Granulocyte Colony-Stimulating Factor Enhances Arteriogenesis and Ameliorates Cerebral Damage in a Mouse Model of Ischemic Stroke

Yukio Sugiyama, MD; Yoshiki Yagita, MD, PhD; Naoki Oyama, MD; Yasukazu Terasaki, MD, PhD; Emi Omura-Matsuoka, MD; Tsutomu Sasaki, MD, PhD; Kazuo Kitagawa, MD, PhD

Background and Purpose—Enhancing collateral artery growth is a potent therapeutic approach to treat cardiovascular ischemic disease from occlusive artery. Granulocyte–macrophage colony-stimulating factor (GM-CSF) has gained attention for its ability to promote arteriogenesis, ameliorating brain damage, by the mechanisms involving monocyte upregulation. However, the recent clinical study testing its efficacy in myocardial ischemia has raised the question about its safety. We tested alternative colony-stimulating factors for their effects on collateral artery growth and brain protection.

Methods—Brain hypoperfusion was produced by occluding the left common carotid artery in C57/BL6 mice. After the surgery, granulocyte colony-stimulating factor, macrophage colony-stimulating factor, or GM-CSF (100 µg/kg/day) was administered daily for 5 days. The angioarchitecture for leptomeningeal anastomoses and the circle of Willis were visualized after the colony-stimulating factor treatment. Circulating blood monocytes and Mac-2-positive cells in the dorsal surface of the brain were determined. A set of animals underwent subsequent ipsilateral middle cerebral artery occlusion and infarct volume was assessed.

Results—Granulocyte colony-stimulating factor as well as GM-CSF promoted leptomeningeal collateral growth after common carotid artery occlusion. Both granulocyte colony-stimulating factor and GM-CSF increased circulating blood monocytes and Mac-2-positive cells in the dorsal brain surface, suggesting the mechanisms coupled to monocyte upregulation might be shared. Infarct volume after middle cerebral artery occlusion was reduced by granulocyte colony-stimulating factor, similarly to GM-CSF. Macrophage colony-stimulating factor showed none of these effects.

Conclusions—Granulocyte colony-stimulating factor enhances collateral artery growth and reduces infarct volume in a mouse model of brain ischemia, similarly to GM-CSF. (Stroke. 2011;42:770-775.)

Key Words: animal models ■ arteriogenesis ■ brain ischemia ■ colony-stimulating factors

The risk of ischemic stroke is greatly enhanced in a patient with reduced cerebral blood flow reserve. Collateral artery growth (arteriogenesis) plays a critical role in maintaining cerebral blood flow reserve after major artery occlusion and determines the severity of subsequent ischemic injury of the brain. Leptomeningeal anastomoses are the most important collateral pathways, especially after middle cerebral artery (MCA) occlusion, and are recruited when the anastomoses flow at the circle of Willis is not adequate. Therapeutic stimulation of arteriogenesis is an attractive approach for treatment of chronic brain ischemia given this natural adaptive process can be enhanced by exogenous application of certain cytokines.

One such cytokine is granulocyte–macrophage colony-stimulating factor (GM-CSF) that stimulates growth and differentiation of hematopoietic cells and is clinically used to treat chemotherapy-induced neutropenia. The arteriogenic effect of GM-CSF was originally reported in heart and peripheral artery disease by mechanisms involved in mobilization of monocytes/macrophages. Buschmann et al for the first time provided evidence that the same scenario could be applied to cerebral ischemia as well. Experimental studies have shown that GM-CSF induces arteriogenesis in the hypoperfused brain of rats and mice, restores cerebral blood flow, and ameliorates severity of stroke. Therapeutic clinical application of GM-CSF was expected in both cardiovascular and cerebrovascular fields; however, recent clinical trial to test the efficacy of GM-CSF in coronary artery disease raised the critical safety issue and was prematurely terminated, in which 2 of the 7 patients given GM-CSF had acute coronary syndrome. Therefore, safer alternatives are awaited.

Granulocyte (G-CSF) and macrophage colony-stimulating factor (M-CSF) are categorized in the same class of hematopoietic growth factors as GM-CSF. We hypothesize that these...
colony-stimulating factors might exert arteriogenic effects
given their potential to induce proliferation and differentiation
to hematopoietic cells into white blood cells. G-CSF, in
particular, has an advantage because it has been in clinical use
for a long time and a comprehensive safety profile has been
demonstrated. In the current study, we focused on and
tested arteriogenic effects of colony-stimulating factors and
their direct impact on stroke severity. We found that G-CSF,
but not M-CSF, induces arteriogenesis and alleviates ischemic
damage to the brain, similarly to GM-CSF.

Methods

Animals
Male C57BL/6j strain mice (12 to 16 weeks of age; Charles River
Japan Inc) were used in this study. In the first experiment, G-CSF,
M-CSF, GM-CSF, or vehicle was administered, respectively, after
left common carotid artery (CCA) occlusion. The distal MCA was
identified from its branch angle and
measured at the point where the distal MCA joined the distal anterior
cerebral artery. The vessel diameter of the leptomeningeal anastomoses
was distinguished from the distal anterior cerebral artery or posterior cerebral
artery.11 The vessel diameter of the leptomeningeal anastomoses
was measured at the proximal point where the distal MCA joined the distal anterior
cerebral artery as reported before.9 The mice were anesthetized with
circle of Willis was measured at the just proximal point where the
distal MCA joined the distal anterior cerebral artery. The vessel diameter of the
leptomeningeal anastomoses was measured at the point where the distal MCA joined the distal anterior
cerebral artery.

Administration of Colony-Stimulating Factors
In the first experiment, recombinant human G-CSF (Kyowa Kirin Inc, Yokohama, Japan), recombinant human M-CSF (Kyowa Kirin Inc), or recombinant mouse GM-CSF (R&D Systems Inc; each at
100 µg/kg diluted in 0.1 mL saline) was administered subcutaneously
4 days after CCA occlusion and 4 days after sham operation. In the second experiment, G-CSF at the different concentrations (1 µg/kg, 10
µg/kg, 100 µg/kg diluted in 0.1 mL saline) or vehicle (0.1 mL saline)
was administered subcutaneously for 5 consecutive days immediately after CCA occlusion.

Visualization of Vessels by Latex Perfusion
After 7 days of CCA occlusion (n=5, each group), latex perfusion
was performed to visualize the leptomeningeal anastomoses and the
circle of Willis as reported before. The mice were anesthetized with
4.0% halothane, and the right atrium of the heart was incised for
allowing venous outflow. The left ventricle of the heart was
cannulated and injected at 150 mm Hg with 2 mL saline and
subsequently 0.5 mL latex compound (Product No. 563; Chicago Latex Products Inc), which was mixed with 50 µL/mL carbon black
(Bokusai; Fueki Inc) beforehand. Then, the brain was removed from
the skull, and photographs of the dorsal and ventral brain surface
were taken. The distal MCA was identified from its branch angle and
distinguished from the distal anterior cerebral artery or posterior cerebral
artery. The vessel diameter of the leptomeningeal anastomoses
was measured at the point where the distal MCA joined the distal anterior
cerebral artery or posterior cerebral artery. The vessel diameter of the
circle of the Willis was measured at the just proximal point where the
left anterior cerebral artery diverges the olfactory artery.

Statistics
All data are presented as mean±SEM. Differences between multiple
groups were compared by analysis of variance followed by Tukey
multiple comparison test. Nonparametric data were analyzed with
the Kruskal-Wallis test followed by the Mann-Whitney U test. A
value of P<0.05 was considered statistically significant.

An expanded “Methods” section is provided in the online supplement
(available at http://stroke.ahajournals.org).

Results

Enhanced Leptomeningeal Anastomoses Growth
by G-CSF
The 5-day treatment effects of colony-stimulating factors
(G-CSF, GM-CSF, and M-CSF) on leptomeningeal anasto-
moses development were assessed after 7 days of CCA
occlusion by quantitative measurement of vessel diameters. G-CSF as well as GM-CSF significantly enlarged the vessel
diameter of leptomeningeal anastomoses as compared with
vehicle treatment (G-CSF, 27.5±1.3 μm, 61 vessels, GM-
CSF, 28.0±1.8 μm, 59 vessels versus vehicle, 22.5±0.9 μm,
60 vessels, P<0.01, respectively; Figures 1A, 1C1, and 1D)
M-CSF failed to show such effects (22.8±0.8 μm, 59
vessels). The vessel diameter of the circle of Willis was
enlarged after CCA occlusion (CCA occlusion, 189±6 μm,
sham CCA operation, 127±8 μm, P<0.01) but was not
altered by any colony-stimulating factor treatment (G-CSF,
201±8 μm, GM-CSF, 192±16 μm, M-CSF, 195±10 μm; Figures 1B and 1C2).

Cirulating Blood Monocytes and Tissue Macrophages
Previous reports have shown that monocyte/macrophage
mobilization is essential for arteriogenesis. Circulating
blood monocytes were markedly increased by G-CSF or
GM-CSF treatment, but not by M-CSF (G-CSF, 547.8±114.1/μL, GM-CSF, 536.8±138.0/μL versus vehicle, 101.0±34.4/μL, P<0.05, respectively; M-CSF, 106.4±34.9/μL; Figure 2A). As expected, granulocytes and lymphocytes
were also increased by G-CSF, but not by M-CSF or
GM-CSF. Macrophages in the dorsal brain surface were
identified with Mac-2 antibody and quantified (Figure 2B).
The number of Mac-2-positive cells was significantly in-
creased by G-CSF versus vehicle in the presence of preceding
CCA occlusion. Similar results were obtained with GM-CSF
treatment but not with M-CSF (G-CSF, 107.4±14.6, GM-
CSF, 104.6±10.1 versus vehicle, 51.4±2.4, P<0.05, respectively;
M-CSF, 65.1±7.7; Figure 2C). The increase in blood
monocytes and tissue macrophage accumulation correlate
well with the arteriogenic effects observed.

To further elucidate the mechanistic link between monocyte/
macrophage mobilization and arteriogenesis, we tested the
impact of monocyte depletion on arteriogenic effect by G-CSF.
A single dose of 5-fluorouracil (5-FU) administration (150
mg/kg intraperitoneally) severely depleted blood monocytes at 4
days and 8 days after the injection (4 days, 13.0±3.6/μL and
8 days, 0/μL). This intervention significantly interfered with
growth response of leptomeningeal anastomoses by G-CSF
treatment (5-FU, 21.5±1.1 μm, 67 vessels versus vehicle,
27.5±1.9 μm, 69 vessels, P<0.01; Figure 2D).

Reduction of Infarct Volume by G-CSF After
Subsequent MCA Occlusion
Next, neuroprotective effects were directly tested by assessing
brain infarct volume after subsequent MCA occlusion (Figure 3A–B). G-CSF did not alter brain infarct volume in animals
without preceding CCA occlusion (sham operation) but signifi-
cantly reduced infarct volume versus vehicle in the presence
of preceding CCA occlusion (G-CSF, 35.4±4.7 mm³ versus
vehicle, 55.1±4.3 mm³, P<0.05), suggesting that the benefit might be attributable to collateral artery development by the treatment.
Importantly, there was no significant difference in the neuropro-
tective impact between G-CSF and GM-CSF treatment (GM-
CSF, 37.8±3.9 mm³). M-CSF again had no such effect (M-CSF,
49.0±3.7 mm$^3$). We further assessed cerebral blood flow using laser Doppler flowmetry. Cortical perfusion after MCA occlusion was significantly improved by G-CSF or GM-CSF treatment in the presence of preceding CCA occlusion, consistent with infarct volume reduction (G-CSF, 36.8%±4.4%; GM-CSF, 37.7%±5.1% versus vehicle, 19.2%±1.8%, $P<0.05$, respectively; Figure 3C). We next tested involvement of angiogenesis in this process by examining capillary density in the peripheral MCA cortex after CCA occlusion. Capillary density was assessed by CD31 staining and was not altered by G-CSF treatment (G-CSF, 220.6±2.3 vessels/field versus vehicle, 226.2±7.9 vessels/field, nonsignificant; Figure 4A–B). These results suggest little contribution of the angiogenesis mechanism to cerebral protection in this model.

Dose-Dependent Response of G-CSF on Leptomeningeal Collateral Growth

Finally, we examined whether G-CSF stimulates collateral growth in a dose-dependent manner (Figure 5A). The vessel diameter of leptomeningeal anastomoses was assessed at 3 different doses of G-CSF treatment (1, 10, and 100 μg/kg) for 5 days after CCA occlusion. G-CSF significantly increased the vessel diameter at 10 and 100 μg/kg but failed to have effects at 1 μg/kg (10 μg/kg, 24.7±0.9 μm, 60 vessels, $P<0.05$, 100 μg/kg, 27.4±1.5 μm, 58 vessels, $P<0.01$ versus vehicle, 20.8±0.7 μm, 61 vessels, 1 μg/kg, 21.3±0.8 μm, 65 vessels). In correlation with the dose-dependent response on leptomeningeal collateral growth, G-CSF significantly reduced infarct volume after subsequent MCA occlusion at 10 and 100 μg/kg but failed to show effects at 1 μg/kg (10 μg/kg, 38.2±3.0 mm$^3$, 100 μg/kg, 34.9±4.4 mm$^3$, $P<0.05$, respectively, versus vehicle, 56.6±4.1 mm$^3$, 1 μg/kg, 55.8±5.8 mm$^3$; Figure 5B).

Discussion

The current study demonstrates that G-CSF, but not M-CSF, has collateral enhancing property in hypoperfused brain similar to GM-CSF, which leads to powerful neuroprotection against subsequent ischemic stroke. Although G-CSF was already reported to act as a direct neuroprotectant, the current study is the first to demonstrate arteriogenic action by G-CSF treatment in the brain. The previously reported mechanisms for neuroprotection include direct neuronal impact by stem cell mobilization, antiapoptosis, neurogenesis, and systemic anti-inflammatory effects. However, these mechanisms might contribute minimally to the alleviated cerebral damage after MCA occlusion in the current protocol, in which colony-stimulating factor treatment was terminated.
3 days before creating stroke (by MCA occlusion) and plasma concentration of G-CSF returns to baseline within 48 hours of subcutaneous injection. Indeed, no infarct-reducing impact was observed in the G-CSF-treated group without preceding hypoperfusion, strongly indicating the major role for collateral artery growth (arteriogenesis) in neuroprotection observed in the current study.

Arteriogenesis is a process in which pre-existing collateral arterioles transform into functional collateral arteries. Although the precise molecular mechanisms for arteriogenesis remain poorly understood, studies have clarified the pivotal role for circulating cells, particularly monocytes, in this process. Monocytes adhere the shear stress-activated endothelium through intracellular adhesion molecule-1, migrate toward the intima and mature into macrophages, producing growth factors and proteases for collateral artery remodeling. Previous studies have shown that the amount of circulating blood monocytes positively correlates with arteriogenesis.

**Figure 2.** Circulating blood monocytes and tissue macrophages. A, Circulating blood monocytes were increased by G-CSF or GM-CSF treatment. G-CSF also significantly increased the number of granulocytes and lymphocytes. #: P<0.05 compared with Sham+Vehicle, CCAO+Vehicle, and CCAO+M-CSF. B, Macrophage staining for Mac-2 in the dorsal brain surface 7 days after CCA occlusion with each CSF or vehicle treatment was represented. C, The number of Mac-2-positive cells was increased after CCA occlusion. Moreover, G-CSF or GM-CSF treatment enhanced the increase in the number of Mac-2-positive cells. *P<0.05 compared with Sham+Vehicle. **P<0.05 compared with Sham+Vehicle and CCAO+Vehicle. D, Monocyte depletion by 5-FU inhibited growth response of leptomeningeal anastomoses by G-CSF treatment after CCA occlusion. 5-FU(+) indicates 5-FU administration. 5-FU(−) indicates vehicle administration. †P<0.01 compared with all other groups. Sham+G-CSF indicates Sham CCA operation with G-CSF treatment.

**Figure 3.** Reduction of infarct volume after subsequent MCA occlusion by G-CSF, similar to GM-CSF. A, 2,3,5-triphenyltetrazolium-chloride/saline (TTC) staining of the brain after MCA occlusion was represented. MCA occlusion was performed 7 days after CCA occlusion with each CSF or vehicle treatment. B, In the presence of preceding CCA occlusion, G-CSF treatment reduced the infarct volume attributable to subsequent MCA occlusion, similar to GM-CSF treatment. C, Cortical perfusion after MCA occlusion was measured by laser Doppler flowmetry. G-CSF or GM-CSF treatment preserved higher cortical perfusion after MCA occlusion than vehicle treatment in the presence of preceding CCA occlusion. *P<0.05 compared with Sham+Vehicle and CCAO+Vehicle.
riogenesis promotion. Osteopetrotic mutant mice, lacking bone marrow macrophages or blood monocytes, show severely depressed arteriogenesis after femoral artery occlusion. On the other hand, 5-FU-induced impaired arteriogenesis is reversed by supplementation with isolated monocytes in a mice model of femoral artery occlusion. In the present study, enhanced arteriogenesis either by G-CSF or GM-CSF was associated with increase in circulating blood monocytes, and the arteriogenic effect of G-CSF was suppressed by monocyte depletion, suggesting G-CSF might share the same mechanism involved in monocyte mobilization. Intracellular adhesion molecule-1 upregulation by G-CSF was also reported in a mouse model of myocardial infarction, facilitating a monocyte migration process. The similar mechanism might be at play in our model, although we did not examine intracellular adhesion molecule-1 expression. Most importantly, however, we did observe an increase in macrophages (Mac-2-positive cells) in the dorsal surface of the hypoperfused brain by G-CSF as well as GM-CSF. These results suggest collateral remodeling might be achieved in a coordinated manner by mobilization of monocytes and their active migration to the tissue. G-CSF induces angiogenesis as well, a process in which new vessels arise from pre-existing ones. Lee et al reported that 3-day treatment of G-CSF (50 µg/kg/day) after MCA occlusion enhances angiogenesis in the rat brain. In the current study, however, the contribution of angiogenesis might be minimal because we failed to detect upregulation of capillary density. Although the reason for the discrepancy is unclear, it could be attributable to several differences used in the protocol (unilateral CCA occlusion versus MCA occlusion, dosage, duration) and/or species (mice versus rats).

Based on ample preclinical data showing the beneficial effects of G-CSF in stroke models, several clinical studies were initiated and some reported. We observed an arteriogenic effect of G-CSF at the dose of 10 µg/kg/day for 5 days. Recent clinical studies used G-CSF at 1 to 10 µg/kg for 5 days in patients with stroke and demonstrated its safety. One particular safety concern might be the possibility that increased blood neutrophils aggregate within microvasculature and impair tissue circulation. However, Strecker et al revealed that leukocytosis by G-CSF is restricted to the vessel compartment and has no deleterious effect on ischemic brain in experimental animals. Furthermore, recent meta-analysis has shown that G-CSF, unlike GM-CSF, does not induce cardiovascular events in patients with myocardial infarction.

In summary, G-CSF enhances arteriogenesis similarly to GM-CSF in a mouse model of chronic brain hypoperfusion, providing powerful neuroprotection against stroke. Although the clinical application of GM-CSF was unsuccessful so far due to the safety issue, safe clinical application of G-CSF has been shown at lower doses. The arteriogenic action of G-CSF could be a potential target for patients with occlusive disease of a major cerebral artery.

Acknowledgments
We thank Ms C. Kurano and K. Nishiyama for secretarial assistance. M-CSF and G-CSF were provided by Kyowa-Kirin Inc, Tokyo, Japan.

Sources of Funding
This research was supported by a Grant-in-Aid from the Ministry of Education, Science, and Culture in Japan.
Disclosures
None.

References
Granulocyte Colony-Stimulating Factor Enhances Arteriogenesis and Ameliorates Cerebral Damage in a Mouse Model of Ischemic Stroke
Yukio Sugiyama, Yoshiki Yagita, Naoki Oyama, Yasukazu Terasaki, Emi Omura-Matsuoka, Tsutomu Sasaki and Kazuo Kitagawa

Stroke. 2011;42:770-775; originally published online January 21, 2011;
doi: 10.1161/STROKEAHA.110.597799

Stroke is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2011 American Heart Association, Inc. All rights reserved.
Print ISSN: 0039-2499. Online ISSN: 1524-4628

The online version of this article, along with updated information and services, is located on the
World Wide Web at:
http://stroke.ahajournals.org/content/42/3/770

Data Supplement (unedited) at:
http://stroke.ahajournals.org/content/suppl/2011/01/20/STROKEAHA.110.597799.DC1
http://stroke.ahajournals.org/content/suppl/2012/02/26/STROKEAHA.110.597799.DC2

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Stroke can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Stroke is online at:
http://stroke.ahajournals.org//subscriptions/
ONLINE SUPPLEMENT

Full Title

Granulocyte Colony-Stimulating Factor Enhances Arteriogenesis and Ameliorates Cerebral Damage in a Mouse Model of Ischemic Stroke

Yukio Sugiyama, MD; Yoshiki Yagita, MD, PhD; Naoki Oyama, MD; Yasukazu Terasaki, MD, PhD; Emi Omura-Matsuoka, MD; Tsutomu Sasaki, MD, PhD; Kazuo Kitagawa, MD, PhD

Division of Stroke, Department of Neurology, Osaka University Graduate School of Medicine, Japan.

Correspondence to Yukio Sugiyama, MD, Division of Stroke, Department of Neurology, Osaka University Graduate School of Medicine, 2-2 Yamadaoka, Suita, Osaka 565-0871, Japan.

Fax number: +81-6-6878-6574
Telephone number: +81-6-6879-3576
E-mail: ysugiyama@medone.med.osaka-u.ac.jp

Cover Title: G-CSF Enhances Arteriogenesis
Supplemental Methods

Common Carotid Artery Occlusion
General anesthesia was induced by 4.0% halothane and maintained at 1.0% halothane with an open facemask. The body temperature was monitored by a rectal thermometer and maintained at 37.0 ± 0.5°C using a heat lamp and mat. The left CCA was exposed and ligated by a silk suture. Sham CCA operation was performed in the same process without ligation.

Blood Analysis
After 4 days of CCA occlusion (n=5, each group), blood was obtained by puncturing the right ventricle of the heart. The hematology analyzer (SE-9000; Sysmex Inc) was used for total leukocyte counting (cells/μl). Microscopic differential leukocyte count was performed on May-Grunwald-Giemsa stained smears and expressed in the percentage of total leukocyte count. Absolute blood monocyte, granulocyte, and lymphocyte counts (cells/μl) were calculated from the total leukocyte count and their percentage of total leukocyte count.

Monocyte depletion
Monocyte depletion was achieved by a single intraperitoneal injection of 5-fluorouracil (5-FU) as reported previously. Before 4 days of CCA occlusion, 5-FU (150mg/kg diluted in 1.0ml saline) or vehicle (1.0ml saline) was administered. To verify the monocyte depletion, blood analysis was performed at 4 days and 8 days after the injection (n=5, each group).

Immunohistochemistry
After 7 days of CCA occlusion (n=7, each group), immunostaining was performed using Mac-2 antibody to assess the macrophages accumulation in the dorsal surface of the brain. Sagittal 50 μm-thick sections between 1.5 mm and 3.0 mm lateral from the midline were incubated with Mac-2 antibody (1:200; Cedarlane Laboratories), and then incubated with the Alexa Fluor 488 anti-rat IgG antibody (1:200, Molecular Probes). Ten sections were investigated and the total number of Mac-2 positive cells accumulating in the dorsal surface of the brain was counted.
After 7 days of CCA occlusion, the borderzone leptomeningeal arteries were immunostained using alpha-smooth muscle actin (α-SMA) antibody. Borderzone was
interpreted as the area between 1.5 mm and 3.0 mm lateral from the midline, based on the location of leptomeningeal anastomoses. Sagittal 5μm-thick paraffin sections were immunostained with α-SMA antibody (1:400, Laboratory Vision) using the Vector M.O.M. Immunodetection Kit (Vector Laboratories).

After 7 days of CCA occlusion (n=5, each group), capillary density was assessed by CD31 staining as reported previously. Coronal 14μm-thick sections between 0.5mm and 1.0mm rostral to the bregma were incubated with CD31 antibody (1:50, BD Bioscience), and then incubated with the Biotinylated anti-rat IgG antibody (1:200, Vector Laboratories). The number of CD31 positive vessels in the peripheral MCA cortex was counted in the same manner through a ×20 objective lens. Capillary density (vessels /field) was calculated as the mean of the vascular counts obtained from three pictures. The stained sections were visualized with a microscope (Eclipse 80i; Nikon Inc).

**Middle Cerebral Artery Occlusion Subsequent to Common Carotid Artery Occlusion**

After 7 days of CCA occlusion (n=6, each group), the MCA was occluded using electrocoagulation. Under general anesthesia, the mice were placed in the recumbent position, and the skin was incised vertically at the midpoint between the left orbit and the external auditory canal. The mandible was pulled downward and then the left MCA was visualized through the skull. A small burr hole was made in the skull using a dental drill. The MCA was occluded permanently by a microbipolar electrocoagulator at the just proximal point where the olfactory branch came off. The body temperature was monitored by a rectal thermometer and maintained at 37.0±0.5℃ using a heat lamp and mat. Twenty-four hours after MCA occlusion, the brain was removed for evaluation of infarct volume. The infarct volume was evaluated in 8 coronal sections of 1 mm-thickness stained with 2,3,5-triphenyltetrazolium-chloride/saline (TTC). The infarct area was measured with NIH Image V. 1.61 software, and the infarct volume was determined by integrating the infarct area of the 8 sections.

**Measurement of Cortical Perfusion by Laser-Doppler Flowmetry**

Under general anesthesia, a polyacrylamide column with an inner diameter of 0.8mm was attached to the skull 3.5mm lateral to the bregma with a dental cement, for measurement of cortical perfusion by laser-Doppler flowmetry (Advance laser Flowmetry, model ALF-21; Advance Co) as reported before. Cortical perfusion was measured before CCA occlusion (baseline), and again after MCA occlusion (n=5, each
group). Cortical perfusion after MCA occlusion was expressed as the percentage of the baseline cortical perfusion.

**Supplemental References**


Abstract

顆粒球コロニー刺激因子は脳卒中マウスモデルの動脈新生を促進し、脳損傷を軽減する

Granulocyte Colony-Stimulating Factor Enhances Arteriogenesis and Ameliorates Cerebral Damage in a Mouse Model of Ischemic Stroke

Yukio Sugiyama, MD; Yoshiaki Tagata, MD, PhD; Naoki Oyama, MD; Yasukazu Terasaki, MD, PhD; Emi Omura-Matsuoka, MD; Tsutomu Sasaki, MD, PhD; Kazu Kitagawa, MD, PhD

Division of Stroke, Department of Neurology, Osaka University Graduate School of Medicine, Osaka, Japan

背景および目的: 顆粒球コロニー刺激因子 (GM-CSF) は、動脈壁の自己更新を促進し、動脈新生物を形成する。脳卒中マウスモデルにおいて、GM-CSF の投与が脳卒中後の脳組織の構築を促進する可能性が示唆されている。著者らは、GM-CSF の影響を調査し、脳卒中後の脳機能の回復を促進する可能性を検討した。

方法: 慢性脳梗塞マウスモデルを用い、GM-CSF の投与を検討した。脳梗塞後 7 日目から 21 日目まで、每日 GM-CSF を皮下投与した。脳梗塞モデルは、左側大脑の梗塞を用いた。GM-CSF の投与群と非投与群を比較し、脳梗塞後の神經回復を評価した。

結果: GM-CSF の投与群では、非投与群に比べて、脳梗塞後の神經回復が促進された。特に、運動機能の回復が顕著であった。

結論: GM-CSF の投与は、脳卒中後の神経機能の回復を促進する可能性が示唆された。今後、より詳細な検討が不可欠である。