obtain a long-lasting prophylactic effect in humans by regular intragastric administration, which is a more convenient route.

It was reported that chronic intraperitoneal administration of TPM dose-dependently suppressed CSD susceptibility, though the dosages (40–80 mg/kg/day) were lower than in our study (23). It should be borne in mind that the administration methods were different; intraperitoneal administration in previous studies and oral gavage in our experiment. We found that the maximum plasma level after intraperitoneal administration was approximately three times that after intragastric administration. It seems possible that intragastric administration may result in lower TPM blood levels because of restricted absorption at the gastrointestinal tract, but it may allow the blood level of TPM to be maintained for a longer period, than with intraperitoneal administration. Thus, higher doses may be required in the case of intragastric administration.

CBF elevation related to potassium-evoked CSD was not affected by chronic TPM treatment, whereas it was suppressed by single administration of TPM in our study. This effect of single administration is consistent with that described previously (20). The mechanism of vasodilation associated with CSD is complicated, being influenced by multiple stimuli arising from cerebral arteries and parenchyma, including various neurotransmitters secreted by sensory and parasympathetic nerves (26). TPM diminished neurogenic dural vasodilation by inhibiting the presynaptic release of calcitonin gene-related peptide (CGRP) from trigeminal neurons, but did not act postsynaptically at blood vessels (27). A single dose of TPM might attenuate vasodilation by reducing release of vasodilative substances, such as CGRP, whereas the suppressive response might be attenuated and/or compensated for by other mechanisms in the chronically treated rats.

TPM has been reported to suppress excitatory amino-acid-related synaptic transmission and ion channels (28,29). Conversely, the drug enhances $GABA_A$ receptor-mediated inhibitory currents and blocks the GluK1 agonist-mediated suppression of GABA release from interneurons (30). Although it has not been demonstrated that GABA receptors directly modulate CSD susceptibility, it is possible that TPM might suppress CSD occurrence and propagation via interference with excitatory amino-acid-mediated ion channels and/or inhibition of GABA-mediated depolarization.

In our study, we used daily administration of TPM for 6 weeks, so it is possible that the suppressive effect of TPM on CSD involves induction of enzyme/receptor(s) or modulation of gene expression. TPM enhanced GABA release by down-regulation of $GABA_B$ autoreceptor expression and up-regulation of astroglial TWIK-related acid-sensitive K^+ channel-1 in gerbils (31,32). A neuroprotective effect of TPM was seen as an enhancement of cell survival on exposure of primary neuronal-astroglial cultures to glutamate- and kainate-induced neurotoxicity (33) and blockade of up-regulation of caspase-3 expression in hippocampus of kindled rats (34). These results suggest a possible mechanism of the antiepileptic effects of TPM. A similar mechanism may be involved for migraine. Thus, chronic TPM treatment may induce up- or down-regulation of certain neuronal and/or astroglial proteins, leading to suppression of neuronal activity associated with CSD and resulting in relief of migraine and/or aura.

Another migraine preventive drug, lamotrigine, had a potent suppressive effect on CSD susceptibility (especially CSD occurrence frequency) and c-Fos expression in the cortex, but did not affect propagation velocity (35). Lamotrigine is clinically effective on migraine with aura, but not on migraine without aura. On the other hand, migraine without aura as well as with aura was relieved by TPM in the clinical trial (17). The relieving effect of TPM on migraine might involve not only a decrease in CSD susceptibility, but also other mechanisms.

Conclusion

Chronic treatment with TPM suppressed CSD occurrence and propagation along the cerebral cortex, and is therefore expected to relieve migraine. However, continuous maintenance of a sufficient blood level of TPM appears to be necessary.

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Conflict of interests

The authors declare that there is no conflict of interest.

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Original Article

Sustained Decrease and Remarkable Increase in Red Blood Cell Velocity in Intraparenchymal Capillaries Associated With Potassium-Induced Cortical Spreading Depression

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ABSTRACT

Objectives: To examine changes in red blood cell (RBC) velocity in intraparenchymal capillaries of rat cerebral cortex in response to KCl-induced cortical spreading depression (CSD).

Methods: In isoflurane-anesthetized rats, the velocity of fluorescently labeled RBCs flowing in capillaries in layer I was measured with a high-speed camera laser-scanning confocal fluorescence microscope, with simultaneous monitoring of DC potential, the electroencephalogram (EEG), partial pressure of oxygen (PO_2), and cerebral blood flow (CBF).

Results: After KCl application, a transient deflection of DC potential (i.e., CSD) repeatedly appeared concomitantly with depression of EEG, and was propagated in the distal direction. PO_2 transiently decreased and CBF was slowly elevated. The frequency distribution of RBC velocity was shifted downward during CSD and was still low after the passage of CSD. When we observed RBC velocity in 38 individual capillaries, 10 capillaries exhibited slowed-down RBC during CSD and RBC velocity remained low in 2 even after the passage of CSD. On the other hand, RBCs with moderately (<3 mm/sec) or remarkably (>3 mm/sec) increased velocities were seen in 10 and 5 capillaries, respectively.

Conclusion: CSD-induced excitation of neurons may sustainably decrease or greatly increase RBC velocity in capillaries.

Key words: confocal fluorescence microscopy, cortical spreading depression, neuro-capillary coupling, red blood cell velocity, thoroughfare channel

Abbreviations used: ABP, arterial blood pressure; CBF, cerebral blood flow; CSD, cortical spreading depression; DC, direct current; EEG, electroencephalogram; FITC, fluorescent isothiocyanate; LDF, laser Doppler flowmeter; MABP, mean arterial blood pressure; PO_2, partial tissue pressure of oxygen; RBC, red blood cell.

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INTRODUCTION

CSD is a phenomenon involving mass depolarization of neurons and glial cells, followed by sustained suppression of spontaneous neuronal activity [14]. It is accompanied by various changes in blood flow and energy metabolism [6], and is thought to be involved in the mechanisms of various pathological conditions, such as migraine [12]. CSD has been experimentally elicited with a variety of chemical, electrical and mechanical stimuli in various animals, and research in animal models has provided information about its pathological role, as well as clues to potential clinical therapies. Artificially evoked CSD spreads through the cortical tissue from the initiation site toward the periphery at a rate of 2–5 mm/min, with suppression of the EEG [3], deflection of DC potential, and repetitive changes in light transmission [31]. CSD induces marked increases in glucose utilization and metabolism in the cerebral cortex [21], and the cerebral metabolic rate of oxygen shows a prolonged increase [18]. This elevation of oxygen consumption often leads to tissue hypoxia [25], and changes in PO_2 elicited by CSD are closely linked to CBF changes [11].

The response of CBF to CSD is complex, being mediated by the production and release of multiple vasodilating and vasoconstricting factors by diverse cells within the neurovascular unit [5]. Although it is accepted that hyperemia during CSD is followed by a long-lasting reduction to

below the prestimulus level [13], some findings are not necessarily consistent with this, especially with respect to vasoconstrictive response [3,8,10,15,16].

Various flow control systems of cerebral vessels serve to supply blood to the capillaries at levels sufficient to meet local neuronal requirements. RBC behavior in capillaries is especially important, as RBCs are the predominant oxygen carrier from the lung to the tissue. We have reported the detection of high-velocity RBCs in urethane-anesthetized rats, using a high-speed camera laser-scanning confocal fluorescence microscope system with Matlab-domain tracking software, KEIO-IS2, developed by us [19,27,33]. We found that RBC velocity in intraparenchymal capillaries was often independent of upstream arteriolar blood flow or tissue perfusion in the surrounding microvasculature. When local CBF was dramatically increased by topical application of nitric oxide on the brain surface, "microflow" in capillaries was rather decreased, while "RBC velocity" remained unchanged [28]. "RBC flow" in capillaries seems to be actively controlled in response to neuronal requirements, that is, there appears to be a neuro-capillary coupling [32].

The nature of RBC flow change during CSD is still controversial; reports have indicated an increase in adult mice [25], a drop and cessation of flow in neonatal rats [7], and a decrease in adult rats [30,32]. In this study, to examine the influence of neuronal activity on RBC velocity in nearby capillaries in terms of the neuro-capillary coupling hypothesis, we evaluated electrophysiological changes, tissue level of oxygen and CBF simultaneously with measurement of RBC velocity in capillaries in response to potassium-induced CSD.

MATERIALS AND METHODS

General Procedures

Animals were used with the approval (No. 09058) of the Animal Ethics Committee of Keio University (Tokyo, Japan), and all experimental procedures were in accordance with the university's guidelines for the care and use of laboratory animals. Male Sprague–Dawley rats (CLEA Japan, Inc., Tokyo, Japan) (10–15 weeks, $n = 26$) were anesthetized with isoflurane (2.5–3.0% in room air with flow rate of 250 mL/min) via a concentration-controllable anesthesia unit (400; Univentor Ltd., Zejtun, Malta). Body temperature was maintained with a heating-pad and thermo-controller (BWT-100; Bioresearch Center Co., Ltd., Nagoya, Japan). Each rat was fixed to a head-holder (SG-4N, modified to be flexible around the horizontal axis; Narishige Scientific Instrument Laboratory, Tokyo, Japan) and a cranial window of approximately 4 mm in diameter was opened in the left side of the skull at the parieto-temporal region of the cerebral cortex. The dura was carefully removed and the exposed cortex was covered with a coverslip to prevent it from drying out. CSD was induced by applying a drop (5 μL) of 1.0 M KCl solution into an additional posterior hole of 2 mm in diameter having its center at the coordinates of 7 mm posterior and 2 mm lateral to the bregma. ABP was continuously recorded through a femoral arterial catheter via a surgical strain-gage (MLT0670 and ML117; ADInstruments Pty. Ltd., Bella Vista, NSW, Australia). KCl solution was administered after confirmation that all parameters had remained stable for at least 10 minutes. Animals in which all parameters were still stable at more than 30 minutes after the last CSD episode were given a further application of KCl solution.

Measurement of PO_2 and CBF

An oxygen electrode (POE-10N; Bioresearch Center Co., Ltd.) with a tip diameter of 200 μm was inserted 300 μm under the pia mater at the coordinates of 2 mm posterior and 0.5 mm lateral to the bregma (medial edge of the cranial window) and fixed with dental cement (see Figure 1). A reference electrode (POR-10N; Bioresearch Center Co., Ltd.) was placed subcutaneously in the back. PO_2 was continuously monitored with an oxygen monitor (PO2-100DW; Inter Medical Co., Ltd., Nagoya, Japan). CBF was monitored with a laser Doppler flowmeter (LDF, ALF 21R; Advance Co., Ltd., Tokyo, Japan). The probe, having a diameter of 0.8 mm, was placed on the surface of the cortex at the coordinates of 2 mm posterior and 4 mm lateral to the bregma (lateral edge of the cranial window; see Figure 1).

Measurement of DC Potential and EEG

Two Ag/AgCl electrodes (tip diameter = 200 μm, EEG-5002Ag; Bioresearch Center Co., Ltd.) were inserted

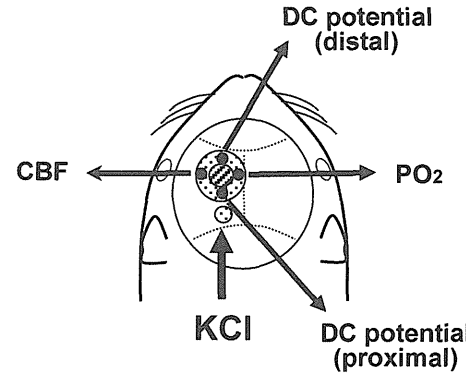

Figure 1. Positioning of electrodes for DC potential and EEG measurement, an electrode for PO_2, and an LDF probe in the cranial window. Flow of FITC-labeled RBCs was recorded with a high-speed camera laser-scanning confocal fluorescence microscope at the center of the cranial window as shown by a dotted circle. KCl solution was administered into the posterior burr hole.

200 μm under the pia mater at the anterior edge (0.5 mm posterior and 2 mm lateral to the bregma) and posterior edge (3.5 mm posterior and 2 mm lateral to the bregma) of the cranial window, and fixed with dental cement (see Figure 1). The locations of the electrodes and the probe were sometimes slightly moved to avoid a large vessel. Ag/AgCl reference electrodes (EER-5004Ag; Bioresearch Center Co., Ltd.) were subcutaneously placed in the space between the skull-bone and the scalp. DC potential was amplified at 1–100 Hz and digitized at 1 kHz with a differential headstage and differential extracellular amplifier (Model 4002 and EX1; Dagan Co., Minneapolis, MN, USA). The signal of DC potential was further digitally filtered with a 5 Hz low cut, to minimize the basal fluctuation due to heart rate and breathing, to obtain the EEG.

Analysis of RBC Velocity

FITC-labeled RBC suspension, prepared beforehand according to Seylaz *et al.* [20], was injected into the bloodstream through the venous catheter so that the final percentage of FITC-labeled RBCs/total RBCs in the circulating blood was approximately 0.4%. The velocity of FITC-labeled RBCs was automatically calculated using the high-speed camera (500 fps) laser-scanning confocal fluorescence microscope and the image analyzing system with MATLAB (The MathWorks, Inc., Natick, MA, USA) environment application software (KEIO-IS2) developed in our laboratory [19], as reported elsewhere [27]. The images acquired with the high-speed system could be recorded only for up to 15 seconds due to the limitation of file size (2 GB) in our analysis system. With reference to the alternatively recorded images obtained using a conventional video camera, we discriminated single capillaries from other vessels such as arterioles and venules, by using the criterion that capillaries should have a diameter of <10 μm [9,35]. The frequency distribution was obtained by classification of velocities in steps of 0.5 mm/sec and counting the RBCs within each step [33].

Data Analysis

ABP, PO_2, CBF, DC potential, and EEG were recorded continuously. The data were stored on a multichannel recorder (PowerLab 8/30; ADInstruments Pty. Ltd.) and analyzed off-line with LabChart software (ADInstruments Pty. Ltd.). The time courses of the responses of PO_2, CBF, and DC potential were determined by taking time zero as the point at which the DC potential at the proximal portion began to decrease. The trough and peak of PO_2, the peak of CBF, and the trough of DC potential were estimated. CSD duration was estimated as the period till the recovery rate became minimal. The response and delay times of the parameters were determined for each CSD episode, and were averaged for each application of KCl. CSD propagation speed was calculated based on the time and the distance between the two recording electrodes. ABP was averaged for one minute before and for every 15 seconds after the beginning of deflection of DC potential at the proximal portion. Post-CSD oligemia was evaluated as the average of the minimum CBF after the last CSD episode elicited by a single application of KCl.

Statistical comparison of RBC velocities between different periods was performed with nonparametric multiple comparison (Games–Howell test) after confirmation of homogeneity of variance with one-way ANOVA (Kruskal–Wallis test). Statistical comparison of two groups was performed with Student's *t*-test. Average data are presented as mean ± SD and a *p*-value of <0.05 was considered to be statistically significant.

RESULTS

General Results

The body weight of the rats was 402 ± 83 g. The initial level of MABP was 77 ± 11 mmHg. MABP was maintained within ±20 mmHg in each rat throughout the experiments, and did not decrease below 60 mmHg in any rat.

As shown in Figure 2A, one application of KCl induced repetitive (between 3 and 16 times) negative deflections of DC potential (i.e., CSD). CSD was detected first at the posterior (proximal) portion, and then at the anterior (distal) portion with a delay time of 27 to 110 seconds. Every CSD episode was accompanied by a long-lasting decrease in EEG amplitude, occasionally preceded by a transient increase. As CSD occurred, PO_2 transiently declined, followed by a slight increase, while CBF slowly increased, then returned toward the baseline. MABP was constant during repetitive CSD after KCl application, namely, the CBF responses were locally elicited, not due to change in systemic blood pressure.

Occasionally, unusual responses were observed. In four applications of KCl among 25 applications for which all parameters were successfully measured, CBF was transiently decreased, followed by a slight increase to above the baseline during CSD, as shown in Figure 2B. In seven rats, oppositely propagated CSD was found, namely CSD was detected first at the anterior (distal) portion and then detected at the posterior (proximal) portion, as illustrated in Figure 2B (second episode of CSD). In total, 11 episodes of CSD out of 162 were oppositely propagated with a time difference of 59.5 ± 56.0 seconds (vs 55.5 ± 28.2 seconds for forward propagated episodes in the same rats). Such CSD was observed only after the second or a later episode in the series of CSD episodes induced by a single KCl application.

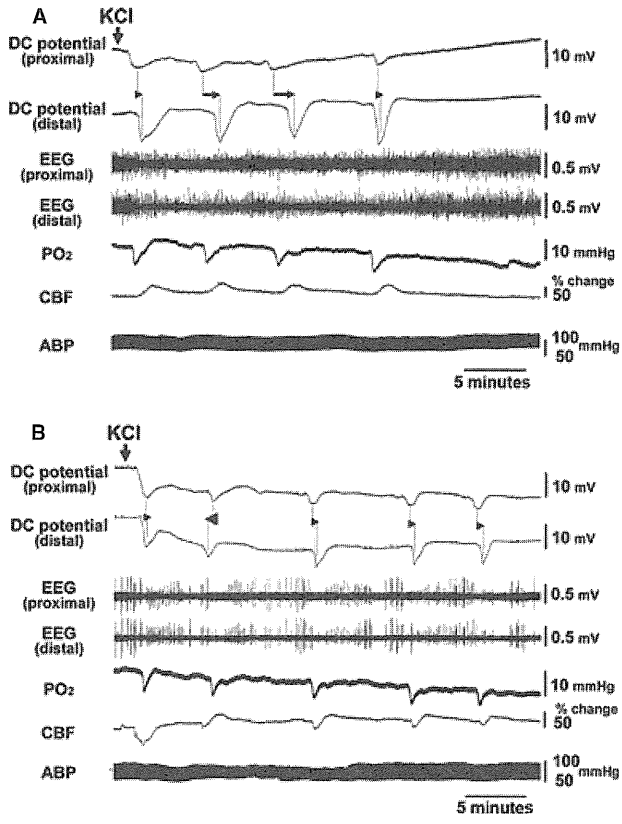

Figure 2. Changes in DC potential, EEG, PO_2, CBF, and ABP in response to KCl application. Typical signals are shown in (**A**). DC potential deflection detected at the proximal portion propagated to the distal portion, as shown with arrows. Occasionally, CBF showed a transient decrease, followed by a slight increase during CSD, and/or DC potential deflection was detected first at the distal portion, as shown with the reversed arrowhead (**B**).

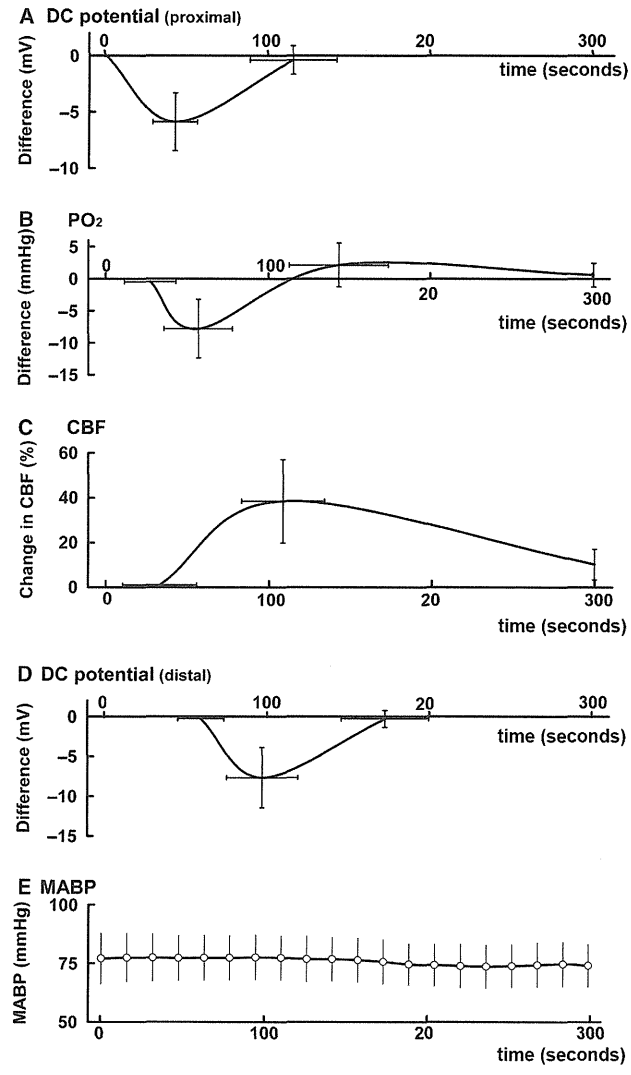

Figure 3. Average response curves of DC potential (proximal portion, **A** and distal portion, **D**), PO_2 (**B**), CBF (**C**), and MABP (**E**) following KCl application. The onset of the DC potential suppression at the proximal portion was defined as time zero. Values of delay time and peak changes are mean ± SD and points were connected with a smooth curve (**A**–**D**). ABP was averaged over every 15 seconds in each rat and plotted as mean ± SD (**E**).

Physiological and Electrophysiological Responses to CSD

On average, 6.5 ± 3.2 episodes of CSD were elicited by one application of KCl. The averages of the responses and delay times of the parameters in 21 applications of KCl in 14 rats are summarized in Figure 3. First, deflection of DC potential at the posterior (proximal) portion was detected (Figure 3A). Secondly, PO_2 began to decrease with a delay of 27.6 ± 15.7 seconds and reached the lowest level (−7.4 ± 3.6 mmHg), followed by a slight increase (+2.6 ± 3.8 mmHg) (Figure 3B). CBF began to increase with a delay of 33.5 ± 22.4 seconds, reached the highest level (+38.5 ± 18.6%) at a time 1.83 times longer than in the case of DC potential deflection, and then gradually declined to the baseline (Figure 3C). Finally, deflection of DC potential was detected at the anterior (distal) portion with a delay time of 54.6 ± 22.1 seconds (Figure 3D). Propagation speed from the proximal to the posterior side was calculated as 3.3 ± 1.3 mm/min according to the distance between the electrodes. MABP did not change for five minutes after CSD elicitation (Figure 3E). Post-CSD oligemia was not observed in this experiment, as indicated by the minimum CBF after the last CSD episode (+5.9 ± 21.1%).

Change in RBC Velocity in Capillaries

Confocal microscopic movies for the analysis of RBC velocity were recorded for 10–15 seconds at representative periods, before KCl application (Before-KCl), just after the trough of DC potential deflection at the proximal portion was detected (Intra-CSD), between CSD when all parameters

had returned to the baseline (Inter-CSD), and approximately one hour after KCl application, when CSD had ceased (After-CSD), as shown in Figure 4A. In the Intra-CSD period, DC potential at the center of the cranial window was presumed to be included within the negative deflection according to the time course of the response (Figure 3).

For each recording period, we obtained the frequency distribution as defined in Materials and Methods. In the Before-KCl period, the mean RBC velocity was 2.02 ± 1.58 mm/sec for 551 detected RBCs (12 rats, total recording time 176 seconds). RBC velocities peaked at around 1.0–2.0 mm/sec, but showed tailing to higher velocities, up to 9.3 mm/sec; 66% of the velocity values lay within the range of 0.5–2.0 mm/sec (Figure 4B). These results are comparable to those in our previous report [33]. In the Intra-CSD period, mean RBC velocity was 1.95 ± 1.80 mm/sec for 802 detected RBCs (12 rats, total recording time 353 seconds). The frequency distribution apparently shifted downward with a reduction in the number of RBCs having a velocity of around 2 mm/sec. Unexpectedly, velocity remained low in the Inter-CSD period, even though CBF and other parameters had returned to the baseline, and the average (1.64 ± 1.52 mm/sec for 562 RBCs in 10 rats, total recording time 206 seconds) was significantly lower than in the Before-KCl period ($p < 0.01$) and the frequency distribution tended to retain its downward shift. The velocity recovered in the After-CSD period (2.18 ± 1.31 mm/sec for 232 RBCs in nine rats, total recording time 188 seconds). Throughout the Intra- and Inter-CSD periods, RBCs with velocities higher than 3 mm/sec remained, but RBCs with velocities lower than 3 mm/sec showed an apparent shift toward slower velocities.

Next, we evaluated RBC velocity in a single capillary for each record period. Capillaries in which moving RBCs were detected both before and after KCl application were picked up from the velocity data (38 capillaries in total). The changes are plotted in Figure 5A–C. RBC velocity in 10 capillaries decreased in the Intra-CSD period (Figure 5A). Within such capillaries, RBC velocity in two capillaries remained low even after passage of CSD, as indicated by arrows, whereas other capillaries showed full or partial recovery of RBC velocity. In contrast, RBC velocity in 20 capillaries increased in the Intra-CSD period. Among the capillaries with accelerated RBCs, we found 15 capillaries in

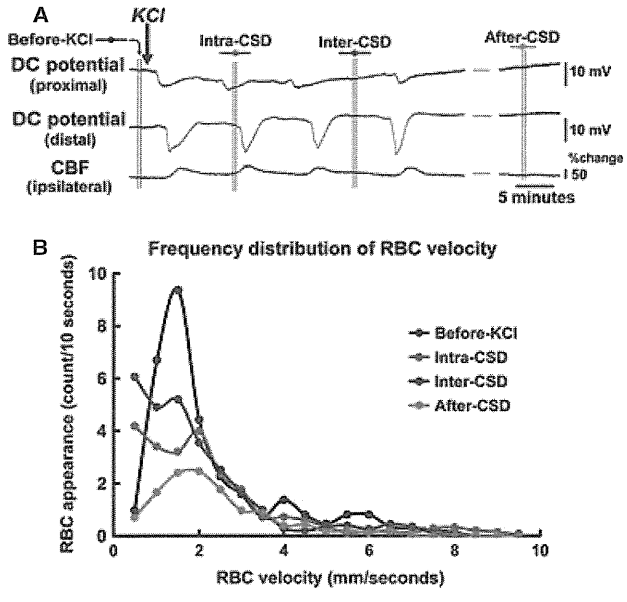

Figure 4. Analysis results of RBC velocities in capillaries. The motion pictures using the high-speed camera laser-scanning confocal fluorescence microscope were obtained at the times shown in (**A**); before KCl application (Before-KCl; black circle and line), just after the trough of DC potential deflection at the proximal portion was detected (Intra-CSD; red circle and line), several minutes after the DC potential at both portions had recovered (Inter-CSD; blue circle and line) and at one hour after KCl application (After-CSD; green circle and line). (**B**) Frequency distribution of RBC velocities in single capillaries in which the velocities of detected RBCs were counted for every 0.5 mm/sec step and RBC appearance per 10 seconds were plotted.

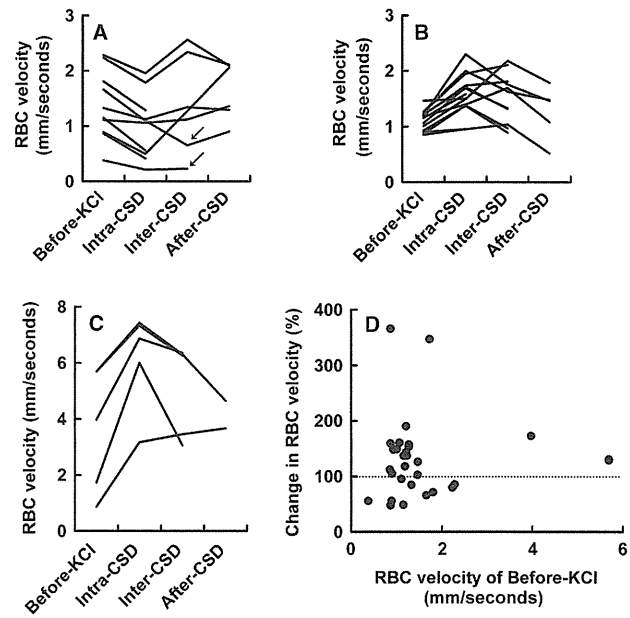

Figure 5. Profiles of RBC velocity in 30 capillaries: plotted for the Before-KCl, Intra-CSD, Inter-CSD, and After-CSD periods. (**A**) RBC velocity in 10 capillaries decreased in the Intra-CSD period. Velocity in two capillaries was still low after passage of CSD (Inter-CSD period) as indicated by arrows. (**B**) Increase in RBC velocity in 15 capillaries in the Intra-CSD period, in which velocity did not exceed 3 mm/sec. (**C**) RBC velocity in five capillaries was remarkably increased (>3 mm/sec) in the Intra-CSD period. (**D**) Scatter diagram of change in RBC velocity in the Intra-CSD period versus the velocity within the identical capillary before KCl application.

which RBC velocity did not exceed 3 mm/sec (Figure 5B) and five capillaries in which RBC velocity was remarkably increased (>3 mm/sec), then returned toward the basal level (Figure 5C). In eight capillaries, moving RBCs could not be detected in the Intra-CSD period, but appeared after CSD passage (Inter-CSD; data not shown). Next, we calculated RBC velocity changes from the period of Before-KCl to Intra-CSD. There was no correlation between basal velocity in the Before-KCl period and velocity change between the period of Before-KCl and Intra-CSD (Figure 5D).

Furthermore, moving RBCs were followed in a certain ROI and tracked with KEIO-IS2 (Figure 6). Capillaries with slowed-down RBCs and those with accelerated RBCs did not appear to be confined to any specific location, but rather were located together in similar regions. The five capillaries in which RBC velocity was greatly increased in the Intra-CSD period (Figure 5C) were all straight; an example is shown with a green solid arrow in Figure 6A.

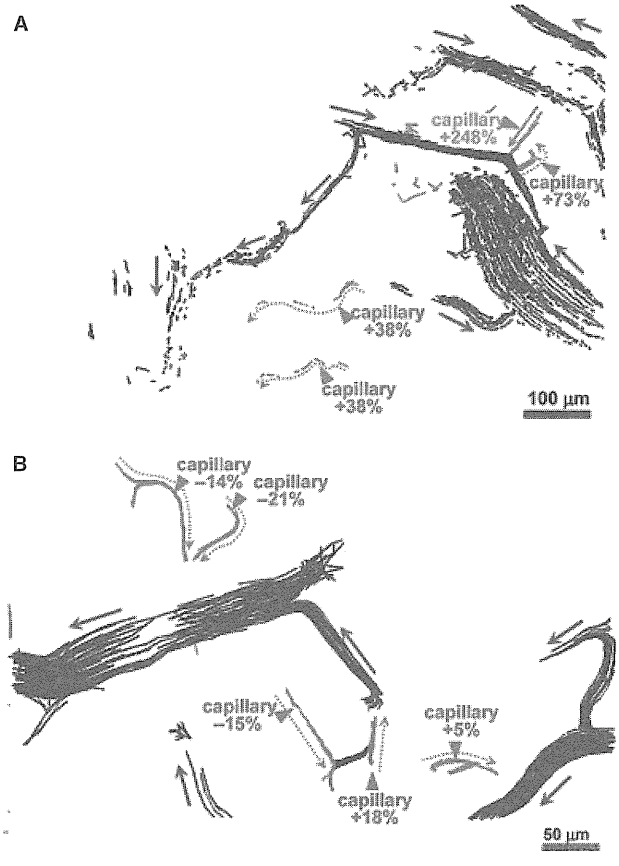

Figure 6. RBC tracking map indicating RBC movement in various vessels. These maps were calculated with KEIO-IS2 from 5000 frames (10 seconds) obtained with the high-speed camera laser-scanning confocal fluorescence microscope in different rats (**A**, **B**). RBC tracks flowing in capillaries are highlighted in red. RBC flow direction in major veins and venules is indicated with blue arrows. Capillaries in which RBC velocities could be calculated in both the Before-KCl and Intra-CSD periods are shown with the velocity changes (%), with the flow direction indicated by green dotted arrows. Greatly accelerated RBCs in a capillary are shown with green letters and a green solid arrow (**A**).

DISCUSSION

CSD-Induced Changes in Metabolism and CBF

MABP of the rats appears to be slightly low, possibly due to the effect of anesthesia, but the values of all rats were within the range of autoregulation and remained quite stable during experiments, so that cerebral circulation seems not to be substantially affected by ABP.

The response of cerebral metabolism to CSD has been well studied. As the wave of CSD passes, the cerebral metabolic rate is increased and the inadequate O_2 supply leads to stimulation of anaerobic glycolysis [10]. Significantly increased O_2 consumption is coupled to an augmentation of blood flow without change in O_2 extraction, suggesting that delivery of O_2 is not an important factor in the cerebral metabolic response to CSD [15]. The decrease in PO_2 which preceded the CBF response in our experiment appears to confirm that metabolic enhancement is due to potassium-induced neuronal activation, not due to the change in CBF.

On the other hand, PO_2 elevation seems to be dependent on CBF increase, as the CSD-induced elevation of PO_2 after transient hypoxia was roughly proportional to blood flow elevation [11], and regional CBF and PO_2 were simultaneously increased in response to CSD [36]. However, we recorded various parameters simultaneously and continuously with ipsilaterally fixed electrodes and probe. Thus, we have obtained convincing evidence that CSD facilitates energy metabolism, thereby consuming oxygen, and the regional hypoxia induces CBF elevation; furthermore, the subsequent elevation of PO_2 is at least partly due to CBF increase in our experiment.

Hypoperfusion After CSD

It has been reported that CSD elicits CBF increase followed by long-lasting decrease, namely post-CSD oligemia [8,13,38]. However, we did not observe prolonged hypoperfusion in our experiment. The reason for the difference is unclear, but may be related to differences in species, anesthesia, method of eliciting CSD, experimental conditions, and so on.

Initial transient hypoperfusion was seen in only three rats in this experiment. Brief hypoperfusion preceding hyperemia has already been reported [8,22,31]. The duration of initial hypoperfusion was correlated with the duration of the DC shift in rats [2]. Hypoxia and/or hypotension amplified the hypoperfusion and diminished the subsequent hyperemia after CSD [23]. A remarkable

initial decrease in CBF was reported to be associated with hypotension [24]. We did not find any correlation of initial hypoperfusion with the duration of the DC shift (92–146 vs 80–160 seconds in the group without hypoperfusion), with frequency of CSD occurrence (3–7 vs 3–16 times), with propagation speed (3.4–8.5 vs 1.6–6.5 mm/min), or with MABP (72 ± 1 vs 77 ± 11 mmHg). CSD-induced vasoconstriction seems to counteract vasodilation [5]. Initial vasoconstriction was observed both in rats and in mice, but the response was much larger in mice [2]. Overall, the vasoconstriction appeared to be suppressed under our experimental conditions, although it might be augmented in some cases.

Retrograde Propagation of CSD

Retrogradely propagated CSD was observed in 6.7% of CSD episodes in this experiment. Such CSD was found at the second or a later episode elicited by a single application of KCl. Approximately 40% of spreading depression waves penetrated through the amygdala into the caudate nucleus, and 70% of these waves returned to the cortex and spread through it toward the site of initiation, namely, a re-entry path for cortico-caudate-cortical propagation was demonstrated [34]. The ratio of the assumed return of CSD waves in our experiment was lower than that previously reported. We observed repetitive CSD in response to KCl application, whereas a single CSD wave was elicited with a small amount of KCl microinjection or electrical stimulation in the literature. The role of the basal ganglion in migraine remains unclear, but it must be involved in the pathogenesis of migraine. Indeed, cortically induced CSD evoked freezing behavior via activation of the amygdala, as indicated by enhancement of c-fos expression in the cerebral cortex and amygdala, in freely moving rats [1]. Increase in CSD due to reentry may result in enhancement of headache. Furthermore, it should be noted that cortico-caudate-cortical propagation may be influenced by external factors, such as stress, so that neuronal activity in the amygdala may be susceptible to modulation by various stimuli.

CBF and RBC Velocity

Theoretical O_2 extraction (E) at capillaries is dependent upon RBC velocity according to the classic Crone–Renkin equation: $E = 1 - e^{PS/f}$, where P is a constant related to the permeability, S corresponds to the capillary surface area, and f is the flow, which is linearly related to RBC velocity [26]. According to this relationship, a slower RBC velocity is more effective for exchange of O_2 between capillary and brain tissue. A transient increase in neuronal and/or glial activity associated with CSD may enhance the local capillary flow resistance, resulting in a reduction in RBC velocity [32]. Thus, a decrease in RBC velocity may enhance O_2 exchange efficiency to satisfy an increase in O_2 demand.

Examination of the effect of CSD on vascular function provides a means to explore the significance of neurovascular coupling under pathophysiological conditions. For this purpose, investigation of microcirculation, including capillary flow, seems to be effective. Line scanning by means of two-photon microscopy showed a prolonged period of increase in capillary flow, with a duration of up to several minutes, followed by a sustained decrease in capillary flow after CSD induction in adult mice [25]. This indicates that CSD induces a transient increase in local perfusion followed by a prolonged oligemia. We did not find post-CSD oligemia with LDF, but a sustained decrease in RBC velocity may indicate the presence of local oligemia after the passage of CSD in this experiment. A decrease and transient cessation of capillary flow were observed in neonatal rats [7]. We have also demonstrated transient slowing, with occasional full stop, of RBC flow in a single capillary in adult rats [30,32]. In the present experiment, decrease in RBC velocity was found during CSD (Intra-CSD) in some capillaries, and the velocity in a subset of such capillaries remained low even after passage of CSD (Inter-CSD). This indicates that the suppressive effect on RBC velocity is persistent, at least in some capillaries. In several capillaries, moving RBCs were not detected during CSD (Intra-CSD), but appeared after passage of the CSD wave (Inter-CSD). RBC flow stop may occur in such capillaries during CSD. As described in our previous report [32], it took several minutes for slowed-down RBC flow to return to the baseline level. As the DC potential deflection returned to the baseline level within one minute, slowed-down RBC flow can still be seen after the CSD wave has passed.

We observed not only slowed RBCs but also accelerated RBCs during CSD. Furthermore, we found some RBCs with extremely high velocities during CSD, and the capillaries in which these RBCs ran were straight. We have previously reported RBCs running at ultra-high velocity in single capillaries (up to 9.4 mm/sec); these RBCs might be missed with a conventional low-speed camera (30 fps), and the vessels may be thoroughfare channels or non-nutritional capillaries [33]. Our present results are consistent with the idea that the highly accelerated RBCs flow in thoroughfare channels and contribute at least in part to the elevation of CBF.

The increased CBF measured with LDF and the slowed-down RBC flow during CSD seem to be paradoxical. A similar phenomenon, that is, decreased RBC flow in some capillaries, was observed when regional CBF was greatly increased by topical application of nitroprusside (a nitric oxide donor) on the brain surface [28]. Inhomogeneous vasoreactivity to CSD was established by the observation that in smaller pial arteries, the initial vasoconstriction was limited and the subsequent vasodilation was more marked during CSD, whereas a much larger vasoconstriction and

smaller vasodilation were found in intracortical arterioles [7]. LDF provides the average blood flow of such inhomogeneous vessels to a depth of approximately 1 mm, and the value obtained is the product of RBC velocity and RBC flux. The observation area and the focus range in our experiment were limited to approximately 50 μm in thickness at the depth of layer I, and we focused on capillary flow, without arterioles or venules. Thus, possible reasons for the paradox may be as follows: vasoreactivity may vary with depth or with the types of vessels; the change in blood flow in the limited layer observed in our experiment may be different from the value indicated by LDF; or RBCs may pass through non-flowing or sparsely flowing capillaries during CSD (RBC recruitment), resulting in an increase in net flux of RBCs.

Neuro-Capillary Coupling

Heterogeneity of the changes in RBC velocity in capillaries and of the location of such capillaries was observed in our experiments. This means that RBC flow in capillaries within a small region is not uniformly controlled by the upstream arteriole. Rather, the capillary RBC flow seems to be actively controlled in response to neuronal requirements. A close correlation between topographical microflow and light transparency changes after topical application of potassium indicated that local depolarization of the neurons induces an immediate decrease, rapidly followed by an increase in microflow [29]. Transient constriction of parenchymal arterioles, often forming spindle-shaped strings, was reported in the early phase of CSD, followed by marked dilation [17]. CSD induced neuronal swelling in anesthetized mice [25] and in cortical slices of rodents [39], but both studies found that the cell volume of astrocytes did not change. However, we observed a morphological change in astrocytes during CSD [32]. Furthermore, a significant role of pericytes in neurovascular function was recently demonstrated [4]. Pericyte contraction induced by oxidative–nitrative stress caused capillary constriction and reduced RBC flow in mouse brain slices [37]. In addition to these facts, the results of our experiments provide further support for the hypothesis that the depolarized neurons alter adjacent capillary resistance through some physical and/or hemorheological mechanism, such as local cellular changes, that is, the phenomenon of so-called neuro-capillary coupling might be involved [32].

CONCLUSIONS

Administration of KCl onto the surface of the cerebral cortex induces repetitive CSD episodes, which involve DC potential deflection and propagate in the distal direction. Enhanced metabolism induces a PO_2 decrease (local hypoxia) and CBF increase to meet the enhanced requirement of O_2. Decrease in RBC velocity may enhance O_2 exchange efficiency to meet the increased O_2 demand, while RBC flow in some capillaries may be greatly enhanced, thereby contributing to the CBF elevation during CSD.

PERSPECTIVE

Potassium application elicited CSD accompanied with transient neuronal excitation and increase in CBF and metabolism in rats. We observed heterogeneous modulation of RBC velocity, including sustained decrease and remarkable increase. Whereas accelerated RBCs may be associated with CBF elevation, slowed-down RBCs may suggest the presence of a regional regulatory mechanism of capillary flow in brain.

ACKNOWLEDGMENTS

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RESEARCH ARTICLE

Effects of Trigger Point Acupuncture Treatment on Temporomandibular Disorders: A Preliminary Randomized Clinical Trial

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trigger point

Abstract
We compared the effects of trigger point acupuncture with that of sham acupuncture treatments on pain and oral function in patients with temporomandibular disorders (TMDs). This 10-week study included 16 volunteers from an acupuncture school with complaints of chronic temporomandibular joint myofascial pain for at least 6 months. The participants were randomized to one of two groups, each receiving five acupuncture treatment sessions. The trigger point acupuncture group received treatment at trigger points for the same muscle, while the other acupuncture group received sham treatment on the trigger points. Outcome measures were pain intensity (visual analogue scale) and oral function (maximal mouth opening). After treatment, pain intensity was less in the trigger point acupuncture group than in the sham treatment group, but oral function remained unchanged in both groups. Pain intensity decreased significantly between pretreatment and 5 weeks after trigger point ($p < 0.001$) and sham acupunctures ($p < 0.050$). Group comparison using the area under the curve demonstrated a significant difference between groups ($p = 0.0152$). Compared with sham acupuncture therapy, trigger point acupuncture therapy may be more effective for chronic temporomandibular joint myofascial pain.

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1. Introduction

Myofascial pain is the most common temporomandibular disorder (TMD) [1]. This condition has also been called facial arthromyalgia, temporomandibular joint (TMJ) dysfunction syndrome, myofascial pain dysfunction syndrome, craniomandibular dysfunction, pain dysfunction syndrome, and myofascial pain dysfunction. The etiology of myofascial pain is multifactorial [2]. Consequently, many different therapies—some conservative, reversible, or irreversible—have been advocated for patients with myofascial pain. A number of successful treatments have been reported such as physiotherapy [3] and pharmacologic interventions [4].

TMD is basically treated using conservative approaches such as occlusal splints, occlusal adjustment, jaw exercise, and counselling, but other options have been used with good clinical results [5–7]. Acupuncture has been reported to have a beneficial role in the management of TMD [5,8–10]. Five randomized controlled trials found that the beneficial effects of acupuncture were similar to those of stabilization splint therapy in the management of TMD [11]. However, a systematic review found no trials with controls for the possible placebo effects of acupuncture, although studies suggest that acupuncture is effective in the treatment TMJ pain and dysfunction [11]. Therefore, due to lack of adequate controls for the placebo effect of acupuncture, the true efficacy of acupuncture has yet to be ascertained.

Our main aim in this study was to determine whether acupuncture at trigger points (compared with sham acupuncture treatment) is an effective treatment for chronic TMJ myofascial pain.

2. Methods

2.1. Patients

Students of an acupuncture school in Kyoto, Japan (Meiji University of Integrative Medicine), who had been clinically diagnosed as having TMD were recruited. Inclusion criteria were (a) orofacial pain lasting for 6 months or longer, (b) a Helkimo clinical dysfunction index of I or III, (c) no acupuncture in the previous 6 months, and (d) failure to respond to the medications prescribed by a specialist. Exclusion criteria were (a) major trauma or systemic disease, and (b) other conflicting or concurrent treatments. A total of 16 patients (five women, 11 men aged 19–24 years) who gave written informed consent were enrolled and randomly allocated to a trigger point acupuncture (TrP) group or sham (SH) group by use of a computerized randomization program. Ethical approval for this protocol was given by the ethics committee of Meiji University of Integrative Medicine.

2.2. Design

This clinical trial was a single-blinded, randomised, sham-controlled trial that used block randomisation to allocate patients to receive one of the two different acupuncture treatments. Each patient received a total of five treatments, one per week, each lasting 30 minutes, and follow-up measurements were taken at 10 weeks after the first treatment.

2.3. Blinding

Patients were blinded to their treatment assignment. They were told before randomization that they would be allocated to one of two groups. The measurements were performed by an independent investigator who was not informed about the treatment sequence or the treatment the patient received before each measurement. Prior to treatment, the patients covered their eyes with an eye mask to ensure that they did not know which treatment they were receiving.

2.4. Treatment

2.4.1. TrP group

The TrP group received treatment at myofascial trigger points. The correct application of the technique requires experience in palpation and localization of taut muscle bands and myofascial trigger points. Precise needling of active myofascial trigger points provokes a brief contraction of muscle fibers. This local twitch response should be elicited for successful therapy, but it may be painful and post-treatment soreness is frequent [1,12]. In this study, the most important masticatory and cervical muscles were examined for myofascial trigger points (Table 1).

Disposable stainless steel needles (0.2 mm × 50 mm, Shizuoka-shi, Shizuoka, Japan, Seirin) were inserted into the skin over the trigger point to a depth of 5–15 mm, appropriate to the muscle targeted, and the 'sparrow pecking' technique was used to elicit a local muscle twitch response. After the local twitch response was elicited or a reasonable attempt made, the needle was retained for a further 15 minutes. The mean number of insertions was 4.2.

2.4.2. SH group

The SH group also received treatment at myofascial trigger points. The methods of choosing trigger points were the same. Similar stainless steel needles (0.2 mm × 50 mm, Shizuoka-shi, Shizuoka, Japan, Seirin) were used, but the tips were cut off to prevent the needle from penetrating the skin. The cut ends were manually smoothed with sand paper under clean conditions [13]. The acupuncturist

Table 1 Muscles treated in the two trigger point acupuncture groups.

Muscle	Trigger point group	Sham group
Temporalis	4	5
Masseter	7	8
Lateral pterygoid	7	8
Digastricus	2	2
Sternocleidomastoideus	4	4
Trapezius	5	4
Splenius capitis	1	3
Other	1	4

pretended to insert the needle and to use the 'sparrow pecking' technique, then removed the needles. A simulation of needle extraction was performed after 10 minutes by touching the patient and noisily dropping needles into a metal case. The mean number of insertions was 4.8.

The acupuncture was performed by an acupuncturist with 4 years of acupuncture training and 3 years of clinical experience.

2.5. Evaluation

Primary outcome measures were pain intensity during daily activities such as eating and talking, quantified on a 10-cm visual analogue scale [(VAS) 0—100 mm], and oral function assessed by measuring maximal mouth opening (MMO). The pain VAS score was assessed immediately before the first treatment and at 1, 2, 3, 4, 5, and 10 weeks after the first treatment. The MMO was measured before the first treatment and 5 and 10 weeks after the first treatment. The VAS and MMO measurements were completed by participants immediately before each treatment.

To examine the efficacy of the blinding technique used in the study, the participants were asked to select an answer to the question, "How did you feel when the acupuncture needle was inserted?" This question was asked at the end of the first phase. The available answers were: (1) "Needles were inserted into the muscle"; (2) "Needles did not penetrate the skin"; or (3) "I could not tell the difference."

2.6. Statistical analysis

The data are reported as mean ± standard deviation (SD). Dunnett's multiple comparison test was applied to detect significant changes within each group. To compare the results of two groups, the area under the curve (AUC) of pain VAS was calculated from the summation of the time-response curves for individual patients. The AUC data (arbitrary units) for each group were used for group comparison by one-way analysis of variance followed by post-hoc multiple comparisons using the Bonferroni correction.

The assessment of the success of blinding was analyzed by the chi square test. SPSS (ver 11.0, SPSS Japan Inc., Shibuya, Tokyo, Japan) software for Windows or SYSTAT 11 (SYSTAT Software Inc., Washington, Chicago, USA) was used for the statistical analysis. A p value < 0.050 was defined as statistically significant.

3. Results

3.1. Patient characteristics

No between-group differences were found in age, pain duration, pain intensity (VAS), and drug use, all of which were measured at baseline (Table 2).

A flow chart describing patient progress through the trial is shown in Fig. 1. One patient in the TrP group dropped out due to adverse effects (worsening of symptoms). There was no between-group difference in drop-out rate ($p = 0.390$; Kruskal-Wallis test). The analyses were performed on the 15 patients who completed the study.

Table 2 Characteristics and baseline values of patients in the two groups.

	Trigger point acupuncture	Sham acupuncture
Sample size	7	8
Age (y)	21.7 ± 2.1	21.4 ± 1.4
Pain duration (y)	5.1 ± 1.8	5.0 ± 3.7
VAS (mm)	67.1 ± 19.1	65.6 ± 15.2
MMO	48.3 ± 11.9	43.6 ± 9.9
Drug user	0	0

MMO = maximal mouth opening; VAS = visual analogue scale.

3.2. VAS score

Pain intensity decreased at Weeks 2—10 in the TrP group and Weeks 4—5 in the SH group when compared with pretreatment levels, respectively. These improvements persisted 5 weeks after the cessation of treatment in the TrP group. The mean VAS score decreased significantly in both groups ($p < 0.001$ in the TrP and $p < 0.050$ in the SH groups by repeated measures of analysis of variance). This is shown in Fig. 2.

The AUCs for pain intensity (VAS score) are shown in Fig. 3. The score was significantly lower in the TrP group than in the SH group ($p = 0.003$).

3.3. Functional impairment

The MMO measurements for all patients were almost in the normal range (men, 45—60 mm; women, 40—55 mm); therefore, they did not significantly increase in either group (Fig. 4).

The AUCs of the MMO score of the two groups are shown in Fig. 5. Although higher in the TrP group than the SH group, the MMO scores were not significantly different ($p = 0.236$).

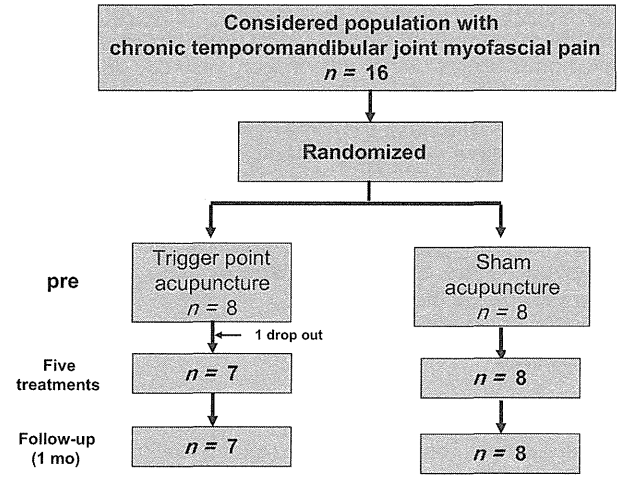

Figure 1 Participation flow in the study. One patient was excluded after she dropped out.

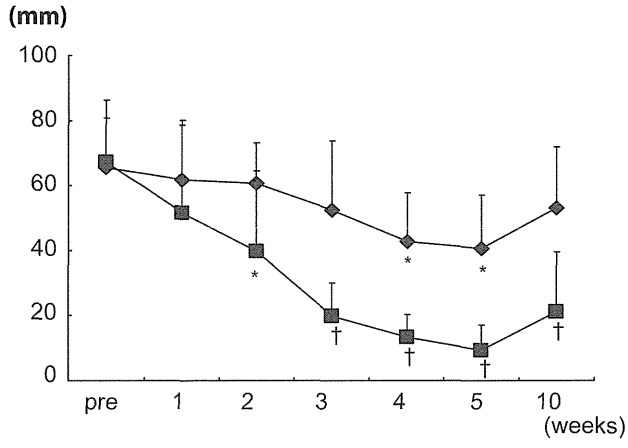

Figure 2 This shows the effect of acupuncture on VAS score for chronic temporomandibular joint myofascial pain. The pain intensity was lower at Weeks 2–10 in the trigger point acupuncture group and Weeks 4–5 in the sham group when compared with pretreatment scores. $^*p < 0.05$. †$p < 0.01$. ■ = trigger point acupuncture group ($n = 7$); ◆ = sham acupuncture group ($n = 8$). VAS = visual analogue scale.

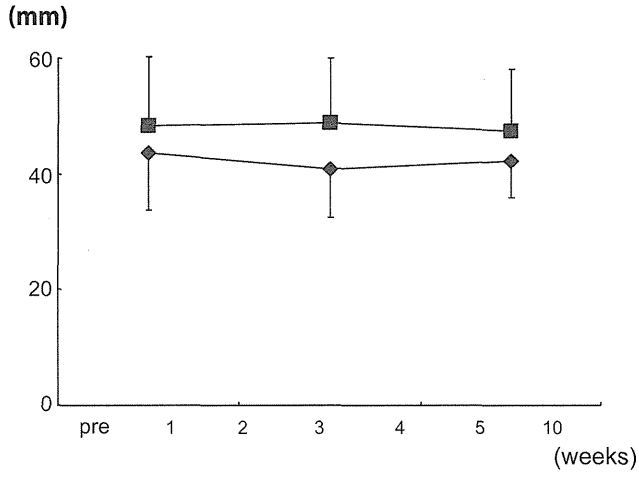

Figure 4 The effect of acupuncture on MMO score indicating oral function. The mean MMO score showed no significant increase both in the sham and in the trigger point acupuncture groups; $p > 0.05$. ■ = trigger point acupuncture group ($n = 7$); ◆ = sham acupuncture group ($n = 8$). MMO = maximal mouth opening.

3.4. Assessment of the blinding technique

All patients regardless of treatment stated that they had received needle insertion to the muscle.

4. Discussion

In the present study, there was a statistically significant difference in pain relief between the TrP acupuncture and SH acupuncture treatments. The results suggest that trigger point acupuncture treatment may be more effective than sham acupuncture treatment for chronic TMJ myofascial pain.

TMD is a major medical and social problem that causes severe discomfort and reduced ability to eat. In many cases, pain is related to deformation of the TMJ and muscle tension around the joint [9–11]. A wide range of treatments are used, including drugs, physical therapies, and manual treatments [3,4]. Acupuncture treatment has been used for pain relief for a long time. Several studies have examined the efficacy of acupuncture treatment for such conditions [9–11]; however, due to confounding methodology and lack of adequate methods of acupuncture control, the true efficacy of acupuncture has yet to be ascertained [11]. Although a high-quality controlled trial has provided evidence for relief of TMJ pain [14], there remains a need for good quality placebo controlled trials in this area.

The importance of the sham-controlled randomized clinical trial to control for the strong placebo effects of acupuncture has been debated [13,15–17]. Nabeta and colleagues [13] reported that various control groups have

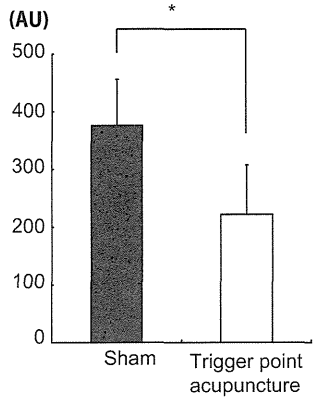

Figure 3 The columns indicate the AUC for changes in the pain VAS score in the two groups. During the observation period, improvement was greater in the trigger point acupuncture group than the sham group ($p = 0.003$). $^*p < 0.01$. AUC = area under the curve; VAS = visual analogue scale.

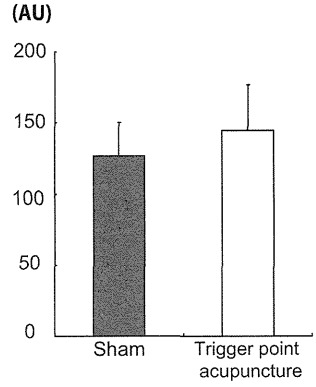

Figure 5 The columns indicate the AUC for changes in oral function in the two groups. The trigger point acupuncture group score was higher than the sham group score, but the difference was not statistically significant ($p = 0.236$). AUC = area under the curve.

been employed in acupuncture randomized controlled trials, such as no-treatment controls [18], mere pricking (without penetration) [19], minimum acupuncture (shallow and weak needling) [20], and mock transcutaneous electrical nerve stimulation [(TENS) without current pulse] [21,22]. However, in most previous studies, results were positive in studies that used a nonacupuncture control group [18,23] and negative in studies that used sham acupuncture or mock TENS as the control [24,25]. Therefore, the choice of control might have important consequences. The sham acupuncture technique used in this study was very simple. We used needles with blunt tips. The practitioner applied the same procedure for both the real and sham acupuncture treatments. Blinding in this study appears to have been successful.

Although one patient withdrew from the study, we considered that the influence of this withdrawal on the results would be small. In fact, if the data from the patient who withdrew because of deterioration of symptoms were included in the analysis, they would have reduced the overall effect in that group. This must be regarded as a limitation of the study. Another limitation to this study is its small sample size. Moreover, previous experience with acupuncture and confidence in acupuncture may influence the measurement of efficacy [13]. Therefore, another limitation of the present study is that the subjects were acupuncture school students, who had considerable knowledge of acupuncture and the special sensation of *deqi*, as well as those who had confidence in the efficacy of acupuncture.

4.1. Effectiveness of myofascial trigger points as sites of acupuncture treatment

The myofascial trigger points have often been used in the treatment of myofascial pain syndrome. The myofascial trigger point has been defined as a highly localized and hyperirritable spot in a palpable taut band of skeletal muscle fibers [1]. Important characteristics of myofascial trigger points include local pain or tenderness, referred pain or referred tenderness, and local twitch response [1,12]. Acupuncture or dry needling of a myofascial trigger point appears to provide immediate relief of pain related to that myofascial trigger point [26,27]. However, the effects of trigger point acupuncture on chronic TMJ myofascial pain are still unclear.

In this study, clinical results suggested that the analgesic effect of trigger point acupuncture is better than that of sham acupuncture. Myofascial active trigger points are supposed to be sites where nociceptors, such as polymodal-type receptors, have been sensitized by various factors [28,29]. In particular, sensitized nociceptors might be a possible cause of localized tenderness, referred pain, and local twitch response [30,31]. Moreover, the trigger point insertion of the needle (but not always acupuncture point insertion) affects sensitized nociceptors [31–33]. Thus, acupuncture stimulation of myofascial active trigger points may produce greater activation of sensitized polymodal-type receptors, resulting in greater pain relief.

Trigger point acupuncture provides significantly more relief on chronic low back pain and neck pain as compared with standard acupuncture [26,34] but not of chronic knee pain [35]. These findings suggest that the myofascial pain near joints in contrast to other types of chronic pain may depend on different factors such as inflammation and joint pain. Therefore, the effects of standard acupuncture on chronic TMJ myofascial pain may be as effective as trigger point acupuncture. However, the limited sample size and poor quality of these studies highlights and supports the need for large scale, good quality, placebo-controlled trials in this area [36].

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第53回日本神経学会総会（2012年）

大会長講演

脳血管疾患病態の多様性と神経伝達物質機能の解明を目指して

鈴木　則宏

（臨床神経 2012;52:819-824）
Key words：脳血管の神経支配，三叉神経，副交感神経，片頭痛，皮質拡延性抑制

「(前略)…僕の視野のうちに妙なものを見つけ出した．妙なものを？――と云ふのは絶えずまはつてゐる半透明の歯車だつた．僕はかう云ふ経験を前にも何度か持ち合せてゐた．歯車は次第に数を殖やし，半ば僕の視野を塞いでしまふ，が，それも長いことではない，暫らくの後には消え失せる代りに今度は頭痛を感じはじめる，――それはいつも同じことだつた．…(後略)」芥川龍之介『歯車』(1927.4.7)［遺稿］(岩波文庫 1957刊)

1．はじめに

脳の活動は神経細胞およびグリア細胞が主役を演じているが，それらが十二分に機能を発揮するためには，細胞のみでは不可能であり，酸素とグルコースの供給が必要である．その供給は専ら脳血管を経路とする脳血流によってまかなわれている．私の研究の最大テーマはこの脳血管と脳血流の調節機序および脳血管自体の病的状態の解明にある．脳血流の調節は，脳組織の代謝を反映する炭酸ガス分圧の変化に対応して稼働する化学的調節と，脳灌流圧変動などの中枢神経外環境変化に応じて稼働する脳血管に分布する多くの種類の神経線維による神経性調節によりおこなわれている．驚くべきことに神経性調節は1970年代まではその存在が否定的であった．しかし，カテコラミン染色同定法のFalck-Hillarp法やグリオキシル酸法そしてアセチルコリンエステラーゼ法などの組織化学手法の進歩により脳血管壁に交感神経と副交感神経の存在が証明され，さらに臨床的に脱交感神経モデルともいえるShy Drager症候群での脳循環自動調節能廃絶にともなう起立性低血圧による失神時の脳循環測定から，神経性調節の重要性が証明された．本会長講演では，私が携わってきた研究のうち，脳血管の神経支配の証明から，各神経線維の分布と起源の同定，各神経の機能，そして脳血管の異常反応が症状の主座を占める片頭痛の病態解明研究の現状までを概説する．

2．脳血管の神経支配

研究の端緒は電子顕微鏡による脳血管壁の超微形態の分析であり，分布する交感神経終末と副交感神経終末内の小胞を定量解析してその動的な変化を確認した．さらに，脳血管に分布する神経系の機能を明らかにするために，げっ歯類，霊長類を対象として，SP，CGRP，VIP，NPY含有神経を免疫組織化学的に同定し，神経切断実験および逆行性軸索トレーサーによる解析により，脳血管壁の感覚神経は三叉神経節に起源を発し鼻毛様体神経を介して脳血管に分布することを（Fig. 1，2），また副交感神経は翼口蓋神経節から眼窩枝を経由して脳血管に分布することを証明した．

3．神経原性脳血管拡張現象

脳血管の拡張現象は専ら，血管内血流の灌流圧の低下（脳血管自動調節反応）および灌流組織内のpHの低下，すなわち二酸化炭素分圧の上昇によって生じるとされてきた．しかし，灌流圧にも二酸化炭素分圧にも依存しない，脳血管に分布する血管拡張性神経刺激による血管拡張現象，すなわち神経原性

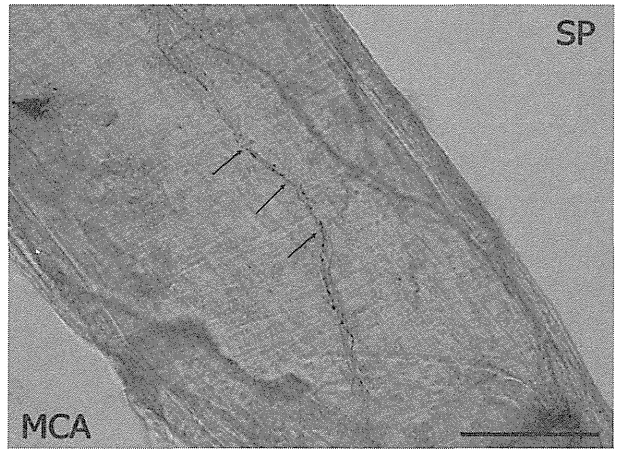

Fig. 1　Appearance of substance-P positive nerve fibers in the middle cerebral artery in the rat. Immunostaining of whole mount preparation. Delicate varicose nerve fibers run longitudinally along the blood vessel (arrows). Scale bar＝50μm.

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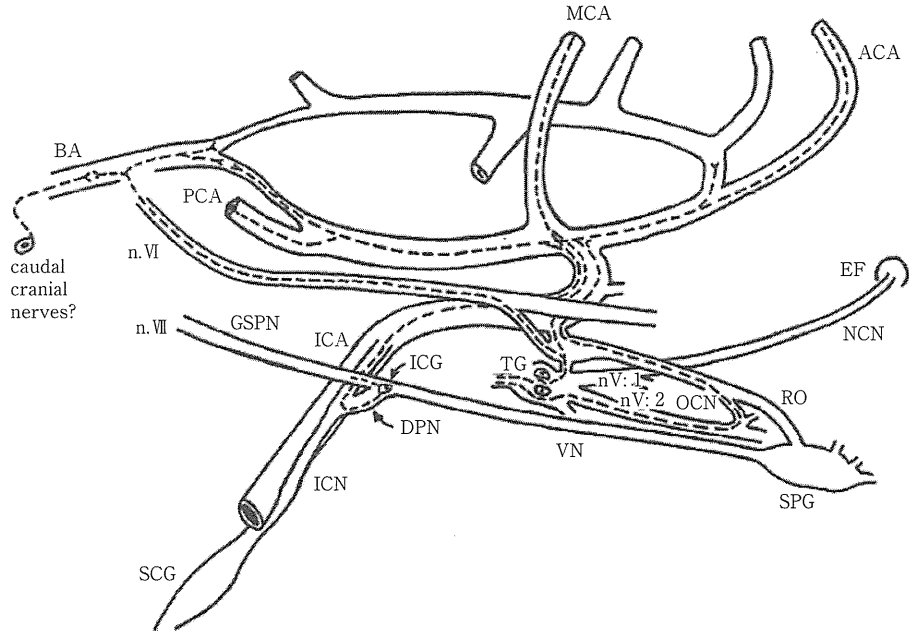

Fig. 2　An overview of the probable origins and pathways of sensory nerve fibers to the intracranial segment of the internal carotid artery (ICA) and the cerebral artery in man. The assumptions are based both on the findings in man and monkey. ACA: anterior cerebral artery, BA: basilar artery, CG: cavernous ganglion, DPN: deep perusal nerve, RF: ethmoidal foramen, GSPN: greater superficial petrosal nerve, ICG: internal carotid ganglion, ICN: internal carotid nerve, LSPN: lesser superficial petrosal nerve, MCA: middle cerebral artery, NCN: nasociliary nerve, nV: 1: ophthalmic nerve, nV: 2: maxillary nerve, OTG: otic ganglion, PCA: posterior cerebral artery, RO: rami orbitales, SCG: superior cervical ganglion, SPG: sphenopalatine ganglion, TG: trigeminal ganglion, VN: vidian (pterygoid) nerve.

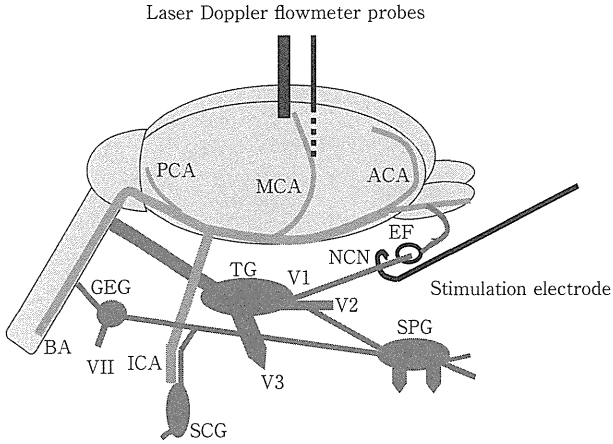

Fig. 3　Schematic representation of measurement of cerebral blood flow through electrical stimulation of the nasociliary nerve (NCN). The cerebral cortical blood flow (ipsilateral side) and the thalamic blood flow (contralateral side) are measured continuously by laser Doppler flowmetry. The nasociliary nerve is electrically stimulated outside of the ethomiodal foramen (EF). ACA: anterior cerebral artery, BA: basilar artery, GEG: geniculate ganglion, ICA: internal carotid artery, SCG: superior cervical ganglion, SPG: sphenopalatine ganglion, TG: trigeminal ganglion, V1: ophthalmic nerve, V2: maxillary nerve, V3: mandibular nerve, VII: facial nerve.

血管拡張現象が想定されていた．そこで，げっ歯類（ラット）で証明した副交感神経の翼口蓋神経由来の脳血管枝あるいは三叉神経脳血管枝（鼻毛様体神経）をラットにおいて単独電気刺激してその脳血流へおよぼす影響をしらべた（Fig. 3）．電気刺激（5V，0.5msec．10Hz，30秒）により全身血圧の変化や血中二酸化炭素分圧の変化をともなわない約10～40％の脳表血流の増加を認めた．すなわち，神経原性脳血管拡張現象を in vivo で証明した．

4．片頭痛の病態研究への発展

4－1．三叉神経終末とセロトニンとの関係の解明

一方，1990年代になり脳血管の異常反応を示す代表的疾患である片頭痛ではセロトニン（5-HT）の機能低下がその基本的病態として知られており，5-$HT_{1B/1D}$受容体アゴニスト（トリプタン）は脳血管の病的状態を即座に是正させることが明らかとなった．この病態の解明を目指して，脳血管壁での感覚神経と5-HT受容体との関係を解明するために，動物で鼻毛様体神経電気刺激による片頭痛発作時の脳血管モデルを作成し，SPおよびCGRP拮抗薬（h-CGRP 8-37）とトリプタンを使用してその関係を分析した．その結果，トリプタンはCGRPを直接抑制する際と同等に，脳血管の反応性を是正することを明らかにした（Fig. 4）．Fig. 5に，脳血管と三叉神経終末，