless cerebral vasospasm occurred. Yoshii et al [20]. examined the changes in blood CO_2 concentration due to hyper ventilation. They compared patients with minor head trauma and healthy individuals, and demonstrated that the decrease in cerebral blood flow was smaller in the minor head trauma group. This finding suggests that cerebrovascular regulation is impaired in patients with SRC.

The present study evaluated the cerebrovascular effects of hyperventilation using TCD. Similarly, there are reports supporting the potential of TCD in assessing cerebrovascular damage due to SRC [8]. Several studies have reported impaired cerebrovascular reactivity, neurovascular coupling, and dynamic cerebral autoregulation [21-23]. Particularly, an inadequate response to hyper ventilation has been reported [24]. It has also been suggested that cerebrovascular dysfunction may persist even after resolution of clinical symptoms. These results demonstrate altered cerebrovascular function in patients with SRC, and support our findings.

Previous studies have evaluated cerebrovascular reactivity using high CO_2 stimulation. The present study examined cerebrovascular reactivity and symptom induction symptoms during a reduction in CO_2 levels at the ventilatory threshold. This finding is highly beneficial for the development of rehabilitation strategies for SRC. The effects of exercise vary considerably between individuals. A dose-response relationship was observed. Identifying the optimal intensity and frequency of exercise for an individual has the potential to enhance the outcomes after SRC. It is crucial to note that SRC symptoms can manifest or worsen with exercise or exertion, even when the symptoms are not evident at rest [25-28]. The decision to resume competition is typically based on symptom resolution and tolerance to aerobic exercise. In the future, it will beis essential to comprehend objective markers of symptom exacerbation and optimize the amount of exercise (intensity, frequency, and duration).

The academic significance of this study lies in its demonstration of the potential for a more objective and comprehensive assessment of pathophysiology in SRC practice through a combination of physiological indices, such as cerebrovascular reactivity, with conventional neurological findings. In light of these results, it may be advisable to consider therapeutic approaches, such as pharmacotherapy, which can promote functional compensations after brain injury and support environmental adaptation through cognitive rehabilitation. The present study wais limited by the small number of cases, lack of blood CO_2 measurements during hyperventilation, and evaluation only during the acute phase. To gain a more comprehensive understanding of SRC pathogenesis, future studies should aim to increase the number of cases, conduct long-term follow-up, and explore more effective therapeutic interventions. The findings of this study have implications in rehabilitation medicine, patient management, and potential treatment strategies.

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Conflicts of interest

We declare no conflict of interest in the preparation of this document.

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