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The Neuroprotective and Vasculo-Neuro-Regenerative Roles of Adrenomedullin in Ischemic Brain and Its Therapeutic Potential

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Adrenomedullin (AM) is a vasodilating hormone secreted mainly from vascular wall, and its expression is markedly enhanced after stroke. We have revealed that AM promotes not only vasodilation but also vascular regeneration. In this study, we focused on the roles of AM in the ischemic brain and examined its therapeutic potential. We developed novel AM-transgenic (AM-Tg) mice that overproduce AM in the liver and performed middle cerebral artery occlusion for 20 min (20m-MCAO) to examine the effects of AM on degenerative or regenerative processes in ischemic brain. The infarct area and gliosis after 20m-MCAO was reduced in AM-Tg mice in association with suppression of leukocyte infiltration, oxidative stress, and apoptosis in the ischemic core. In addition, vascular regeneration and subsequent neurogenesis were enhanced in AM-Tg mice, preceded by increase in mobilization of $CD34^+$ mononuclear cells, which can differentiate into endothelial cells. The vasculo-neuro-regenerative actions observed in AM-Tg mice in combination with neuroprotection resulted in improved recovery of motor function. Brain edema was also significantly reduced in AM-Tg mice via suppression of vascular permeability. *In vitro*, AM exerted direct antiapoptotic and neurogenic actions on neuronal cells. Exogenous administration of AM in mice after 20m-MCAO also reduced the infarct area, and promoted vascular regeneration and functional recovery. In summary, this study suggests the neuroprotective and vasculo-neuro-regenerative roles of AM and provides basis for a new strategy to rescue ischemic brain through its multiple hormonal actions. (*Endocrinology* 147: 1642–1653, 2006)

ADRENOMEDULLIN (AM) IS a potent vasodilating peptide comprising 52 amino acids, which was originally isolated from human pheochromocytoma tissues in 1993 as a substance to elevate cAMP concentration in platelets (1). It is secreted mainly from the vascular wall into circulating blood to reduce pre- and post-load on the heart via vasodilation, natriuresis, and suppression of aldosterone release. Intravenous administration of AM to patients with heart failure or pulmonary hypertension has already been initiated and beneficial hemodynamic effects have been reported (2).

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Abbreviations: AM, Adrenomedullin; ANCOVA, analysis of covariance; BP, blood pressure; BrdU, bromodeoxyuridine; CGRP, calcitonin gene-related peptide; diHE, dihydroethidium; GFAP, glial fibrillary acidic protein; LDPI, laser Doppler perfusion imager; MCA, middle cerebral artery; 20m-MCAO, middle cerebral artery occlusion for 20 min; NeuN, neuronal marker; NHNP, normal human neuronal progenitor cells; PAMP, proadrenomedullin N-terminal 20 peptide; PECAM, platelet endothelial cell adhesion molecule; PI3K, phosphatidyl inositol-3 kinase; PKA, protein kinase A; ROS, reactive oxygen species; ssDNA, single-strand DNA; Tg, transgenic; Wt, wild type.

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Along with its vasodilating effect, a number of studies have demonstrated various and significant effects of AM on the regulation of vascular structure, including its development, remodeling, and regeneration. Mice lacking the AM gene did not survive their embryonic stage and showed abnormal vasculature with sc hemorrhage (3, 4). Mice overexpressing AM in endothelial cells were revealed to be hypotensive and resistant to vascular remodeling such as neointima formation caused by cuff injury, and atherogenesis associated with a high-cholesterol diet (5). We have recently established that AM promotes endothelial regeneration in the wound healing assay using cultured endothelial cells and enhances neovascularization *in vivo* into sc implanted gelplugs in mice (6, 7). We and others (8–11) have further demonstrated that the potentiating action of AM on vascular regeneration is mediated by activation of the phosphatidyl inositol-3 kinase (PI3K)-Akt pathway.

Recently, it has been known that AM is secreted from various organs including the heart, lung, kidney, adipose tissues, and central nervous system (12). Moreover, AM expression has been demonstrated to be markedly enhanced by ischemia through the activation of hypoxia-responsive elements in the AM gene via transcription factor hypoxia-inducible factor-1. In the central nervous system, where AM is

mainly expressed in neurons and the endothelium (13), it is reported that transient ischemia boosted AM expression for more than 15 d (14). However, the role of augmented AM has remained unclear for inconsistent previous results: three studies reported neuroprotective effects of AM by demonstrating reduction of infarct size after transient ischemia (15–17), whereas one study detected exacerbation of infarction as a result of AM infusion (14).

In this context, our study presented here focused on the roles of augmented AM in ischemic brain and examined its therapeutic potential. We generated new lines of transgenic mice that overproduce AM (AM-Tg) in the liver that mimics chronic AM administration. After inducing 20-min middle cerebral artery occlusion (20m-MCAO) to produce a nonfatal stroke model in the AM-Tg mice, we observed the long-term effects of AM on the ischemic brain up to postoperative d 56. We examined the mice for the recovery of blood flow in the ischemic region and impaired motor function after stroke, and immunohistochemically examined the ischemic striatum to determine effects of AM on neuronal loss/apoptosis, gliosis, leukocyte infiltration, oxidative stress, vascular regeneration, and neurogenesis after 20m-MCAO. In addition, another stroke model, 2-h middle cerebral artery occlusion (2 h-MCAO), was performed to observe the effect of AM in acute phase of the fatal stroke. *In vitro* studies using neuronal progenitor cells or rat pheochromocytoma PC12 cells were performed to examine direct antiapoptotic and neurogenic actions of AM on these neuronal cells. Finally, we investigated the effect of exogenous AM administration after 20m-MCAO to determine the appropriate amount and timing of AM treatment after cerebral ischemia.

Materials and Methods

Generation of transgenic mice which overproduce human AM but do not overproduce mature proadrenomedullin N-terminal 20 peptide (PAMP)

The AM gene contains coding regions for not only AM but also PAMP, a different vasodilating peptide. Amidation at their carboxyl terminals after their synthesis is needed for both AM and PAMP to exert their biological activity. The bioactive amidated forms are known as mature AM and mature PAMP, respectively. To identify the specific effects of AM, we generated a transgene construct with a point mutation on the PAMP amidation signal in the full-length AM gene cDNA. Guanine was substituted for cytosine on the 3′ end of the PAMP coding region so that glycine on the C′ terminal of the PAMP product was replaced with alanine. In this way, amidation and maturation of PAMP by peptidylglycine α-hydroxylase and α-hydroxyglycine N-C lyase were inhibited (Fig. 1A). The mutant AM gene cDNA was then inserted into a plasmid containing the human serum amyloid P component promoter, which is widely used to target gene expression specific to the liver. When the product is secreted from the liver, it mimics intravenous administration of the agent. The *Hin*dIII-*Xho*I fragment of the plasmid was microinjected into the pronucleus of fertilized C57BL/6J mice eggs.

The copy number of transgenes was quantified by means of genomic Southern blotting according to standard procedure. Plasma concentrations of human total AM and mature AM were measured with a commercially available immunoradiometric assay (Cosmic, Tokyo, Japan).

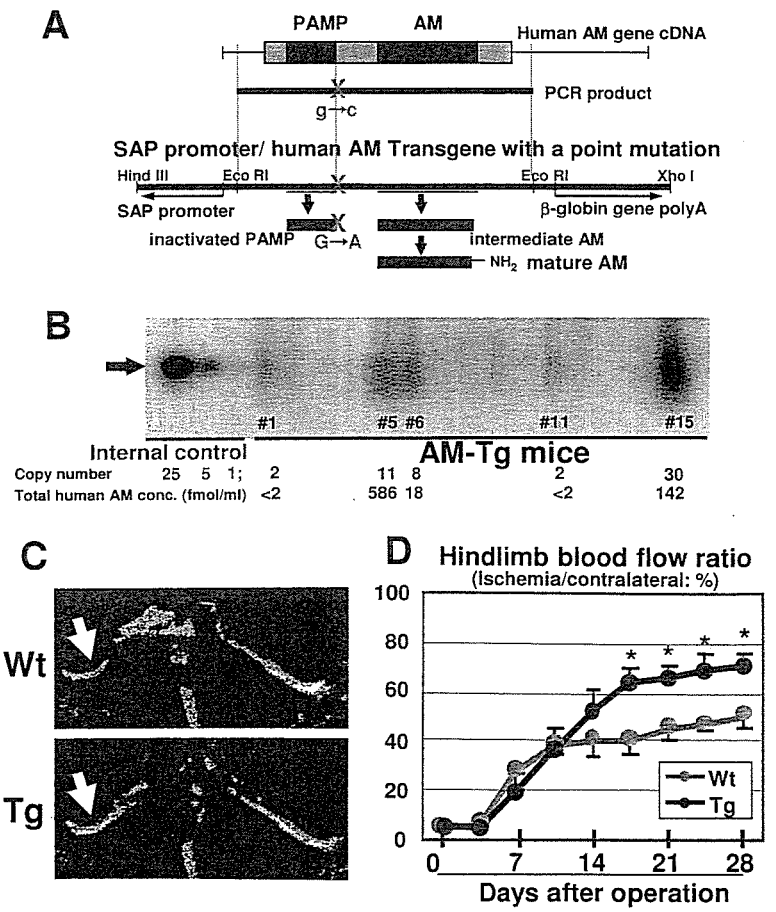

FIG. 1. Generation of transgenic mice which overproduce AM but do not overproduce mature PAMP in the liver and augmented angiogenesis in the transgenic mice after femoral artery occlusion. A, Schematic representation of the transgene construct derived from human AM gene cDNA with a point mutation in the amidation signal of PAMP. B, Southern blot analysis of the tail DNA of the founder mice. *Arrow*, Blots for the transgene. Internal controls for indicated copies are located in the *left three lanes*. The line No. indicates the mice in which the transgene was detected by PCR. The copy numbers estimated by densitometry and the plasma concentrations of total human AM in F3 mice of the lines are shown. C, Hindlimb blood flow analyzed by LDPI. *Red* or *white* indicates a higher flow than *blue* or *green*. *Arrows*, Comparison of ischemic hindlimbs between Wt and AM-Tg on d 28 after femoral artery ligation. D, Quantitative analysis of the hindlimb blood flow in ischemia. *, $P < 0.05$ for Wt *vs.* AM-Tg by ANCOVA; n = 6.

Human mature PAMP concentration was measured with a recently developed enzyme immunoassay (18). To determine the brain concentration of AM, we used the RIA kits for measurement of human and mouse total AM (Phoenix, Belmont, CA), according to the manufacturer's instruction. Blood pressure (BP) was measured with tail cuff (Softron, Tokyo, Japan). Hindlimb ischemia was induced by ligating the right femoral artery and blood flow of the ischemic limb was estimated with a laser Doppler perfusion imager (LDPI; Moor Instruments Ltd., Devon, UK) to confirm the angiogenic effect of AM-Tg mice. The perfusion ratio (%) was calculated as that of the ipsilatereal to the contralateral side. Animal care and experiments were in accordance with the guidelines for animal experiments of Kyoto University.

Induction of stroke by MCAO

We performed nonfatal 20m-MCAO and fatal 2 h-MCAO by the standard *trans*-luminal method, which has been described in various previous reports (19). Briefly, a 8–0 nylon monofilament coated with silicone was inserted from the left common carotid artery via the internal carotid to the base of the left middle cerebral artery (MCA) of 12-wk-old mice anesthetized with 5% halothane and maintained on 1%. After 20 min or 2 h of occlusion, the filament was withdrawn; and the arteries were reperfused, whereas the left common carotid artery was permanently ligated. Occlusion and reperfusion of the MCA was confirmed by means of fiber-shaped laser Doppler perfusion imager (Omegawave, Tokyo, Japan). We observed the mice until postoperative d 56 to examine blood flow in the ischemic region with an LDPI and motor function with a rota-rod exercise test.

Immunohistochemical examination of the ischemic striatum

After the induction of 20m-MCAO, mice were killed on postoperative d 0–56 and the harvested brains were subjected to immunohistochemical examination using a standard procedure described elsewhere (20). We used these primary antibodies: neuronal marker, NeuN (1:200; ChemiCon, Temecula, CA); astrocyte marker, glial fibrillary acidic protein (GFAP) (1:400; Chemicon); apoptosis marker, single-strand DNA (ssDNA) (1:50; Dako, Carpinteria, CA); leukocyte marker, CD45 (1:100, PharMingen, San Diego, CA); endothelial marker, platelet endothelial cell adhesion molecule (PECAM)-1 (CD31) (1:100, PharMingen); and a marker for proliferating cells, bromodeoxyuridine (BrdU) (1:50, Molecular Probes, Eugene, OR); to examine infarct area, gliosis, leukocyte infiltration, apoptosis, vascular regeneration and neurogenesis. Briefly, free-floating 30-μm coronal sections at the level of the anterior commissure were stained and observed with a confocal microscope (LSM5 PASCAL; Carl Zeiss SMT AG, Oberkochen, Germany). The infarct area (mm^2/field) was defined and quantified as the region where loss of NeuN immunoreactivity was observed and gliosis (mm^2/field) as the area stained GFAP in the ischemic striatum at × 5 fields. CD45 or ssDNA-positive cells (cells/mm^2) were quantified to serve as an index of leukocyte infiltration or of apoptosis, respectively, in the ischemic core at ×20 magnification. Capillary density was quantified as the number of PECAM-1-positive cells (cells/mm^2). The vessel counts were performed in the region of ischemic core at 0.5~1.0 mm anterior from the bregma. We prepared two thin sections (6 μm thickness) per mouse for vessel counting and four representative fields from each section were evaluated for capillary density in the ischemic core. To examine neurogenesis, mice were injected ip with BrdU 50 mg/kg (Sigma-Aldrich Co., St. Louis, MO) twice daily on postoperative d 4–6 and the number of BrdU-NeuN double-positive cells (cells/mm^2), which are generally defined as regenerated neurons, were quantified to serve as an index of neurogenesis. We also examined the production of reactive oxygen species (ROS) *in situ* by using the oxidative fluorescent dye dihydroethidium (diHE; 2×10^{-6} M; Sigma).

Quantification of CD34$^+$ mononuclear cells after 20m-MCAO

We counted peripheral $CD34^+$ mononuclear cells according to the International Society of Hematotherapy and Graft Engineering (ISHAGE) guidelines (21). Briefly, peripheral blood was taken from the orbital vein and stained with CD34-PE and CD45-FITC monoclonal antibodies (BD PharMingen, San Jose, CA) in a TruCOUNT tube (BD PharMingen) according to the manufacturer's instruction. After the reaction, $CD34^+$-$CD45^{dim}$ cells were quantified as $CD34^+$ mononuclear cells by a fluorescence-activated cell sorting machine Aria (BD) by using the ISHAGE sequential gating strategy (21).

Analysis of infarct volume and brain edema after 2 h-MCAO

We performed 2 h-MCAO to examine the effect of AM in the acute phase of fatal stroke. To estimate infarct or edema volume, mice were killed 24 h after the occlusion. The brain was removed and cut into 2 mm-thick slices and immersed in saline containing 2% 2,3,5-triphenyltetrazolium chloride for 30 min at 4 C. Infarct or edema volume was calculated as the percentage volume of the contralateral hemisphere with a standard procedure as described elsewhere (22). We estimated Evans Blue leakage in the brain parenchyma as previously reported (23), to serve as an index of vascular permeability *in situ*. Briefly, 0.2 ml of 2.5% Evans Blue solution was injected into mice via a tail vein 10 min before 2 h-MCAO and mice were killed at 24 h after the ischemia. Brain tissues were weighed and homogenized in 50% trichloroacetic acid solution to extract the dye in the supernatant. The tissue content of Evans Blue was estimated from the absorbance of 620 nM.

Estimation of apoptosis and differentiation of neuronal cells

The ratio of apoptotic cells was examined using normal human neuronal progenitor cells (NHNP; Cambrex Bioscience, Walkersville, MD). Cells were plated at a density of 5×10^4 cells/cm^2 on a laminin-coated 24-well dish and incubated in serum-free neuronal basal medium for 48 h. After the experimental period, the cell number was assessed by 5-mercapto-1-methyltetrazole assay (Nakalai Tesque), and the cells were stained with an anti-ssDNA antibody and nuclear staining propidium iodide to calculate the ratio of apoptotic cells to the total cells in each microscopic image.

Neuronal differentiation was examined as described previously (24), using rat pheochromocytoma PC12 cells (Riken Gene Bank, Tsukuba, Japan). Briefly, the length of the neuronal process (micrometers/cell) was calculated to serve as an index of neuronal differentiation after plating at a density of 10^4 cells/cm^2 on a collagen I-coated 24-well dish and incubated in 1% serum DMEM for 7 d. The cells were treated with 10^{-5}mol/liter AM or 100 ng/ml nerve growth factor as a positive control, and with the following inhibitors: the two AM antagonists, 10^{-5}mol/liter AM (22–52) and 10^{-5} mol/liter calcitonin gene-related peptide(8–37) [CGRP(8–37)] (Peptide Institute Inc., Osaka, Japan), the two protein kinase A (PKA) inhibitors, 10^{-5} mol/liter adenosine 3P,5P-cyclic monophosphorothioate Rp-isomer (Rp-cAMP) and 10^{-6} mol/liter myristoylated cell-permeable PKA inhibitor peptide sequence (14–22) (PKA Inh), and the two PI3K inhibitors, 10^{-5} mol/liter LY294002 and 10^{-7} mol/liter wortmannin (Calbiochem, San Diego, CA). For endothelial cell coculture experiments, human umbilical vein endothelial cells (HUVEC; Cambrex) were plated into transwell membrane inserts at a density of 10^5 cells/cm^2.

Exogenous administration of AM and hydralazine

Recombinant human mature AM dissolved in 0.9% saline was exogenously administrated to C57BL/6J wild-type mice (Wt) by means of osmotic pumps (Alzet Model 2002; Alzet Osmotic Pumps Co., Cupertino, CA) at a rate of 50 ng/h, which is estimated to achieve a plasma concentration of 2 fmol/ml (25). To determine appropriate timing to start AM treatment after 20m-MCAO, we implanted the pump ip just after the operation (d 0), or at 24 (d 1) or 72 h (d 3) later. We killed the mice on d 7 for histological examination and the period of the exogenous AM treatment was from d 0, 1, or 3 to d 7. In some experiments, low-dose (0.1 mM) hydralazine was exogenously administrated in drinking water.

Statistics

All data were expressed as mean ± SE. Comparison of means between two groups was performed with Student's *t* test. When more than two groups were compared, ANOVA was used to evaluate significant differences among groups, and if significant differences were confirmed, each difference was further examined by means of multiple comparisons. We

TABLE 1. Plasma concentrations of human AM and systolic BP in Wt and three lines of AM-Tg mice

	Wt	Low conc.	Medium conc.	High conc.
Total AM (fmol/ml)	1.1 ± 0.2	17.6 ± 4.4[a]	142.2 ± 18.4[a]	585.5 ± 117.7[a]
Mature AM (fmol/ml)	0.5 ± 0.4	2.6 ± 0.6[a]	10.4 ± 2.4[a]	24.9 ± 4.2[a]
Systolic BP (mm Hg)	122.7 ± 1.6	113.0 ± 2.5[a]	113.4 ± 2.6[a]	109.4 ± 2.5[a]

conc., Concentration.
[a] $P < 0.01$ *vs.* Wt; n = 4–12.

performed analysis of covariance (ANCOVA) when repeated-measurement had done, specifically, in the rota-rod test and laser Doppler flowmetry. Probability was considered to be statistically significant at $P < 0.05$.

Results

Generation of transgenic mice that overproduce human AM but do not overproduce mature PAMP

We generated seven lines of founder mice carrying the transgene and maintained three of them (lines 5, 6, and 15). Their plasma concentrations of human total AM were 585.5 ± 117.7, 17.6 ± 4.4 and 142.2 ± 18.4 fmol/ml and the copy numbers of the transgene estimated by Southern blot densitometry analysis were 11, 8, and 30, respectively (Fig. 1B). The physiological concentration of mouse total AM is reportedly 5~10 fmol/ml, so that the transgenic mice were expected to overproduce AM about 100, 3, and 30 times more than endogenous AM. The three lines were designated low (no. 6), medium (no. 15), and high (no. 5) concentration line according to their plasma AM concentration. The high concentration line (no. 5) was used for further study unless otherwise indicated. The plasma concentration of human mature AM, the bioactive amidated form, increased to 2.6~24.9 fmol/ml in the AM-Tg mice (Table 1). On the other hand, plasma human mature PAMP did not change in AM-Tg mice. The concentration (fmol/ml) was 2.21 ± 0.58 in Wt *vs.* 2.15 ± 0.35 in AM-Tg (n = 6), so that the point mutation on the amidation signal in the PAMP coding region was expected to successfully inhibit maturation of PAMP. There were no apparent differences in overall appearance, behavior, growth or fertility between Wt and AM-Tg mice. The systolic BP in 12-wk-old mice was significantly reduced in all three lines of AM-Tg compared with Wt. The BP (mm Hg) was 122.7 ± 1.6 in Wt *vs.* 109.4 ± 2.5~113.4 ± 2.6 in AM-Tg, depending on the line ($P < 0.05$; n = 5; Table 1).

Therapeutic angiogenesis in hindlimb ischemia model was promoted in AM-Tg mice

The recovery of blood flow in the ischemic hindlimb of Wt and AM-Tg mice was compared and was found to have

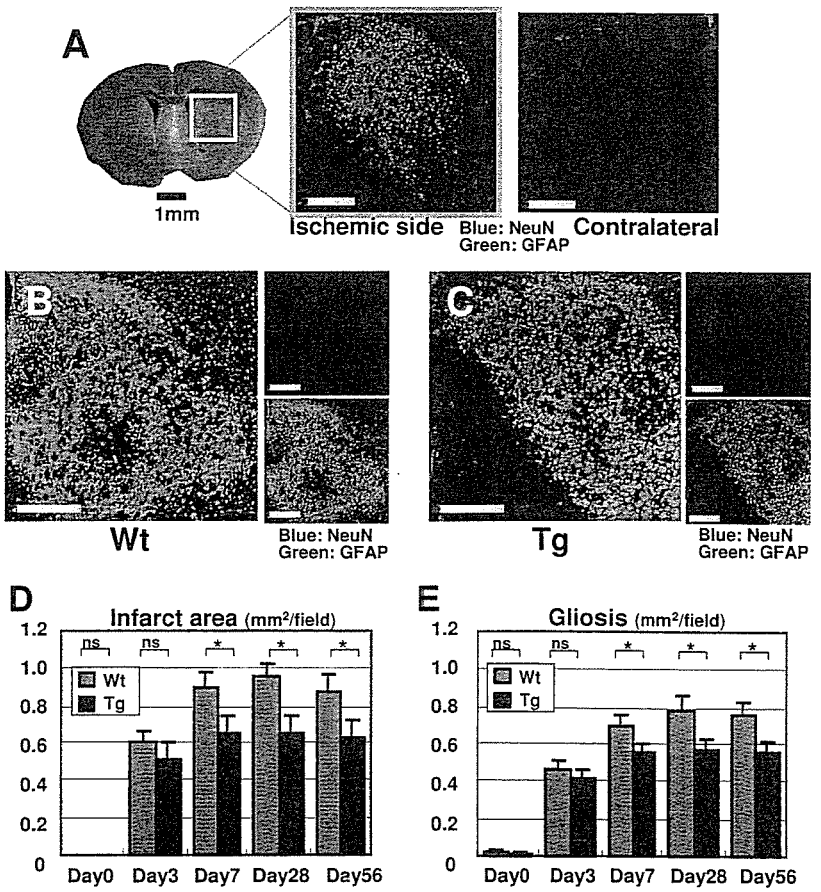

FIG. 2. Effects of AM on infarct area and gliosis after the nonfatal stroke, 20m-MCAO. A, Histological examination of the ischemic striatum. The outlined field was examined for infarct area and gliosis. The ischemic side and contralateral side on d 3 after 20m-MCAO are shown. *Scale bar*, 500 μm (×5 magnification). B and C, Representative images of the ischemic striatum on postoperative d 7 stained for NeuN (*blue*) and GFAP (*green*). Infarct area, defined as the region where NeuN immunoreactivity was lost, and gliosis, defined as the area where GFAP immunoreactivity was observed, in Wt (B) and AM-Tg (C) are shown. *Scale bar*, 500 μm (×5 magnification) D and E, Quantitative analysis of the infarct area (D) and gliosis (E) *, $P < 0.05$; ns, not significant for Wt *vs.* AM-Tg; n = 12.

significantly improved in AM-Tg mice after postoperative d 17. The hindlimb blood flow ratio on d 28 (ipsilateral/contralateral, %) was 56.6 ± 8.3 in Wt *vs.* 73.8 ± 5.3 in AM-Tg ($P < 0.05$; n = 6; Fig. 1, C and D). In this way, promotion of therapeutic angiogenesis by AM was confirmed in AM-Tg mice.

Brain remodeling in ischemic striatum after 20m-MCAO

We investigated the time course of neuronal loss, reactive gliosis, vascular regeneration, and neuronal regeneration; the entire process can be defined as "brain remodeling" after ischemia.

20m-MCAO caused selective loss of NeuN-positive cells and marked reactive gliosis (Fig. 2A) in the ipsilateral striatum within 24 h after the operation; this condition was different from pan-necrosis caused by longer MCAO (*e.g.* 2 h-MCAO). The infarct area, that is, the area of neuronal loss, expanded progressively up to d 7, and then showed gradual increase in size until d 56, whereas gliosis spread in parallel. The expansion of the infarct area in the subacute to chronic phase after mild stroke was compatible with previously reported findings (26). Vascular regeneration in the striatum with enhanced capillary density was obvious after postoperative d 7, and subsequent neurogenesis became obvious after d 28.

The concentrations of the overproduced human AM (fmol/g tissue) in the ischemic brain of AM-Tg mice before and on postoperative d 1 and 28 after 20m-MCAO were 27.8 ± 10.3, 87.4 ± 4.0 and 30.3 ± 16.8, respectively. Those of endogenous mouse AM (fmol/g tissue) were 3.7 ± 2.1, 7.2 ± 2.5, and 4.6 ± 3.0.

Infarct area and gliosis were reduced in AM-Tg mice after 20m-MCAO along with suppression of leukocyte infiltration and ROS production

A significant decrease in infarct area and gliosis was observed in AM-Tg mice (Fig. 2, B–E) after postoperative d 7, but was not obvious on d 3. The infarct area (mm^2/field) on d 56 was 0.88 ± 0.08 in Wt *vs.* 0.64 ± 0.08 in AM-Tg ($P < 0.05$; n = 12; Fig. 2D), and gliosis (mm^2/field) on the same day was 0.76 ± 0.08 in Wt and 0.56 ± 0.07 in AM-Tg ($P < 0.05$; n = 12; Fig. 2E). Leukocyte infiltration quantified as the number of $CD45^+$ cells was significantly suppressed in AM-Tg mice especially from d 3–7. $CD45^+$ cells on d 3 (/mm^2) numbered 197.5 ± 16.6 in Wt *vs.* 140.7 ± 14.6 in AM-Tg ($P < 0.05$; n = 12; Fig. 3, A, B, and G). *In situ* ROS production detected by immunostaining for diHE, which stained the nucleus of $NeuN^+$ or $GFAP^+$ cells, was enhanced in Wt compared with that in AM-Tg mice (Fig. 3, C and D). Apoptotic cells quantified as the number of $ssDNA^+$ cells in the ischemic core were significantly reduced in the AM-Tg mice on d 3–7. $ssDNA^+$ cells (/mm^2) on d 3 numbered 214.8 ± 19.6 in Wt *vs.* 123.2 ± 11.1 in AM-Tg ($P < 0.01$; n = 12; Fig. 3, E, F, and H).

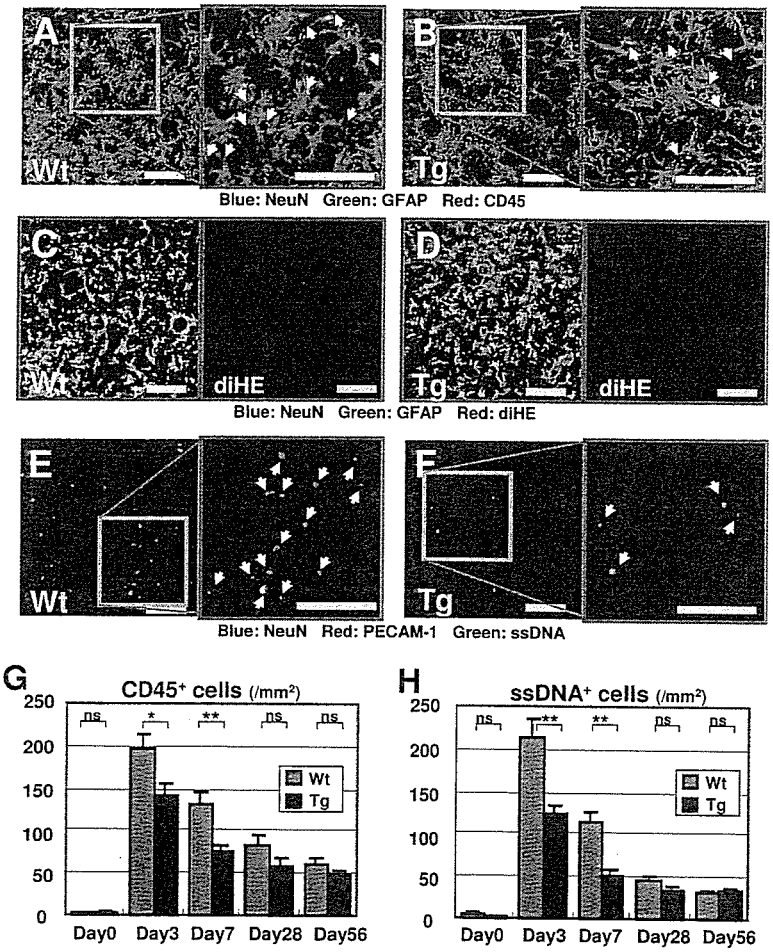

FIG. 3. Effects of AM on leukocyte infiltration, ROS production, and apoptosis in the ischemic brain after 20m-MCAO. A and B, Detection of leukocyte infiltration in the ischemic core on postoperative d 7 by immunostaining for $CD45^+$ cells (*red*) in Wt (A) and AM-Tg (B). *Arrows*, $CD45^+$ cells. C and D, *In situ* detection of ROS in ischemic striatum on postoperative d 7 by immunostaining for diHE (*red*) in Wt (C) and AM-Tg (D). E and F, Detection of apoptotic cells in the ischemic core on postoperative d 7 by immunostaining for $ssDNA^+$ cells (*green*) in Wt (E) and AM-Tg (F). *Arrows*, $ssDNA^+$ cells. G and H, Quantitative analysis of $CD45^+$ cells (G) and $ssDNA^+$ cells (H) in the ischemic core. *, $P < 0.05$; **, $P < 0.01$; ns, not significant for Wt *vs.* AM-Tg; n = 12. *Scale bar*, 100 μm (×20 magnification).

Vascular regeneration was augmented in AM-Tg mice after 20m-MCAO associated with increased mobilization of CD34$^+$ mononuclear cells

The blood flow in the ischemic brain estimated by LDPI was significantly higher in AM-Tg mice after postoperative d 7 and higher flow was maintained until d 56. The brain blood flow ratio (ipsilateral/contralateral, %) on d 56 was 88.9 ± 2.8 in Wt *vs.* 97.6 ± 3.0 in AM-Tg ($P < 0.01$ by ANCOVA; n = 8; Fig. 4, C, D, and H). We were also able to confirm that capillary density determined as the number of PECAM-1$^+$ cells was augmented in AM-Tg mice. The density (/mm^2) on d 56 was 468.8 ± 21.8 in Wt *vs.* 536.6 ± 13.6 in AM-Tg ($P < 0.05$; n = 8; Fig. 4I). Thus, the physiological neovascularization in the ischemic core after stroke was augmented in AM-Tg mice. Peripheral CD34$^+$ mononuclear cells were physiologically enhanced after 20m-MCAO and further increased in AM-Tg mice on d 3–7. The cells (/ml) on d 3 numbered 1774 ± 272 in Wt *vs.* 3199 ± 562 in AM-Tg ($P < 0.05$; n = 6; Fig. 5, A–C).

Augmented neurogenesis and improved recovery of impaired neurological function were observed in AM-Tg mice after 20m-MCAO

BrdU injection on postoperative d 4~6 proved that most BrdU-positive cells were costained with GFAP (data not shown) and that there were far fewer BrdU-PECAM-1 or BrdU-NeuN double-positive cells. We found that regenerated neurons defined as BrdU-NeuN double-positive cells were frequently detected adjacent to the vasculature and the number of these cells on d 56 was correlated with capillary density ($P = 0.003$; n = 12; Fig. 6, A and B; and Table 2). The cells increased from postoperative d 7–56, and their number was significantly higher in AM-Tg mice. The regenerated neurons (/mm^2) on d 56 numbered 20.4 ± 3.9 in Wt *vs.* 33.9 ± 4.7 in AM-Tg ($P < 0.05$; n = 12; Fig. 6C).

Recovery of impaired motor function after 20m-MCAO, quantified as the exercise time on an accelerating rota-rod from the start to collapse down, was significantly better in AM-Tg mice. The exercise time (second) on d 49 was 21.5 ± 1.5 for Wt *vs.* 27.1 ± 2.0 for AM-Tg ($P < 0.01$ by ANCOVA; n = 14; Fig. 6D). To confirm whether vasculogenesis and neurogenesis are the contributing factor to the recovery from the ischemic damage, we analyzed the relation between capillary density, the number of regenerated neuron and the rota-rod result in AM-Tg mice after 20m-MCAO. As shown in Table 2, we found that the capillary density was significantly correlated with the rota-rod exercise time ($P = 0.005$; n = 24) and neurogenesis tended to be correlated with it ($P = 0.08$; n = 12).

Low-concentration AM-Tg mice also showed reduced infarct area and promoted vascular regeneration

We performed 20m-MCAO, using the low-concentration AM-Tg mice (plasma mature AM, 2.6 ± 0.6 fmol/ml) as well as the high-concentration line (plasma mature AM, 24.9 ± 4.2 fmol/ml) to determine appropriate concentration for AM

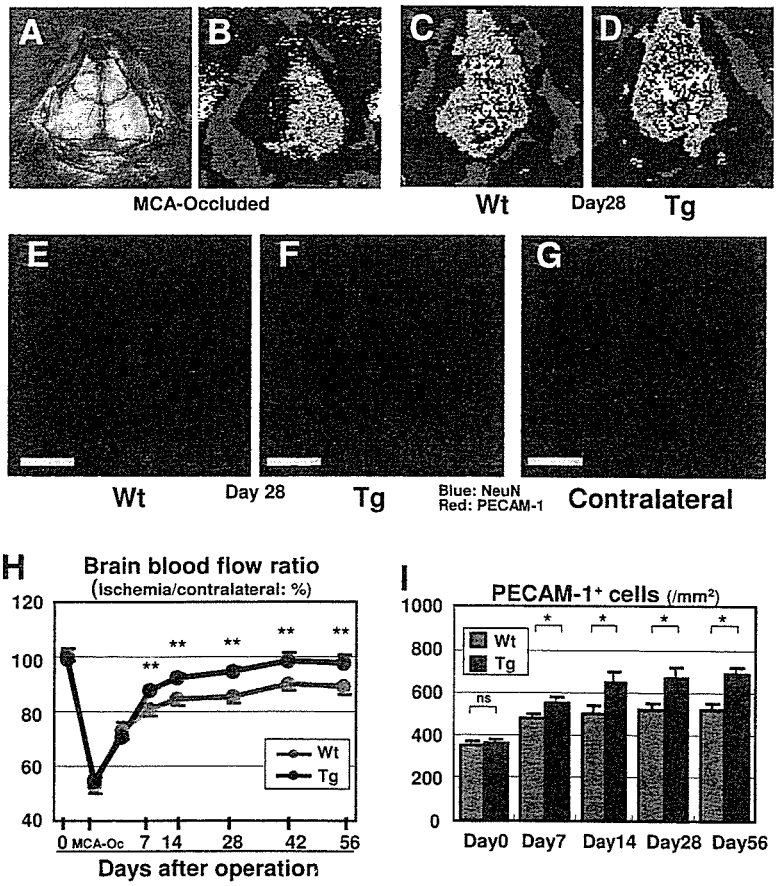

FIG. 4. Effects of AM on vascular regeneration in the ischemic brain after 20m-MCAO. A–D, Analysis of the blood flow in the ischemic brain by LDPI evaluated in mice with the scalp removed (A). Flowmetric analysis of the ischemic brain during MCA-Occlusion (B) and on d 28 after 20m-MCAO in Wt (C) and AM-Tg (D). *Red* or *white* indicates higher flow than *blue* or *green*. E–G, Histological examination of the vasculature in the ischemic core with PECAM-1 staining. Ischemic striatum on d 28 after 20m-MCAO in Wt (E) and AM-Tg (F), and contralateral nonischemic striatum (G). *Scale bar*, 100 μm (×20 magnification). H, Quantitative analysis of the blood flow in the ischemic brain. Comparison of recovery from ischemia after 20m-MCAO between Wt and AM-Tg. MCA-Oc, blood flow during MCA occlusion; **, $P < 0.01$ for Wt *vs.* AM-Tg by ANCOVA; n = 8. I, Quantitative analysis of capillary density in the ischemic brain. Comparison of time course for increase in capillary density, determined as the number of PECAM-1$^+$ cells, between Wt and AM-Tg mice. *, $P < 0.05$; ns, not significant; n = 8.

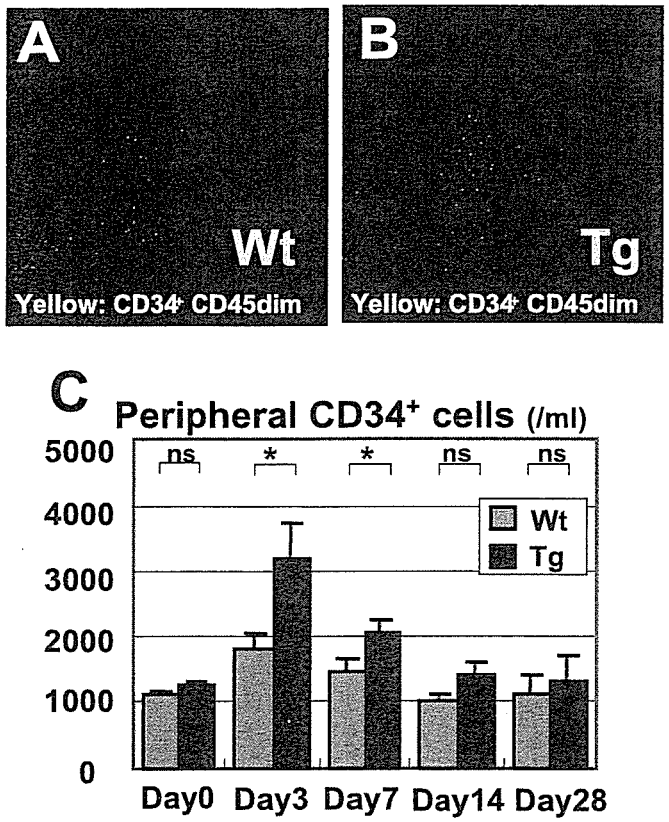

FIG. 5. Effects of AM on mobilization of $CD34^+$ mononuclear cells into peripheral blood after 20m-MCAO. A–C, Quantification of $CD34^+$ mononuclear cells after 20m-MCAO. Scatter plots for fluorescence-activated cell sorting analysis of the $CD34^+$ cells in peripheral blood of Wt (A) and AM-Tg (B) on postoperative d 3. *Yellow*, $CD34^+$-CD45dim mononuclear cells. Comparison of the time course for mobilization of $CD34^+$ cells into peripheral blood between Wt and AM-Tg (C). *, $P < 0.05$; ns, not significant; n = 6.

treatment. The result showed comparable levels of neuroprotection and vascular regeneration between the low-concentration line and the high-concentration line (Table 3). We further analyzed BP-matched mice by administration of low-dose hydralazine (0.1 mM in drinking water) to exclude the possibility that lower BP observed in AM-Tg mice caused beneficial effects after 20m-MCAO. As shown in Table 3, lower BP alone did not reduce the infarct area nor promote vascular regeneration, although hydralazine administration caused BP reduction comparable to that in AM-Tg mice.

Brain edema was reduced in AM-Tg mice at 24 h after 2 h MCAO

The survival rate of mice after the fatal stroke, 2 h-MCAO, was 0% on d 7. We observed no significant difference in the rate between Wt and AM-Tg mice. The edema volume was reduced in AM-Tg mice 24 h after 2 h-MCAO; although the infarct volume showed no significant difference between them. Edema volume (% volume of contralateral hemisphere) was 13.5 ± 1.2 in Wt *vs.* 9.7 ± 0.9 in AM-Tg ($P < 0.05$; n = 9, Fig. 7C), whereas infarct volume (% volume of contralateral hemisphere) was 39.0 ± 4.9 in Wt *vs.* 44.5 ± 7.3 in AM-Tg (not significant; n = 9; Fig. 7, A and B). As shown in Fig. 7D, we found that Evans Blue leakage into the ischemic

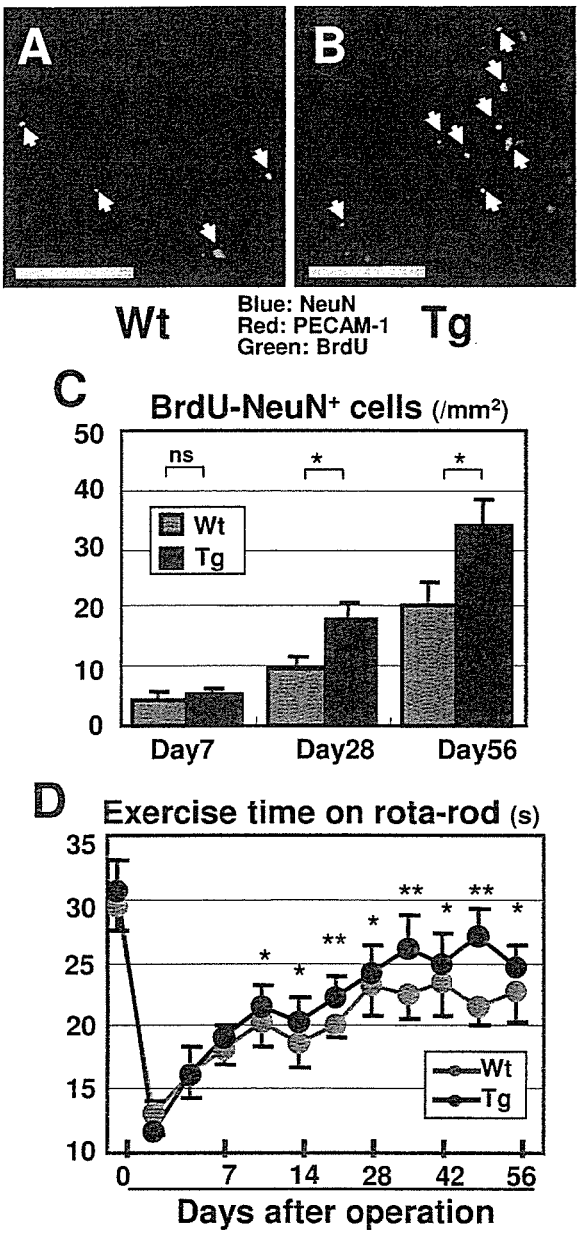

FIG. 6. Effects of AM on neurogenesis and recovery of impaired motor function after 20m-MCAO. A and B, Detection of regenerated neurons on postoperative d 56 by immunostaining for BrdU and NeuN. *Arrows*, BrdU-NeuN double-positive cells in the ischemic core of Wt (A) and AM-Tg (B). *Scale bar*, 100 μm. C, Quantitative analysis of regenerated neurons. *, $P < 0.05$; ns, not significant; n = 12. D, Recovery of impaired motor function after 20m-MCAO, quantified as the exercise time on an accelerating rota-rod from the start to collapse down. *, $P < 0.05$; **, $P < 0.01$ for Wt *vs.* AM-Tg by ANCOVA; n = 14.

core was significantly reduced in AM-Tg mice. The content of Evans Blue (ng/g tissue) in the ischemic brain at 24 h after 2 h-MCAO was 239.4 ± 37.3 in Wt *vs.* 133.9 ± 9.4 in AM-Tg ($P < 0.01$; n = 4; Fig. 7E).

AM exerted direct antiapoptotic and neurodifferentiating effects on neuronal cells in vitro

After 48 h incubation of NHNP under serum-free apoptotic conditions, in which the number of the cells had decreased

TABLE 2. Significant correlation between the regenerative elements and apoptosis, neurogenesis, and functional recovery after 20m-MCAO

X	Y	Regression line	*P*
Capillary density (% field)	Apoptotic cells (/mm^2)	Y = −2.3X+37	0.01
Capillary density (% field)	Regenerated neuron (/mm^2)	Y = 3.2X-21	0.003
Capillary density (% field)	Rota-rod result (sec)	Y = 1.3X+9	0.005
Regenerated neuron (/mm^2)	Rota-rod result (sec)	Y = 0.3X+19	0.08

n = 12–24.

to half, the viable cell number was increased in the AM 10^{-8} mol/liter-treated group to 38.8 ± 7.1% over the control ($P < 0.01$; n = 4; Fig. 8C). The ratio of ssDNA$^+$ cells to total cells (%) was 9.8 ± 1.9 in Wt *vs.* 4.0 ± 0.6 in the AM 10^{-8} mol/liter-treated group ($P < 0.05$; n = 4; Fig. 8, A, B, and D).

After 7-d incubation of PC12 cells under differentiation condition, both the cell number and the length of neuronal process increased dose dependently as a result of AM treatment ($P < 0.01$; n = 6; Fig. 8, E and I). Coculture with endothelial cells also increased the cell number and the length of neuronal process. The effect of AM was canceled by AM blockers, PKA inhibitors, and PI3K inhibitors (Table 4).

Exogenous administration of AM reduced infarct area, promoted vascular regeneration, and improved neurological function after 20m-MCAO

We further examined the effects of exogenous infusion of mature AM by means of an osmotic pump in the amount reported to achieve a plasma concentration of 2 fmol/ml. Implantation of the pump just after the operation resulted in increase in the blood flow and reduction of the infarct area on postoperative d 7 to a comparable level to those in AM-Tg mice. Moreover, the treatment started at 24 h after the operation (d 1) showed almost the same therapeutic effect. However, the implantation at 72 h after the operation (d 3) failed to reveal any significant effect (Fig. 9, A and B). The rota-rod exercise time was significantly improved in the AM-treated group. The exercise time (second) on d 7 was 17.0 ± 1.5 in vehicle group *vs.* 18.1 ± 2.0 in AM-treated group (n = 6 for vehicle group and 12 for AM-treated group; $P < 0.05$ by ANCOVA).

Discussion

In the present study, we generated novel transgenic mice that overproduce AM in their liver without overproduction of mature PAMP and investigated the roles of AM in degeneration or regeneration processes after brain ischemia, which can be defined as brain remodeling, as summarized in Fig. 10. Brain edema in acute phase, neuronal loss and gliosis in subacute to chronic phase after 20m-MCAO were reduced in AM-Tg mice. Furthermore, vascular regeneration, mobilization of CD34$^+$ mononuclear cells and subsequent neurogenesis were enhanced in them. These effects resulted in improved recovery of motor function after the nonfatal stroke. AM was also found to exert direct antiapoptotic and neuro-differentiating effects on neuronal cells *in vitro*. Exogenous administration of AM in mice after 20m-MCAO also

TABLE 3. Comparison of the effects on neuroprotection and vascular regeneration after 20m-MCAO between Wt control mice, hydralazine-administrated mice, and the low and high concentration lines of AM-Tg

Mice	Infarct area (mm^2/field)	Brain blood flow (% Contralateral)	Systolic BP (mm Hg)
Control	0.90 ± 0.09	80.8 ± 2.3	120.1 ± 2.2
Hydralazine	0.94 ± 0.17^{ns}	79.6 ± 2.6^{ns}	101.0 ± 3.9^a
Low-conc. AM-Tg	0.58 ± 0.12^b	88.4 ± 2.9^b	105.1 ± 1.8^a
High-conc. AM-Tg	0.67 ± 0.09^b	86.3 ± 2.0^b	106.4 ± 3.5^a

conc., Concentration.
^{a} $P < 0.01$; ^{b} $P < 0.05$; ns, not significant *vs.* control; n = 6.

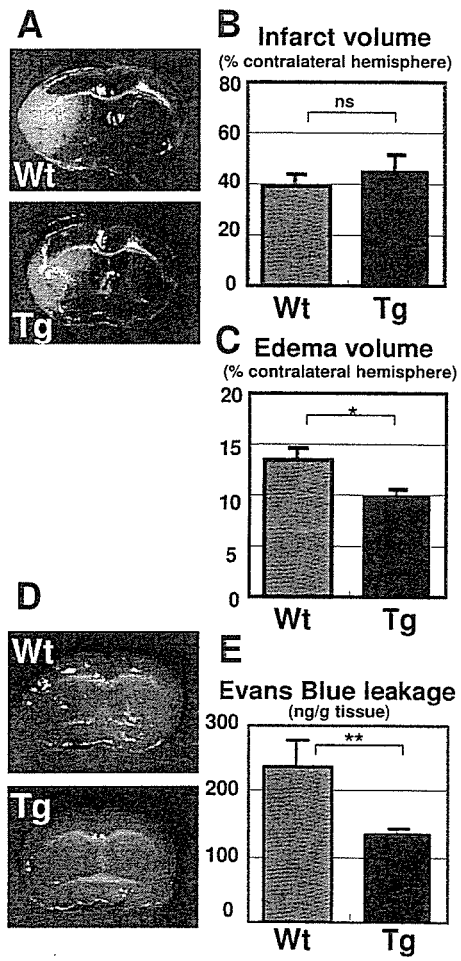

FIG. 7. Effects of AM on infarct size and brain edema in the fatal stroke, 2 h-MCAO. A, Comparison of infarct size between Wt and AM-Tg with 2,3,5-triphenyltetrazolium chloride staining at 4.0 mm from the frontal pole. *White area* represents infarction. B and C, Infarct (B) and edema (C) volumes quantified 24 h after the operation of 2 h-MCAO. *, $P < 0.05$; ns, not significant for Wt and AM-Tg; n = 9. D: Representative image of *in situ* Evans Blue leakage into the ischemic core at 24 h after 2 h-MCAO. E, Quantification of Evans Blue in the ischemic brain. **, $P < 0.01$; n = 4.

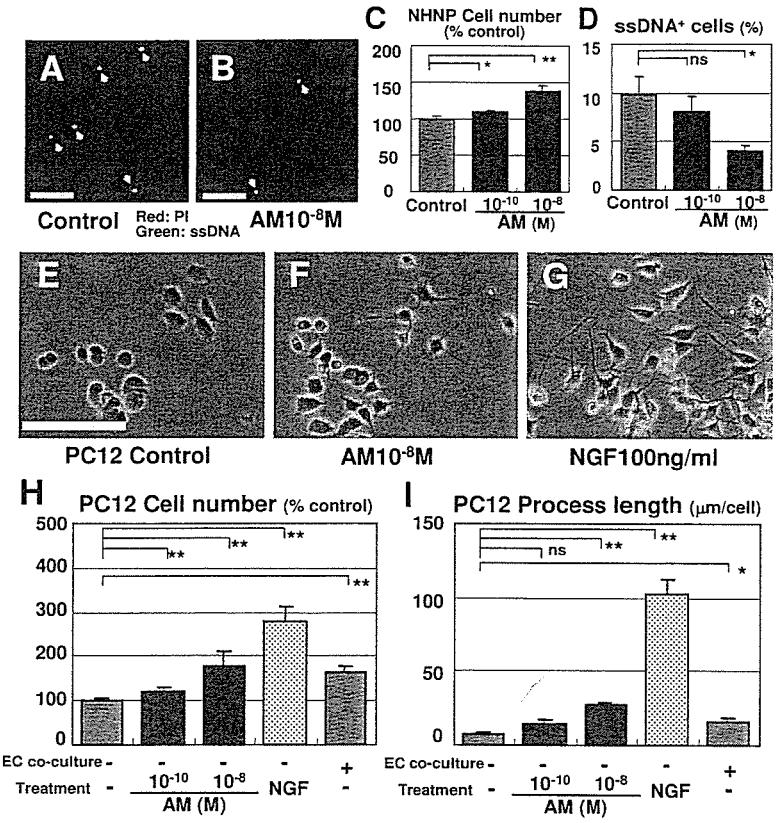

FIG. 8. Effects of AM *in vitro* on apoptosis of NHNP neuronal progenitor cells and neuronal differentiation of PC12 cells. A–D, *In vitro* analysis of apoptotic NHNP after incubation with (B) or without (A) AM. NHNP cell number (C) and the ratio of ssDNA$^+$ cells to total cells (D) after 48 h incubation. *, $P < 0.05$; **, $P < 0.01$; ns, not significant *vs.* control; n = 4; *scale bar*, 100 μm. E–G, Effects of AM on neuronal differentiation of PC12 cells evaluated by the length of neuronal process. Microscopic examination of PC12 cells after incubation for 7 d (E). AM (F) or nerve growth factor (G) was added to the culture medium. Quantification of cell number (H) and the length of neuronal process (I). *, $P < 0.05$; **, $P < 0.01$; ns, not significant; n = 6; *scale bar*, 100 μm.

reduced the infarct area, and promoted vascular regeneration and functional recovery.

Stroke causes two different types of neuronal death: necrosis and apoptosis. Acute neuronal loss, which is completed within a few days after ischemic damage, is necrotic, whereas delayed neuronal loss, which may start several days after transient ischemia, is considered to be apoptotic (27, 28). Many studies have found that treatments that reduce inflammation or oxidative stress are beneficial for the prevention of apoptotic neuronal loss (29, 30).

In this study, we demonstrated that AM exerts neuroprotective actions in the ischemic brain. A significant reduction in neuronal loss in AM-Tg mice after 20m-MCAO became obvious after postoperative d 7, but was not obvious before d 3. A significant decrease in ssDNA-positive cells inside and on the border of the ischemic area was observed in AM-Tg mice in association with a reduction in CD45$^+$ cells and *in situ* ROS production in the subacute phase. AM is therefore assumed to reduce delayed neuronal loss through suppression of the apoptotic process. Furthermore, we confirmed that AM directly suppresses apoptosis of neuronal progenitor cells *in vitro*. These findings suggest that AM exerts neuroprotective effects on the ischemic brain by reducing apoptotic neuronal loss through both its direct antiapoptotic action on neurons and indirect effect via antiinflammation and anti-ROS production. Consistent with the findings in this study, several recent reports have provided evidences for the organ-protective effects of AM against inflammation and oxidative stress (31–33). In addition, we found significant negative correlation between capillary density and apoptotic cells in the same section on postoperative d 7 after 20m-MCAO. Moreover, the infarct area kept expanding between d 7–28 in Wt mice, whereas AM-Tg mice did not show the increase in size in this period. These findings suggest that the increased blood flow in AM-Tg mice was one of the causes of neuroprotection after 20m-MCAO, although we suppose that multiple actions of AM, as described above, could also contribute for neuroprotection.

Increased vascularity is reported to be associated with improved neurological recovery in human patients with stroke (34). This implies that physiological vascular regeneration in the ischemic brain constitutes a beneficial response for the recovery of impaired neurological function. Moreover, neurogenesis after stroke even in adulthood has been demonstrated to occur in a place surrounded by the vascu-

TABLE 4. Effects of AM-antagonists, PKA inhibitors, and PI3K inhibitors on AM-induced neural differentiation of PC12 cells

	Process length (μm/cell)
PC12	6.8 ± 1.7
+AM (10^{-8} mol/liter)	23.6 ± 4.0[a]
+AM+AM(22–52) (10^{-5} mol/liter)	11.8 ± 3.4[b]
+AM+CGRP(8–37) (10^{-5} mol/liter)	14.8 ± 1.9[c]
+AM+Rp-cAMP (10^{-5} mol/liter)	10.2 ± 2.7[b]
+AM+PKA Inh (10^{-6} mol/liter)	7.2 ± 2.3[b]
+AM+LY294002 (10^{-5} mol/liter)	4.6 ± 1.6[b]
+AM+wortmannin (10^{-7} mol/liter)	5.4 ± 1.1[b]
PC12-EC coculture	20.7 ± 2.1[a]

EC, Endothelial cell.

[a] $P < 0.01$ *vs.* PC12 without AM; [b] $P < 0.01$ *vs.* PC12 with AM (10^{-8} mol/liter); [c] $P < 0.05$; n = 8.

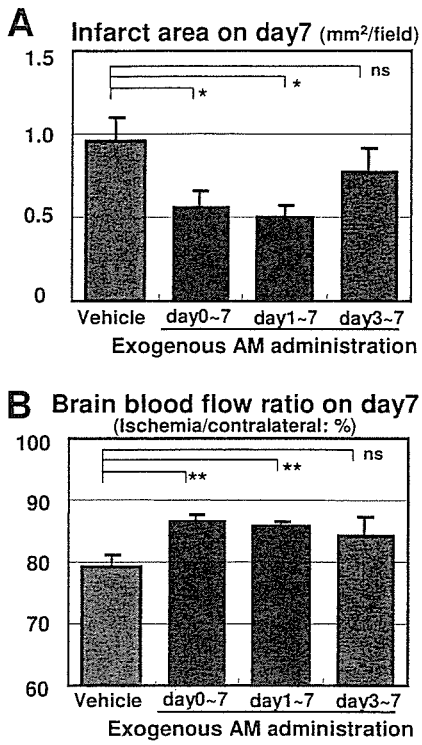

FIG. 9. Effects of exogenously administrated AM on neuroprotection and vascular regeneration after 20m-MCAO. 50 ng/h AM was administrated to mice with an ip implanted osmotic pump. Infarct area (A) and blood flow (B) on postoperative d 7 with different starting points for AM administration. *, $P < 0.05$; **, $P < 0.01$; ns, not significant *vs.* vehicle; n = 6.

lature, the so-called "vascular niche" (35), where endothelial cells secrete neurogenic factors, including basic fibroblast growth factor, vascular endothelial growth factor, and brain-derived neurotrophic factor, and create conditions conducive to neurogenesis (36). Therefore, vascular regeneration is assumed to rescue ischemic brain via not only supply of oxygen and nutrition but also promotion of neurogenesis. We confirmed in this study that neurogenesis occurred adjacent to neovessels in the ischemic core and the number of regenerated neurons was correlated with vascular density.

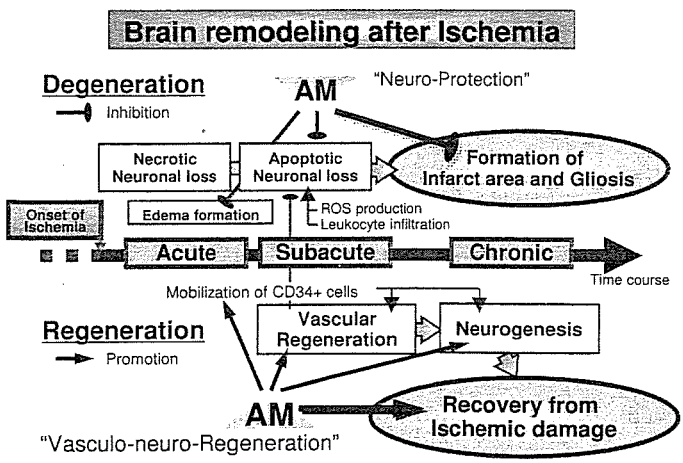

FIG. 10. Summary of brain remodeling after ischemia and effects of AM on the ischemic brain observed in this study.

We have assigned the term "vasculo-neuro-regeneration" to the entire process of enhancement of vasculogenesis and subsequent neurogenesis.

We demonstrated that AM promotes vasculo-neuro-regeneration in the ischemic brain. Blood flow and capillary density in the ischemic brain after 20m-MCAO was significantly enhanced in AM-Tg mice after postoperative d 7 with subsequent promotion of neurogenesis after d 28. The promoted vasculogenesis and neurogenesis observed in AM-Tg mice was significantly correlated with the functional recovery after 20m-MCAO. This result suggests that these two regenerative elements might contribute to the functional recovery after 20m-MCAO. The neovascularization was preceded by augmented mobilization of $CD34^+$ mononuclear cells, which are known to differentiate into endothelial cells and contribute to vasculogenesis (37). Recently, iv infusion of $CD34^+$ cells has reported to promote not only neovascularization but also neurogenesis (38). Furthermore, we observed the direct promoting action of AM on neural differentiation of PC12 cells via cAMP/PKA- and PI3K/Akt-dependent pathways. The totality of these findings suggests that the neurogenic action of AM *in vivo* comprises at least two different mechanisms: a direct action on neuronal cells through activation of PKA and Akt and an indirect action on neurogenesis after enhanced neovascularization.

Judging from the ratio of mature AM to total AM as shown in Table 1, the mature AM concentration in the ischemic brain of AM-Tg mice was expected to be 1~4 fmol/g tissue. The concentration seems to be comparable to the reported effective concentration of mature AM *in vivo* (25, 39). The *in vivo* concentration of human mature AM in the whole brain (1 fmol/g tissue level) and in the plasma (10 fmol/ml level) might be lower than the minimal concentration required for its *in vitro* action (100 fmol/ml) observed in this study. The actual effective concentration *in vitro*, however, might be lower because the administrated peptide is rapidly degradated *in vitro*. In addition, it is demonstrated in previous reports including ours (40, 41), that peptides could exert their significant actions at the stably maintained concentration, that is, by 2 orders of magnitude lower than that of bolus administration. In AM-Tg mice, the AM concentration was maintained at the same level due to the constitutive overproduction by the human serum amyloid P component promoter. Thus, we suppose that the direct neuronal action of AM *in vivo* could be possible in this stroke model.

In view of clinical application, we also tried exogenous administration of AM by ip implanted osmotic pump to determine appropriate amount and timing of AM administration after 20m-MCAO. Previous reports on AM administration for rodents or human set the therapeutic dose at 2~25 fmol/ml (25, 39). For our experiments, therefore, we used two lines of transgenic mice with a plasma concentration of mature AM of 24.9 ± 4.2 and 2.6 ± 0.6 fmol/ml. The results showed comparable effects of AM in these two lines on neuroprotection and vascular regeneration. This led us to conclude that a plasma level of 2~3 fmol/ml of mature AM, 3~5 times higher than its physiological concentration, was sufficient to attain therapeutic effects for the mice after 20m-MCAO. We next tried exogenous infusion of AM with an osmotic pump in the amount reported to achieve a plasma

concentration of 2~3 fmol/ml. The exogenous AM treatment which started just after the induction of 20m-MCAO or at 24 h after produced significant effects that were comparable to those seen in the two lines of AM-Tg mice. However, that from 72 h postoperatively failed to reveal significant effects. These results showed that appropriate timing to start AM administration after stroke is less than 72 h after the event.

We performed two different stroke models, nonfatal 20m-MCAO and fatal 2 h-MCAO. In 2 h-MCAO, we observed significant reduction of brain edema in AM-Tg mice through reduction of vascular permeability, which is compatible with previous report (42). However, infarct size was not reduced on postoperative d 1 after 2 h-MCAO. The result suggests that AM exerts more significant therapeutic effect on the brain tissue after nonfatal ischemia. The therapeutic potential for brain edema after fatal stroke is further to be elucidated.

Cerebral ischemia, including stroke, vascular Parkinson's disease and vascular dementia, is one of the most serious medical problems because it causes critical impairment of activity and quality of daily life. Regenerative medicine is now in the spotlight as a promising therapy to treat ischemic brain which has been considered to be irreversible and indicated for no active treatment. Various humoral factors are anticipated for their therapeutic potential for ischemic brain through neurogenic (*e.g.* basic fibroblast growth factor and epidermal growth factor) and angiogenic (*e.g.* vascular endothelial growth factor and hepatocyte growth factor) effects (43–47). Among them, we believe that the vascular hormone AM has several advantages as a therapeutic agent for ischemic brain. We can expect multiple effects of AM through its neuroprotective and vasculo-neuro-regenerative actions as shown in this study. In addition, AM has already been safely used for human patients with heart failure or pulmonary hypertension without any mention of critical adverse effects resulting from iv administration (39).

Thus, we are prompted to propose a new strategy to rescue ischemic brain by using vascular hormone AM for the combined neuroprotective and vasculo-neuro-regenerative therapy to improve impaired neurological function.

Acknowledgments

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Expression of the adrenomedullin gene in adipose tissue

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Abstract

Adrenomedullin (AM) is a potent vasodilating peptide originally isolated from human pheochromocytoma cells. This report concerns the expression and secretion of AM from adipose tissue. Northern blot analysis demonstrated marked expression of AM mRNA in mouse adipose tissue. Expression levels in adipose tissues were 2.5–3.2 times higher than in the kidney. AM mRNA level in mature adipocytes was 7.3 times higher than in the stroma–vascular fraction of adipose tissue. In mature adipocyte culture, time-dependent increase of AM peptide concentration in the culture medium was detected. AM expression was also detected in human subcutaneous adipose tissue. Adipose AM expression significantly increased in obesity mouse model, high-fat diet fed mice and ob/ob mice. These results suggest that adipose tissue, especially mature adipocytes, is major source of AM in the body, and that adipocyte-derived AM plays a pathophysiological role in obesity.

Keywords: Adrenomedullin; Adiopocyte; Fat; Obesity; ob/ob mice

1. Introduction

It has recently been suggested that adipose tissue is an endocrine organ. A wide variety of factors secreted from adipocytes, including leptin, TNF alpha, adiponectin, resistin and free fatty acid, are playing crucial roles in energy expenditure and glucose metabolism [1]. Adipocytes produce a host of vasoactive substances including angiotensinII [2], endothelin-1 [3], nitric oxide [4], prostacyclin [5] and natriuretic peptide [6]. Recent studies have suggested the paracrine/autocrine involvement of these molecules in the regulation of adipocyte growth and differentiation.

Adrenomedullin (AM) is a potent vasodilating peptide that was originally isolated from human pheochromocytoma cells [7]. Structural analysis indicates that AM belongs to the calcitonin gene-related peptide (CGRP) superfamily. AM and CGRP share a common receptor known as the calcitonin-receptor-like-receptor (CRLR). The ligand specificity of CRLR is regulated by the receptor-activity-modifying proteins (RAMPs), which is a family of proteins with a single transmembrane domain [8]. CRLR associated with RAMP1 acts as a CGRP receptor, while it binds to AM when coexpressed with RAMP2/3. It has been reported that AM-producing cells are distributed widely throughout the body, including the adrenal glands, lungs, heart and kidneys [9]. In vitro studies have demonstrated that vascular smooth muscle cells and endothelial cells secrete AM, and have suggested that the major source of AM in the body is the vascular wall [10].

We have previously reported that RAMPs are highly expressed in rat adipose tissue [11], and have posited the existence of an AM system in adipose tissue. The study reported here found massive expression of the AM gene in mouse and human adipose tissue, and its upregulation in obesity mouse models.

2. Materials and methods

2.1. Ethics

This study conforms to the policy of the Ethics Committee on Human Research of the Kyoto University Graduate School of Medicine, and written informed consent was obtained from all subjects.

Abbreviations: AM, adrenomedullin; CGRP, calcitonin gene-related peptide; RAMPs, receptor-activity-modifying protein; sv-f, stroma–vascular fraction; BAT, intrascapular brown adipose tissue; VEC, vascular endothelial cells; VSMC, vascular smooth muscle cells.

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2.2. Mouse adipose tissue

Male C57BL/6 and ob/ob mice aged 14 weeks provided by Shionogi Research Laboratories (Osaka, Japan) were used in this study. They were treated in accordance with our institutional guidelines for animal research, housed in an animal room maintained at 24 °C with a 12:12-h light-dark cycle, fed a standard laboratory diet and given water ad libitum. The retroperitoneal, subcutaneous, omental, epididymal white adipose tissue, intrascapular brown adipose tissue (BAT), kidney, lung and heart were removed and stored at −80 °C until total RNA preparation.

2.3. Mature adipocytes

Murine mature adipocytes were isolated from subcutaneous adipose tissue of C3H/He mice (female, 8 months old) with a modificied version of the method of Rodbell [12]. In brief, the adipose tissue was minced and digested in a 0.2% collagenase solution at 37 °C for 1 h with constant shaking. The digested fluid was filtered through 100 μm nylon mesh and separated by centrifugation performed three times at 180 g for 5 min. Mature adipocytes appeared and were collected as a floating layer, while the sediment consisted of stroma–vascular fraction (sv-f).

2.4. Human adipose tissue

Human abdominal subcutaneous adipose tissue was obtained during plastic surgery after written permission had been obtained. Human kidney and lung mRNA were commercially available (Clontech Laboratories, Inc., Palo Alto, CA, USA).

2.5. RNA extraction and Northern blot analysis

Total RNA was extracted with TRIzol reagent (Invitrogen Co., Carlsbad, CA, USA). Northern blot analysis was performed as previously described using mouse and human AM cDNA as probes [11].

2.6. Measurements of AM released from isolated adipocytes

500 μl (2.5×10^5 cells) of isolated adipocytes from subcutaneous adipose tissue of ICR mouse (male, 12 weeks old) were incubated together with DMEM/H-12 (total volume: 500 μl) containing 10% fetal bovine serum in a CO_2 incubator for 24 h at 37 °C [13]. Aliquots of the incubation medium were removed at 6 and 24 h and stored at −20 °C for measurement of AM. The AM content in 100 μl of the incubation medium was determined by means of a radioimmunoassay (Phoenix Pharmaceuticals, Inc., Belmont, CA, USA).

2.7. TaqMan real time PCR

The quantitative real time RT-PCR was employed to examine the murine AM gene expression. Briefly, AM cDNA was synthesized with Superscript II reverse transcriptase (Gibco-BRL, St. Louis, MO, USA) and used as a template. The primers and probes for TaqMan PCR analysis were designed with primer-express software (Applied Biosystems, Foster City, CA, USA) as follows:

AM forward, 5′-CTCGCTGATGAGACGACAGTTC-3′,
AM reverse, 5′-CTCTGGCGGTAGCGTTTGAC-3′,
detection probe: 5′-CAGCAATCAGAGCGAAGCCCA-CATT-3′.

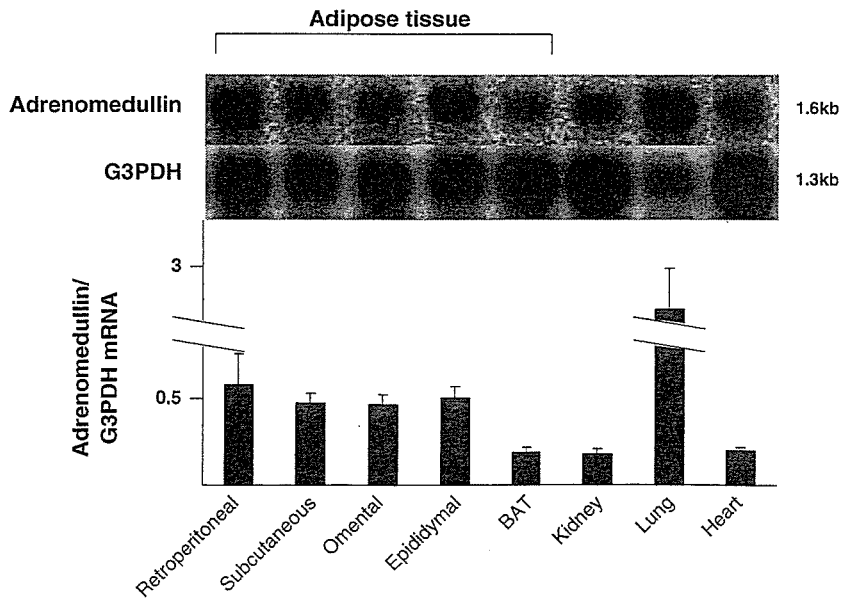

Fig. 1. Northern blot analysis of AM mRNA content of C57BL/6 mice. 10 μg of total RNA in each lane was electrophoresed and hybridized with mouse AM cDNA probes. The lower panel indicates hybridization with a G3PDH probe as an internal control. The ratio of AM to G3PDH mRNA is shown below. Bars represent mean ± S.E.M.

Rodent ribosomal 18S as an internal control was amplified using a commercially available kit (Applied Biosystems) at the same time. Thermal cycling was performed at 40 cycles of 95 °C for 15 s and of 60 °C for 1 min. Reactions were performed in triplicate with the ABI Prism 7700 Sequence Detection System (Applied Biosystems). Input RNA amounts were calculated with a multiplex comparative method for mRNAs of AM and 18S protein.

2.8. High-fat diet (HFD)

Male C57BL/6 mice aged 10 weeks were randomly divided into two groups, one fed a standard fat diet (11% fat by energy) and the other a high-fat diet (60% fat by energy, Research Diets, Inc., New Brunswick, NJ, USA). After 11 weeks, the retroperitoneal, subcutaneous, omental, epididymal white adipose tissue and kidney were removed and stored at −80 °C until total RNA preparation. Mouse plasma AM and leptin concentrations were determined with a radioimmunoassay (Phoenix Pharmaceuticals, Inc.) and an enzyme immunoassay (Immune Biological Laboratory, Gunma, Japan), respectively.

2.9. Statistical analysis

All data are expressed as the mean±S.E.M. Statistical analysis was performed with Student's *t*-test. Values of $P<0.05$ were considered to be statistically significant.

3. Results

3.1. AM gene expression in adipose tissue and mature adipocytes

The expression of AM gene was examined by means of Northern blotting (Fig. 1). A marked expression of AM mRNA was detected in all white adipose tissues from C57BL/6. The expression levels in the retroperitoneal, subcutaneous, omental, and epididymal adipose tissue were 3.2, 2.6, 2.5 and 2.7 times higher than the corresponding levels in the kidney. In addition to mature adipocytes, adipose tissue contains blood vessels, fibroblasts and preadipocytes, among which especially the vascular wall has been regarded as a site of AM production. We therefore separated the adipose tissue into a mature adipocytes fraction and sv-f, and examined AM expression in each fraction (Fig. 2). The AM mRNA level in the mature adipocyte

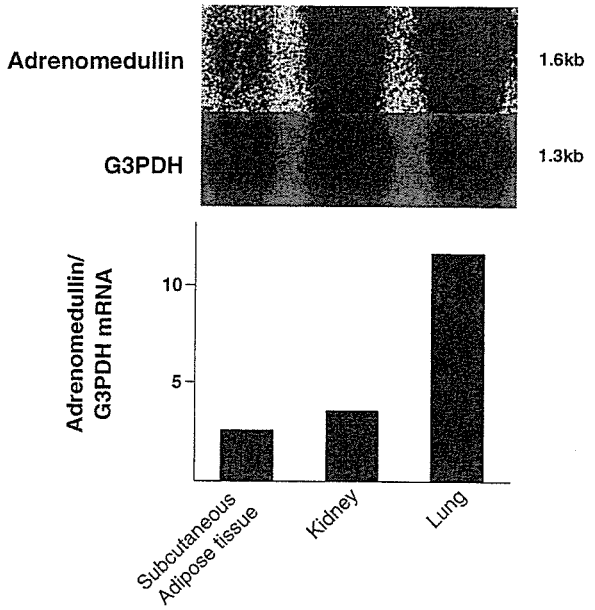

Fig. 3. Northern blot analysis of human AM mRNA content. 10 μg of total RNA in each lane was electrophoresed and hybridized with human AM cDNA probes. The lower panel indicates hybridization with a G3PDH probe as an internal control. The ratio of the AM to G3PDH mRNA is shown below.

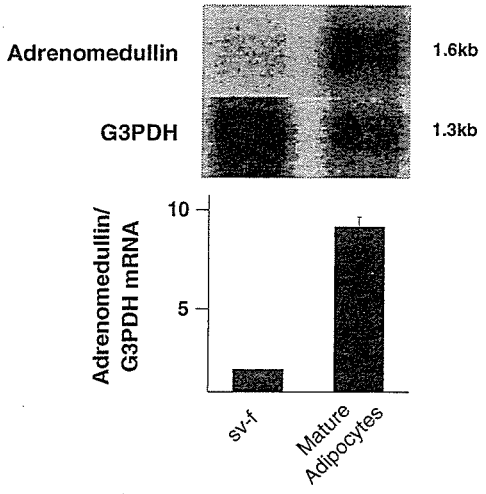

Fig. 2. Northern blot analysis of AM mRNA content in stroma–vascular fraction and isolated mature adipocytes of C3H/He mice. 10 μg of total RNA in each lane were electrophoresed and hybridized with mouse AM cDNA probes. The lower panel indicates hybridization with a G3PDH probe as an internal control. The ratio of AM to G3PDH mRNA is shown below. Bars represent the mean±S.E.M.

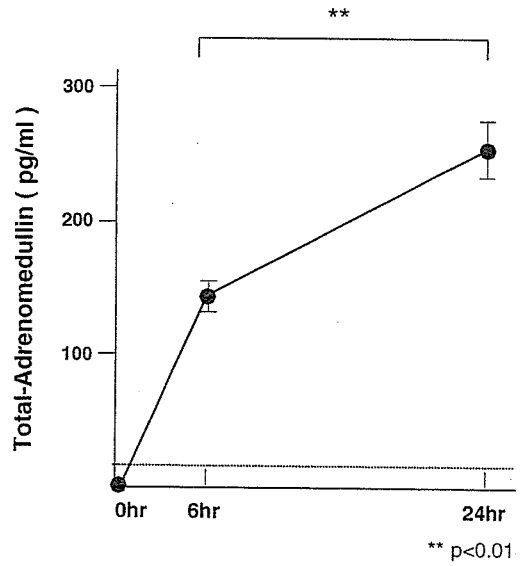

Fig. 4. Time course of AM levels in culture medium of mature adipocytes isolated from ICR mice (12 wk old, male, $n=5$). Mature adipocytes released AM, which significantly increased in a time-dependent manner. Bars represent the mean±S.E.M. Statistical analysis was performed with the *t* test. $^{**}P<0.01$.

Table 1
Body weight and plasma parameters in mice fed with high-fat diet or standard chow

	Standard chow	High-fat diet
Body weight(g)	31.3±1.2	48.6±2.1**
BS (mg/dl)	87.0±8.5	141.5±12.7**
FFA (mEq/ml)	0.51±0.08	0.94±0.18*
Leptin (ng/ml)	0.23±0.02	18.5±3.7***
Total AM (pg/ml)	56.3±17.5	84.9±6.2*

*$P<0.05$; **$P<0.01$, ***$P<0.001$ vs. standard chow group.

fraction was 7.3 times higher than that in the sv-f. In view of the tissue volume, this suggests that the major source of AM mRNA in the adipose tissue is mature adipocytes.

In the human subcutaneous adipose tissues obtained during plastic surgery, AM expression comparable to that in the kidney was detected (Fig. 3).

3.2. AM secretion from mature adipocytes

In addition to AM mRNA expression in the adipose tissue and mature adipocytes, we cultured mature adipocytes and measured AM peptide secretion in the medium. As shown in Fig. 4, AM peptide detected in the cultured medium increased in a time-dependent manner, indicating that AM is secreted from mature adipocytes.

3.3. Changes in AM gene expression in obesity

In order to assess the relationship between obesity and adipose AM production, we examined the AM mRNA expression after administration of the high-fat diet. As shown in Table 1, the HFD group weighed 1.5 times more than the standard chow group, and plasma leptin concentration was significantly higher as well as concentrations of plasma free fatty acid (FFA) and glucose. Plasma AM concentration in the HFD group was significantly higher than that in the standard chow group. After the high-fat diet, AM expression level was elevated in all adipose tissue compared with that in the control group, especially in retroperitoneal, subcutaneous and epididymal white adipose tissue (Fig. 5). In contrast, AM expression levels in the kidney of the HFD group and the control group were comparable.

In addition to HFD, we also examined AM mRNA expression in the obesity mouse model, ob/ob. Fig. 6 shows the AM mRNA level in the adipose tissues of ob/ob and the control, namely, C57BL/6 mice. In ob/ob mice, AM expression level was elevated in all adipose tissues compared with that in C57BL/6, especially in subcutaneous, omental, epididymal white adipose tissue and BAT.

4. Discussion

AM has been implicated in the regulation of circulation and the development of vasculature. Although AM was originally isolated from pheochromocytoma cells, the major site of production in the physiological state is believed to be vascular endothelial cells. Our findings demonstrate that adipose tissue strongly expresses the AM gene. In C57BL/6 mice, AM mRNA expression in all white adipose tissues examined was found to be higher than that detected in kidney. Adipose tissue is capillary-rich, containing blood vessels, fibroblasts and preadipocytes in addition to mature adipocytes. In order to exclude the possibility that AM mRNA in the adipose tissue is of vascular endothelial cell origin, we examined the AM expression in the mature adipocyte fraction and sv-f separately and found that the AM mRNA level in the mature adipocyte fraction was much higher than that in the sv-f, which consists of small vessels, preadipocytes and connective tissue. Moreover, we determined AM peptide secretion from isolated mature adipocytes in the medium. These findings indicate that the major source of AM in the adipose tissue consists of mature adipocytes. A few reports about adipose tissue and AM have

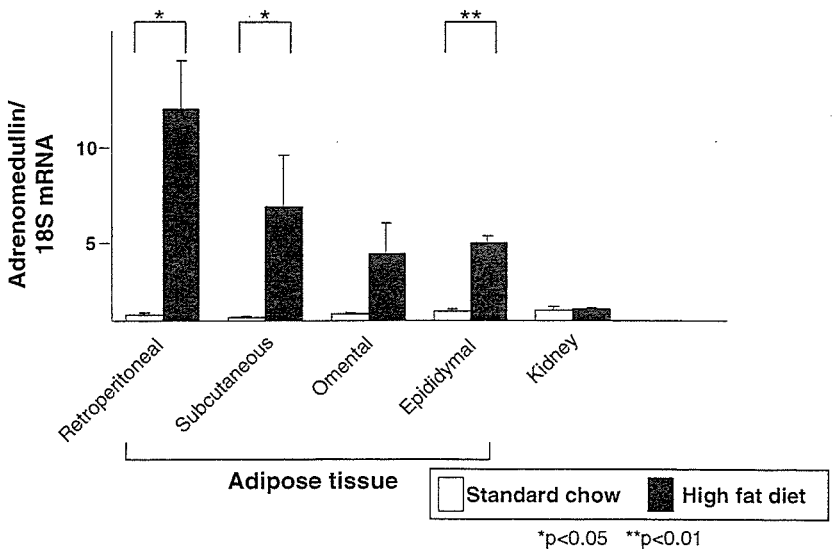

Fig. 5. AM mRNA levels from C57BL/6 mice (21 wk old, male, $n=5$) after 11 weeks of standard chow diet (open bars) or high-fat diet (closed bars). Bars represent the mean±S.E.M. Statistical analysis was performed with the t test. *$P<0.05$; **$P<0.01$.

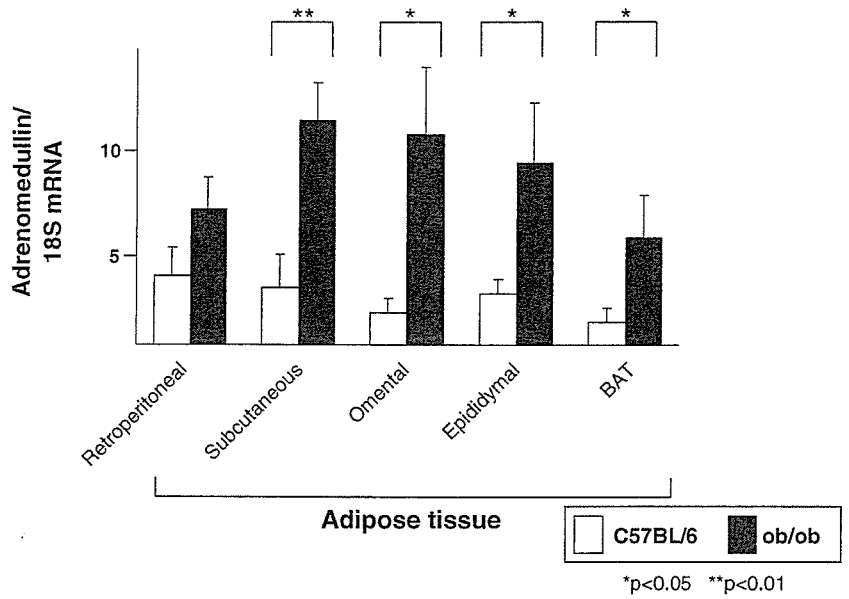

Fig. 6. AM mRNA levels in C57BL/6 (open bars) and ob/ob mice (closed bars) (14 wk old, male, $n=5$). Bars represent the mean ± S.E.M. Statistical analysis was performed with the t test. $^{*}P<0.05$; $^{**}P<0.01$.

been published. Using NIH 3T3-L1 cells, Li et al. reported observing AM mRNA expression and secretion in mature adipocytes [14,15]. Recently Fukai et al. found AM mRNA expression in rat and human adipose tissue [16], which agrees with the results of our study.

Human subcutaneous adipose tissue obtained from healthy subjects during plastic surgery exhibited marked AM expression, too. In view of the tissue volume, these results suggest that adipose tissue is one of the major sites of AM production in the body.

The physiological significance of adipocyte-derived AM remains to be clarified. Since it has been reported that the plasma concentration of AM in the physiological state is not high enough to exert a vasodilatory effect [17], it stands to reason that AM secreted from adipocytes functions in an autocrine/paracrine manner. Adipose tissue is distributed throughout the body and works as supportive tissue. AM is a potent vasodilator and a growth factor for vascular endothelial cells (VEC) and vascular smooth muscle cells (VSMC) [18,19]. Many blood vessels are surrounded by fat and AM produced by the adipocytes and the vascular wall itself may make the local concentration of AM high enough to work as a vasodilator or a growth factor for VEC and VSMC. In reconstruction culture of the skin, the epidermal layer is known to grow better on the subcutaneous adipose layer [20]. It has also been reported that AM has a mitogenic effect on human keratinocytes [21]. Along with its enhancing effect on the proliferation and migration of VEC and VSMC, AM secreted from subcutaneous adipose tissue may be crucial for the maintenance and regeneration of the skin. Bone marrow is another organ which is rich in adipose tissue, while it has been reported that AM is expressed in cord blood hematopoietic cells and stimulates their clonal growth [22]. It thus seems reasonable to speculate that bone marrow fat may contribute to haematopoiesis.

It is extremely interesting that AM expression in adipose tissue and plasma AM concentration were significantly augmented with the increase in body weight after the high-fat diet. The same results were observed in ob/ob, leptin-deficient obesity model mice [23]. Furthermore, the massive increase in adipose tissue volume in obesity makes the total AM production in adipose tissue much greater. It has also been reported that the expression of the AM receptor components CRLR and RAMP2 was heightened in HFD rat adipose tissue [16]. Shimosawa et al. reported that heterozygous AM-deficient mice showed obesity, higher blood pressure and insulin resistance in their old age [24]. Taken together, these findings suggest that adipose tissue-derived AM protects against obesity.

The relationship between human plasma AM levels and obesity is not clear yet, although several studies have shown that plasma human AM levels are elevated in obesity [25,26].

In conclusion, our study presented here demonstrated that adipocytes produce AM in human and mouse and the AM production in adipose tissue is enhanced in obesity. Adipose AM may thus have a pathophysiological function in obesity.

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