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JB Review

Biology of the apelin-APJ axis in vascular formation

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Apelin is a bioactive peptide with diverse physiological actions on many tissues mediated by its interaction with its specific receptor APJ. Since the identification of apelin and APJ in 1998, pleiotropic roles of the apelin/APJ system have been elucidated in different tissues and organs, including modulation of the cardiovascular system, fluid homeostasis, metabolic pathway and vascular formation. In blood vessels, apelin and APJ expression are spatiotemporally regulated in endothelial cells (ECs) during angiogenesis. *In vitro* analysis revealed that the apelin/APJ system regulates angiogenesis by the induction of proliferation, migration and cord formation of cultured ECs. Moreover, apelin seems to stabilize cell–cell junctions of ECs. In addition, genetically engineered mouse models suggest that apelin/APJ regulates vascular stabilization and maturation in physiological and pathological angiogenesis. In this review, we summarize the current understanding of the apelin/APJ system for vascular formation and maturation.

Keywords: apelin and APJ/development/regenerative medicine/tumour angiogenesis/vascular formation.

Abbreviations: bFGF, basic fibroblast growth factor; CAM, chorioallantoic membrane; DCs, dendritic cells; ECs, endothelial cells; ERK, extracellular-regulated kinases; HIF, hypoxia inducible factor; iNKT, invariant natural killer T; ISVs, intersomitic vessels; PI3K, phosphatidylinositol-3 kinase; VEGF, vascular endothelial growth factor.

Characteristics of Apelin and APJ

Apelin was initially identified as an endogenous ligand for the orphan G protein-coupled receptor with seven transmembrane domains, APJ, isolated from bovine stomach extracts in 1998 (*1*). Apelin is secreted as a 77 amino acid pre-proprotein, an immature peptide, which is cleaved by protease to form C-terminal products, including apelin-13, apelin-17 and apelin-36 (*2*). These isoforms have distinct activities, with the shorter isoform seeming to be the more potent activator for APJ. In mammals, the sequence of preproapelin is strongly conserved in different species, and it has complete identity for the last 23 residues of the C-terminal. Apelin (65–77) activates extracellular signal-regulated kinases through a pertussis toxin sensitive G protein (*3*). Apelin-13 and apelin-36 have different receptor binding affinity and cause different intracellular trafficking of APJ (*4*). The gene encoding the APJ receptor was identified by homology cloning in 1993 (*5*). APJ has high-sequence homology with the angiotensin II type I receptor, but it does not bind angiotensin II. Apelin is believed to be the only endogenous ligand for APJ.

Apelin and APJ mediate a wide range of physiological actions, including regulation of cardiovascular function, fluid homeostasis, adipo-insular axis and angiogenesis. Studies on APJ function have been focused on the cardiovascular system, because of its similarity to the angiotensin II receptor. It seems that intravenous injection of apelin induces a reduction in blood pressure (*6*). The hypotensive effect of apelin is a consequence of intracellular activation of nitric oxide synthase (*7*). Apelin also causes vasoconstriction because of contraction of the vascular smooth muscle cells (*8*). Plasma apelin levels and APJ expression are clearly modulated in patients with heart failure (*9*, *10*). It has been reported that apelin has positive inotropic effects in *in vitro* and *in vivo* studies (*11–14*). Apelin has been shown to be expressed and released from adipocytes by fasting and refeeding factors, such as insulin, and can act as an adipokine (*15*). For these reasons, apelin is now attracting attention in the context of metabolic disease. In patients with type 2 diabetes, plasma apelin concentrations are increased (*16*, *17*). It has also been suggested that apelin may have other effects, such as on fluid homeostasis (*18*), gastrin stimulation (*19*) and immune responses (*20*).

Distribution and Regulation of Expression of Apelin and APJ

Tissue and cellular distribution

In mammals, APJ expression is widely distributed in various peripheral tissues of adult and embryo. Highest levels of APJ are found in the lung and heart, and significant but lower levels of APJ mRNA are present in skeletal muscle, pituitary gland, kidney and ovary (*21*) (*22*). In these tissues, APJ expression was localized in the vascular and endocardial

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endothelial cells (ECs) and smooth muscle cells (*23*). APJ expression is also observed in the brain, including the cerebral cortex, hypothalamus, hippocampus and pituitary gland (*6*, *22*). Apelin expression is also detected in a range of peripheral tissues, including heart, liver, kidney, adipose tissues and brain, with highest levels found in the lung and the mammary gland (*2*, *6*, *20*, *24*). Localization of apelin expression in tissue was observed in vascular ECs, adipose tissue and epithelial cells (*7*).

An important physiological role for apelin and APJ is suggested by the observation of widespread distribution of receptor and ligand expression in tissues, as described previously. Apelin and APJ were found to be abundantly expressed in various peripheral tissues, and localization was restricted to blood vessels (*2*, *7*, *8*, *20*, *22–26*), suggesting a role for apelin/APJ in angiogenesis and vascular formation.

Regulation of transcription

Many transcription factors that may regulate apelin gene expression have been reported. Rat and human apelin core promoter sequences contain putative binding sites for upstream stimulatory factor 1/2, and overexpression of USF upregulates apelin transcription (*27*). Multiple signal transducer and activator of transcription binding sites have been identified in the rat apelin promoter, and apelin expression is elicited by stimulation using inflammatory cytokines associated with binding of phospho-Stat3 (*28*). In white adipocytes, apelin is upregulated by the transcriptional co-activator peroxisome proliferator-activated receptor γ co-activator 1 α (*29*). Under hypoxic conditions, hypoxia inducible factor-1α (HIF1-α) binds to the hypoxia-responsive element (-813/-826) located within the first intron of the human apelin gene and increases apelin expression in vascular cells (*30*).

The molecular mechanism of APJ gene transcriptional regulation has not been well characterized so far. Analysis of the 5′-flanking region of a rat APJ genomic clone identified sites with the strongest promoter activity in a region between (-966/-165) where the Sp1 motif suggested to play a major role (*31*). Other investigations using gene-based single-nucleotide polymorphism analysis have also shown that both APJ and apelin genes are probably regulated by Sp1 (*32*).

Cell effects and intracellular responses

Apelin has been shown to induce the proliferation and migration of APJ-expressing ECs (*33*). The major signalling pathways of apelin are mediated initially by Gi-protein coupled to the APJ receptor and protein kinase C (Fig. 1). It has been reported that apelin causes concentration-dependent inhibition of forskolin-stimulated production of cAMP and increases the phosphorylation of extracellular-regulated kinases (ERK) or protein kinase B in umbilical ECs (*3*, *20*). Apelin/APJ-induced ERK activation is mediated by pertussis toxin sensitive G protein (*3*). On binding of apelin to APJ, the phosphatidylinositol-3 kinase (PI3K) pathway and the ERK pathway lead to the phosphorylation of p70S6K. It has been reported that the PI3K-protein kinase B pathway contributes to EC migration (*34*) and that the ERK/PI3K-p70S6K pathway regulates EC proliferation (*35*). Acceleration of cell motility by apelin was also reported using Chinese hamster ovary cells expressing APJ (*21*). Recently, it has been shown that APJ forms a heterodimer with κ-opioid receptors and leads to phosphorylation of ERK, resulting in increased cell proliferation (*36*). In addition, apelin inhibits the mouse pulmonary arterial EC apoptosis, observed in pulmonary arterial hypertension (*37*). It has been reported that apelin-induced anti-apoptosis is mediated by the induction of Bcl2 protein expression and activation of the PI3K/protein kinase B signalling pathway (*38*). Apelin-36 and apelin-13 can activate the same set of intracellular effectors, but they display some differences in their Gi-protein coupling and differ greatly in their desensitization pattern (*39*).

Role of Apelin in Blood Vessel Formation

Developmental stage

The establishment of vascular network is absolutely necessary for the growth and maintenance of tissues/organs. New blood vessel formation in vertebrates is known to occur by two different processes, vasculogenesis and angiogenesis (*40*). Vasculogenesis is the process of formation of *de novo* primitive vascular networks directly from angioblastic precursor cells. In contrast, angiogenesis is a process of formation of new vascular segments by sprouting from the pre-existing vessels. Vasculogenesis is normally observed in early embryogenesis, whereas angiogenesis occurs during development and in post-natal life.

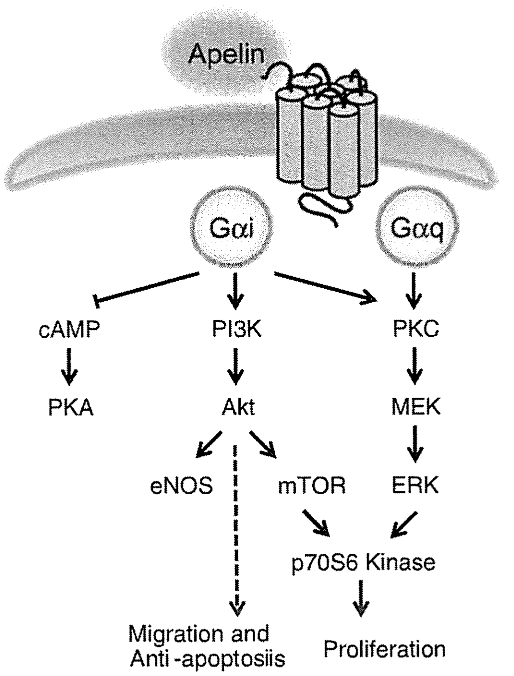

Fig. 1 Schematic of intracellular signal transduction pathways and cellular effects in the apelin/APJ system.

Apelin seems to have important roles in angiogenesis during embryogenesis. In *Xenopus laevis* embryos, expression of homologues of apelin and APJ are observed in developing vascular structures of the inter-somitic vein (*41*). Implantation of beads carrying apelin peptide stimulated prominent outgrowth of ECs and, conversely, morpholino-based translational inhibition of apelin and APJ suppressed inter-segmental angiogenesis (*42*). During segmentation of zebrafish embryos, expression of an ortholog of APJ is observed in epithelial structures, such as venous vasculature (*43*). Consistent with these results, APJ is expressed on ECs in newly formed blood vessels in mouse embryos. At E8.5, APJ expression was observed in ECs that had sprouted from the dorsal aorta, but not in those that were forming the dorsal aorta by the process of vasculogenesis. At E9.5, APJ expression was observed in the migrating end region of inter-somitic vessels sprouting from the dorsal aorta, gradually disappearing as the blood vessels matured. Furthermore, apelin protein was also detected in the somite region at E9.5 (*44*). These expression profiles suggest that the apelin/APJ system plays a spatiotemporal role in blood vessel formation by its transient expression on blood vessel~~s~~ ECs during angiogenesis. The role of apelin in vascular formation has been studied in our group using mouse embryos. We previously showed that the apelin/APJ system induces cell–cell assembly and the proliferation of vascular ECs. When the apelin gene was knocked out, the caliber of inter-somatic vessels in the embryo was narrower. These results indicated that the apelin/APJ system is involved in maturation of blood vessels by caliber size modification during angiogenesis (*44*) (Fig. 2).

In the neonatal mouse retina, APJ expression is upregulated in ECs of the radial vessels sprouting from the optic nerve head region, but attenuated after vessel stabilization. Expression of the apelin gene was also observed in the sprouts of extending vessels at the leading edge (*45*, *46*). During sprouting angiogenesis, growing vascular capillaries are spearheaded by specialized ECs, termed outgrowing tip cells, which act as a guide for the direction of migration of newly developed blood vessels. Behind the tip cells, proliferating ECs, termed stalk cells, induce elongation of the blood vessels, and tip and stalk cells are dynamically challenged and replaced alternately during sprouting angiogenesis (*47*, *48*). Recently, apelin was identified as one of the genes with high expression in tip cells and has been suggested to modulate proliferation of stalk cells expressing the APJ receptor (*49*) (Fig. 2); therefore, apelin-APJ signalling may have a role in tip-cells and stalk-cells characterization. Using apelin-deficient mice, it was suggested that the apelin/APJ system participates in retinal vascularization and ocular development by modulating the angiogenic response to vascular endothelial growth factor (VEGF) and/or basic fibroblast growth factor (*50*). Moreover, we recently proposed that apelin/APJ activation in ECs is a trigger for finalization of blood vessel formation, indirectly mediated by the induction of astrocyte maturation (*51*). During development of the retinal vasculature, APJ mRNA expression is specifically restricted to the venules and the associated capillaries (*46*), indicating a possible function of apelin signalling for venous vascular formation.

Tumour angiogenesis

Apelin has been reported to be broadly expressed in ECs of tumours of different origins. By comparing gene expression profiles in tumours versus normal endothelium, apelin has been identified as a tumour endothelial-specific gene (*52*). In human breast carcinoma, apelin expression was detected in the vascular ECs by immunohistochemical analysis (*53*). As described previously, apelin expression is physiologically modulated by tissue hypoxia and regulated by HIF-1α (*30*). The hypoxic tumour microenvironment may thus induce HIF1α-dependent apelin expression in tumour ECs.

It has been reported that the expression level of the APJ receptor is also increased in tumour endothelium. In glioblastoma, both APJ and apelin transcripts are highly upregulated within the microvasculature compared with blood vessels in normal brain tissue (*41*). Consistent with this result, we detected high-level expression of apelin and APJ mRNA in ECs from tumours generated by the inoculation of Lewis lung carcinoma and colon 26 adenocarcinoma cells into mice. In addition, immunohistochemical analysis of colon 26 tumour revealed that ~13% and 27% of the vessels were APJ-positive and apelin-positive, respectively, and most ECs co-expressed apelin and APJ (*54*). Of course, the ratios of apelin or APJ positivity in ECs may be different depending on the tumour size and tumour growth course. Observation of high APJ expression in angiogenic blood vessels in tumours was similar to that during normal development. Co-expression of ligand and receptor in ECs of the newly formed tumour blood vessels suggests the possibility that APJ in ECs is stimulated by autocrine and paracrine loops.

Several attempts have been made to determine the role of the apelin/APJ system in tumour angiogenesis, using apelin-overexpressing tumour cells. In a human non-small cell lung cancer xenograft model, apelin gene transfer significantly stimulated tumour growth and increased microvessel densities and diameters *in vivo* (*55*). Another group reported that mammary tumour cells stably overexpressing apelin cDNA also stimulated tumour growth *in vivo*, probably associated with enhanced angiogenesis in the tumours (*56*). However, in our own research, we found that overexpression of apelin in colon 26 tumours significantly suppressed tumour growth by inducing tumour vascular maturation (*54*). This difference might depend on the particular apelin/APJ signalling pathway, probably involved in individual tumours and different tumour models, i.e., syngeneic mouse model or allogeneic mouse model using immunodeficient mice. Recent reports indicate that anti-angiogenic cancer drugs, such as VEGF signalling inhibitors, cause 'normalization' of aberrant tumour vasculature and, thus, induce the formation of functional mature vasculature (*57*, *58*). One of the major therapeutic benefits of tumour

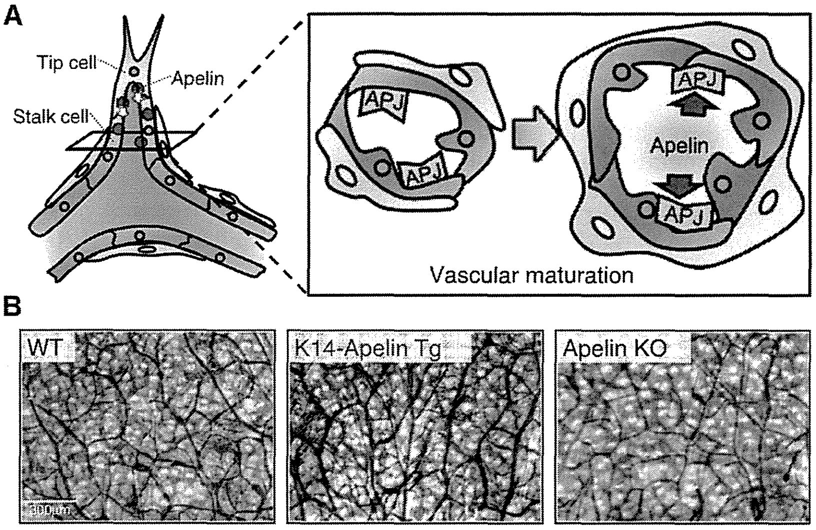

Fig. 2 (A) **Schematic representation showing how apelin/APJ signalling induces vascular maturation.** High levels of expression of apelin protein in tip cells probably activates APJ signalling in the neighbouring stalk cells. Subsequently, these cells will adopt proliferating and aggregating behaviour to form enlarged mature vessels. (B) Image of ear-skin blood vessels in apelin-transgenic mice under regulation of the K14 promoter, and apelin-deficient mice. Compared with wild-type mice, more enlarged mature vessels are observed in apelin-transgenic mice and more narrow immature vessels in apelin-deficient mice.

vascular normalization is enhancement of the effects of conventional anti-tumour therapies, such as chemotherapy and radiation therapy (*58*). In our study, apelin-mediated vascular maturation enhanced the effect of immunotherapy with dendritic cells. These therapeutic effects resulted from induction of tumour cell apoptosis by effective infiltration of activated invariant natural killer T cells (*54*).

Thus, regulation of APJ activity might lead to the development of new vascular normalization drugs, which should be more efficacious than anti-angiogenic agents because of their unique ability to induce vascular enlargement.

Vascular regeneration

Several lines of evidence indicate that apelin can significantly enhance migration, proliferation and capillary tube-like formation of cultured ECs (*30*, *33*, *35*, *44*, *59*). In *in vivo* Matrigel plug assays for angiogenesis, addition of apelin resulted in the formation of capillary-like structures (*33*). Moreover, apelin peptide stimulates angiogenesis in the chicken chorioallantoic membrane assay (*42*). Downregulation of apelin expression by the local delivery of apelin-targeting small interfering RNA into grafted adipose tissue leads to dramatic inhibition of angiogenesis (*59*). In the rat portal hypertension model, treatment with the APJ-specific antagonist F13A markedly reduced splanchnic neovascularization and formation of portosystemic collateral vessels (*60*). According to these reports, it is suggested that apelin can be used for therapeutic angiogenesis.

Analysis of transgenic mice expressing apelin in the epidermis under the transcriptional control of the K14 promoter revealed that apelin can induce the formation of enlarged capillaries, but not arteriola and venula in the dermis. Moreover, overexpression of apelin inhibited vascular leakage caused by VEGF or histamine. These results indicate that apelin can induce non-leaky larger blood vessels *in vivo* (*61*).

In cardiac failure, endothelial apelin expression correlates with other hypoxia-responsive genes, and apelin and APJ are upregulated in ECs of various tissues after systemic hypoxia (10% FIO_2) *in vivo*. It has been suggested that apelin expression in the endothelium of the heart is induced through the endothelial-specific HIF-2α pathway (*62*). Another group also reported that apelin expression was significantly increased in lungs of mice under hypoxic conditions (10% O_2) in an HIF-1α-dependent manner. Small interfering RNA-mediated apelin or APJ knockdown inhibited hypoxia-induced vessel regeneration in the caudal fin regeneration model in zebrafish (*30*). In accordance with these observations, we found that endogenous apelin is required for recovery of hind limb perfusion after induction of ischaemia (*58*). Using mouse hind limb ischaemia models produced by occlusion of the femoral artery, expression of APJ and apelin mRNA was significantly increased in ECs from the ischaemic muscle. In apelin-deficient mice, severe necrosis of the toes and delayed recovery of blood flow were observed when inducing ischaemia. These results suggested the involvement of the apelin/APJ system in collateral vessel formation during the process of recovery from ischaemia states. Thus, we found that APJ expression is induced after ischaemia treatment, and endogenous apelin is required for functional recovery.

Apelin gene transfer promotes formation of enlarged and non-leaky blood vessels in the hind limb ischaemia model. Simultaneous overexpression of apelin and VEGF by plasmid administration was superior to VEGF alone at restoring tissue integrity after ischaemia damage by improved generation of enlarged blood vessels in the ischaemic muscle (*61*). Moreover, apelin induced vascular stabilization by inhibiting VEGF-mediated internalization of vascular endothelial cadherin resulted in suppression of hind limb oedema (*61*). In addition to its role in blood vessel formation, APJ is expressed in human lymphatic ECs, and apelin induces their migration and cord formation. Transgenic mice harbouring apelin in the dermis showed reduced development of oedema by promoting stabilization of lymphatic vessels (*63*). Taken together, these findings suggest that the apelin/APJ system represents a new therapeutic target for ischaemic disease.

Conclusions

Recent studies have revealed multiple roles of the apelin/APJ system in vascular formation in physiological and pathological situations, including during development, tissue regeneration and tumourigenesis. Apelin has a unique function as a regulator of vascular maturation and stabilization by increasing the caliber of newly formed blood vessels and strengthening barrier function between ECs. Moreover, expression of apelin and APJ genes is temporally upregulated during blood vessel development and downregulated in stabilized vasculature. Detailed understanding of the function of the apelin/APJ system and expression analysis in blood vessels will provide insights for improving the use of agonists and antagonists that modulate apelin signalling in different vascular diseases.

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Conflict of interest

None declared.

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A role for endothelial cells in promoting the maturation of astrocytes through the apelin/APJ system in mice

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SUMMARY

Interactions between astrocytes and endothelial cells (ECs) are crucial for retinal vascular formation. Astrocytes induce migration and proliferation of ECs via their production of vascular endothelial growth factor (VEGF) and, conversely, ECs induce maturation of astrocytes possibly by the secretion of leukemia inhibitory factor (LIF). Together with the maturation of astrocytes, this finalizes angiogenesis. Thus far, the mechanisms triggering LIF production in ECs are unclear. Here we show that apelin, a ligand for the endothelial receptor APJ, induces maturation of astrocytes mediated by the production of LIF from ECs. *APJ* (*Aplnr*)- and *Apln*-deficient mice show delayed angiogenesis; however, aberrant overgrowth of endothelial networks with immature astrocyte overgrowth was induced. When ECs were stimulated with apelin, LIF expression was upregulated and intraocular injection of LIF into *APJ*-deficient mice suppressed EC and astrocyte overgrowth. These data suggest an involvement of apelin/APJ in the maturation process of retinal angiogenesis.

KEY WORDS: Astrocytes, Endothelial cells, Apelin, Mouse

INTRODUCTION

The retina is composed of several cell types. Interactions between endothelial cells (ECs), astrocytes and neuronal cells is crucial for fine capillary network formation by ECs. Before the onset of interactions between ECs and astrocytes in the retina of postnatal mice, astrocytes invade from the optic nerve head via the axons of retinal ganglion cells. Controlling this association between different cell components, platelet-derived growth factor A (PDGFA) from retinal ganglion cells promotes growth of immature astrocytes expressing PDGF receptor α (PDGFRα). This results in astrocyte network formation (Fruttiger et al., 1996). Subsequently, ECs from the optic nerve head invade and migrate over the network-forming astrocytes as a template. A crucial role of vascular endothelial growth factor (VEGF), produced by astrocytes, in guiding endothelial tip cells in the vascular branch and in the proliferation of endothelial stalk cells behind the tip cells has been reported (Gerhardt et al., 2003).

In the course of retinal angiogenesis, astrocytes act as proangiogenic accessory cells, as described above; however, upon becoming overlaid with ECs, it has been suggested that their proangiogenic activity ceases and they instead stabilize newly developed blood vessels (West et al., 2005; Kubota et al., 2008). Anatomical analysis has revealed that astrocytes expressing low levels of glial fibrillary acidic protein (GFAP) firstly invade the retina, gradually express higher levels of GFAP, and become quiescent (Chu et al., 2001; Gariano, 2003). Therefore, it has been suggested that ECs might change astrocyte characteristics (Zhang and Stone, 1997), with several lines of evidence suggesting that leukemia inhibitory factor (LIF) derived from ECs is a direct maturation factor for immature astrocytes in vitro (Mi et al., 2001) and in vivo (Kubota et al., 2008). However, the mechanism responsible for controlling LIF production by ECs for maturation of astrocytes has not been elucidated.

During the process of angiogenesis, maturation of blood vessels is induced by angiopoietin 1 (ANG1; also known as ANGPT1), a ligand for endothelial receptor tyrosine kinase TIE2 (also known as TEK), produced by mural cells, which directly adhere to ECs. This results in structural stabilization of the blood vessels (Sato et al., 1995; Suri et al., 1996; Augustin et al., 2009). Apelin is a ligand for the G protein-coupled receptor APJ expressed on ECs. We previously reported that activation of TIE2 promotes apelin production from ECs and that ANG1/TIE2-mediated maturation of blood vessels, such as their enlargement and non-leaky blood vessel formation, is partly dependent on APJ activation by apelin ligation (Kidoya et al., 2008; Kidoya et al., 2010). Recently, involvement of the apelin/APJ system in retinal angiogenesis has been reported (Kasai et al., 2008; del Toro et al., 2010) in which delayed angiogenesis and reduced proliferation of stalk cells was observed in gene ablation analysis of apelin (*Apln*) and apelin receptor (*APJ*; *Aplnr* – Mouse Genome Informatics) (Kasai et al., 2008; del Toro et al., 2010; Kidoya et al., 2010). In contrast to the constitutive expression of TIE2, as well as of VEGF receptor 2 (VEGFR2; also known as FLK1 and KDR), APJ expression in ECs is transient. From the onset of retinal angiogenesis, most network-forming ECs express APJ until postnatal day (P) 7; however, after reaching the marginal zone of the retina, ECs stop expressing APJ at P12, except for the larger veins (Saint-Geniez et al., 2003). Taken together, these findings imply that apelin/APJ acts as a maturation factor for newly developed blood vessels, in addition to its proangiogenic function.

During retinal angiogenesis, it is suggested that ECs and astrocytes mature simultaneously in a mutually dependent manner. However, whether maturation arrest of blood vessels affects

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astrocyte maturation is not yet clear. Because apelin/APJ is mainly involved in the maturation of blood vessels, we used mice with *Apln* as well as *APJ* mutations to ask whether the maturation of astrocytes is affected by a deficiency of apelin or APJ. Moreover, we investigated how astrocyte maturation conversely affects the growth of ECs in order to understand mutual EC/astrocyte regulation.

MATERIALS AND METHODS

Mice

All experiments were carried out under the guidelines of the Osaka University Committee for Animal Research. C57BL/6 (Japan SLC, Shizuoka, Japan), *APJ* knockout (KO) (Ishida et al., 2004) and *Apln* KO (Kidoya et al., 2008) mice were used in these studies. Animals were housed in environmentally controlled rooms of the animal experimentation facility at Osaka University.

Quantitative reverse transcription real-time PCR (qRT-PCR)

Total RNA was extracted from cells and tissues using the RNeasy Plus Mini Kit (Qiagen) and transcribed into cDNA using the ExScript RT Reagent Kit (Takara) according to the manufacturers' protocols. Real-time PCR analysis was performed using Platinum SYBR Green qPCR SuperMix-UDG (Invitrogen) and an Mx3000P QPCR System (Stratagene). The baseline and threshold were adjusted according to the manufacturer's instructions. PCR was performed on cDNA using the primers listed in supplementary material Table S1. The level of expression of the target gene was normalized to that of *Gapdh* in each sample.

Tissue immunostaining and in situ hybridization (ISH)

Tissue preparation and staining were as previously reported (Takakura et al., 2000). Enucleated eyes were fixed in 4% paraformaldehyde. Antibodies for staining were anti-PECAM1 (BD Biosciences, 1:100; or Chemicon International, 1:100), anti-GFAP (Sigma-Aldrich, 1:100), anti-PDGFRα (eBioscience, 1:100), anti-desmin (DAKO, 1:100), anti-PAX2 (Covance, 1:100), anti-KI67 (DAKO, 1:100), anti-neurofilament (American Research Products, 1:100), anti-type IV collagen (Cosmo Bio, 1:100), anti-HIF1α (1:100) (Kurihara et al., 2010), anti-apelin (1:100) (Kidoya et al., 2008) and anti-APJ (1:100) (Kidoya et al., 2008). The secondary antibodies used were Alexa Fluor 488/546/647-conjugated IgGs (Invitrogen, 1:200) or FITC/Cy5-conjugated IgGs (Jackson ImmunoResearch Laboratories, 1:200).

For whole-mount ISH, retinas were briefly digested with proteinase K and hybridized with digoxigenin-labeled antisense RNA probes.

For determination of hypoxic tissue, mice were injected intraperitoneally with 60 mg/kg body weight Hypoxyprobe-1 (pimonidazole hydrochloride) (Natural Pharmacia International) before harvesting retinas for tissue processing and staining according to the manufacturer's instructions. Six animals per group were analyzed. A total of eight straight lines were drawn in each retina: four from the optic nerve to the vascular front representing a vascularized area; and four from the vascular front to the peripheral retina as an avascular area. Samples were visualized using conventional microscopy (with a DM5500B equipped with HCX PL FLVOTAR 5/0.15 and HCX PL FLVOTAR 0/0.15 dry objective lenses, Leica) or confocal microscopy (TCS/SP5 equipped with HC PLAN APO 2/0.70 and HCXPL APO 4/1.25-0.75 oil objective lenses, Leica) at room temperature. Images were acquired with a DFC 500 digital camera (Leica) and processed with the Leica application suite and Adobe Photoshop CS3 software. All images shown are representative of three to six independent experiments.

Retina quantification

Complete high-resolution three-dimensional (3D) rendering of whole-mount retinas was achieved using the confocal microscope described above. The cells of interest (PAX2$^+$ astrocytes, PAX2$^+$ KI67$^+$ astrocytes and HIF1α$^+$ cells) were manually scored in six random 350×350 μm or 250×250 μm (HIF1α$^+$ cells) fields of view (FOV) per retina photographed at 40× or 63× magnification using the software of the Leica application suite. To determine cell number and measure the capillary density of the retinas, six animals per group were analyzed. After conversion to 8-bit grayscale using ImageJ software, the capillary density in the vascularized area was quantified from the pixels. The vascularized areas were defined as the region near the vascular front without the regions from the very tips to the first vascular loop. The avascular areas were defined as the regions ~500 μm ahead of the vascular front. HIF1α$^+$ cells were counted in different areas.

Flow cytometry analysis

Retinas of at least five WT and *APJ* KO mouse neonates were incubated for 30 minutes at 37°C in DMEM containing 1% collagenase (Wako, Osaka, Japan) before cells were dissociated by gentle trituration. Cells were pretreated with Fc-Blocker (BD Biosciences Pharmingen) and stained with FITC-conjugated anti-CD140a (PDGFRα) monoclonal antibody and phycoerythrin-conjugated anti-CD31 monoclonal antibody (BD Biosciences Pharmingen). Procedures for cell preparation and staining were as previously reported (Kidoya et al., 2008). The stained cells were analyzed and sorted using a FACSAria flow cytometer (BD) with FlowJo (TreeStar) or CellQuest (BD) software. Dead cells were excluded from the analyses using the 2D profile of forward versus side scatter. Using these negative and positive control tubes, we set fluorescence voltages and the compensation matrix according to the instructions of the manufacturer. We applied these setting parameters to all samples analyzed.

Intraocular injection

Sterile PBS with or without 1 mg/ml apelin (Bachem), 0.5 mg/ml LIF (ESGRO, Chemicon) or 1 mg/ml sFLT1 was injected into the vitreous humor of P3 mice using a sterile injection capillary with an automatic microinjector (FemtoJet, Eppendorf). Mice were sacrificed 48 hours later and the retinas isolated for cell purification or immunohistochemistry.

Cell culture

The mouse microvascular endothelial cell line bEnd.3 or HUVECs were cultured in six-well plates for 12 hours in DMEM or Humedia EG2 (Kurabo, Osaka, Japan), respectively. Cells were then incubated in medium supplemented with 1% fetal bovine serum (FBS). After 6 hours of serum deprivation, cells were stimulated with basal medium containing 20 ng/ml VEGFA 165 (PeproTech) for 18 hours and subsequently incubated with 50 or 500 ng/ml apelin. Culturing of retinal cells was performed as described previously (West et al., 2005). P1 WT retinas were dissected as indicated above, redissociated in DMEM containing 10% FBS and then plated on poly-D-lysine-coated coverslips in 24-well plates at 1.5×10^6 cells/well and incubated at 37°C, 5% CO_2 for 24 hours. Retinal cells were incubated for 24 hours with supernatant of bEnd.3 cells that had been treated with apelin for 24 hours.

Statistical analysis

Data are presented as mean±s.d. for the in vitro studies and mean±s.e. for in vivo studies. For statistical analysis, the Statcel 2 software package (OMS) was used with analysis of variance performed on all data followed by Tukey-Kramer multiple comparison testing. When only two groups were compared, a two-sided Student's *t*-test was used. $P<0.05$ was considered statistically significant.

RESULTS

Dense astrocyte network formation is induced in APJ-deficient mice

Because it has been reported that *APJ* mutant mice show retarded endothelial network formation in the retina (del Toro et al., 2010), we first investigated the development of, and network formation by, astrocytes from P0 to P7 (Fig. 1A). Using anti-PDGFRα antibody in immunohistochemistry (IHC) to identify these cells, we found that astrocyte network formation was similar in wild-type (WT) and *APJ* KO mice at P1; however, a dense network appeared in *APJ* KO mice at P5 and continued at least until P7. PDGFRα$^+$ astrocytes were also analyzed by flow cytometry and their number calculated as a proportion of the total number of retinal cells at P5. A significantly greater proportion of astrocytes was found to be present in *APJ* KO

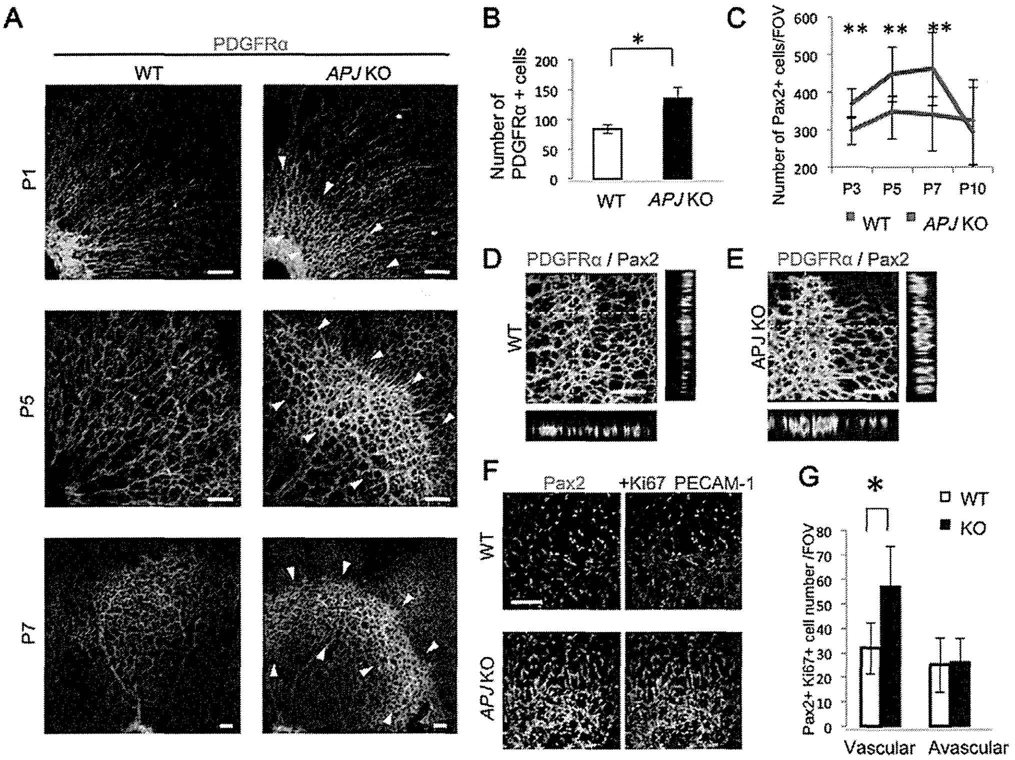

Fig. 1. ***APJ* KO mice show irregular remodeling and proliferation of retinal astrocytes.** (**A**) Immunohistochemistry (IHC) for PDGFRα (green) in the P1, P5 and P7 developing retina of wild-type (WT) or *APJ* KO mice. Note the dense astrocyte network (surrounded by arrowheads) in *APJ* KO mice. (**B**) Quantitative evaluation of the number of PDGFRα$^+$ cells per 5×10^4 cells analyzed by FACS. Dissociated retinal cells from P5 WT or *APJ* KO mice were used (n=4, *P<0.05). (**C**) Transition of the number of astrocytes identified as PAX2$^+$ nuclei in vascularized areas. Data are the mean of six random fields of view (FOV) in the vascularized area per retina (n=6, **P<0.01). (**D**,**E**) Confocal microscopy images of PDGFRα$^+$ (green) and PAX2$^+$ (red) astrocytes in WT (D) and *APJ* KO (E) P5 retinas. z-stack images show two-layered astrocytes in *APJ* KO retina. (**F**) Proliferation status of astrocytes in P5 retinas from WT and *APJ* KO mice. Retinas were stained with antibodies against PAX2 (green), KI67 (magenta) and PECAM1 (blue). Note the marked proliferation of PAX2$^+$ KI67$^+$ astrocytes (white or light blue) in vascular areas of *APJ* KO mice. (**G**) Quantification of PAX2$^+$ KI67$^+$ astrocytes in the vascularized or non-vascularized retinal areas. Six random FOV were examined per retina (n=6,*P<0.05). Error bars indicate s.d. Scale bars: 100 μm.

than WT mice (Fig. 1B). We next calculated the number of astrocytes expressing PAX2, a nuclear transcription factor present in all cells of the astrocyte lineage (Fig. 1C-E). Although the number of PAX2$^+$ astrocytes in *APJ* KO mice was higher than in WT mice from P3 to P7, it gradually decreased to WT levels, suggesting negative-feedback regulation (Fig. 1C). z-stack images suggested that a thicker retinal astrocyte layer was induced in *APJ* KO than in WT mice owing to the generation of two layers of astrocytes at P5 (Fig. 1D,E). Next, we stained the retina for the EC marker PECAM1 (CD31) and with anti-PAX2 antibody, as well as for the cell proliferation marker (KI67). High-density areas of PAX2$^+$ KI67$^+$ proliferating astrocytes were present in vascular but not avascular areas (Fig. 1F,G), suggesting that astrocyte proliferation is associated with ECs.

Next we assessed the degree of astrocyte maturation in *APJ* KO mice. In WT mice, astrocytes that are initially weakly GFAP positive start to express a high level of GFAP at P5 (Fig. 2A-C). The strongly GFAP-positive astrocytes present from the optic nerve head up to the beginning of the dense astrocyte sheet area did not differ substantially between *APJ* KO and WT mice. However, within the dense astrocyte sheet there were fewer strongly GFAP-positive astrocytes in the *APJ* KO mice (Fig. 2A,D,E). Consistent with this, levels of *Gfap* mRNA were reduced in *APJ* KO mice at all periods examined (Fig. 2F). Comparing other astrocyte differentiation markers in *APJ* KO and WT mice revealed similar levels of expression for the lineage markers vimentin (*Vim*) and *Pax2* but a significant reduction in the mature astrocyte markers *S100b* and *Gfap* in the knockouts (Fig. 2G). These data suggest that APJ deficiency does not affect the development of astrocytes but influences their maturation.

APJ deficiency indirectly induces dense endothelial sheets via overgrowth of immature astrocytes

It has been reported that both *APJ* KO and *Apln* KO mice show delayed retinal angiogenesis (Kasai et al., 2008; del Toro et al., 2010). However, as we found aberrant overgrowth of immature astrocytes in *APJ* KO mice, we hypothesized that abnormal overgrowth during blood vessel formation should also be induced in *APJ* KO mice indirectly owing to the defect of APJ in ECs, as weakly GFAP-positive astrocytes possess proangiogenic properties. Although retinal vessel outgrowth from the optic nerve head was indeed impaired in *APJ* KO mice (supplementary material Fig. S1) as previously reported (del Toro et al., 2010), a dense endothelial network-forming area was frequently observed at the migrating front of the retinal vasculature after P5 (Fig. 3A-C).

Consistent with hyperproliferation of ECs in *APJ* KO mice, the retinas of these mice were found by in situ hybridization (ISH) to express more *Vegfa* mRNA in the peripheral region of

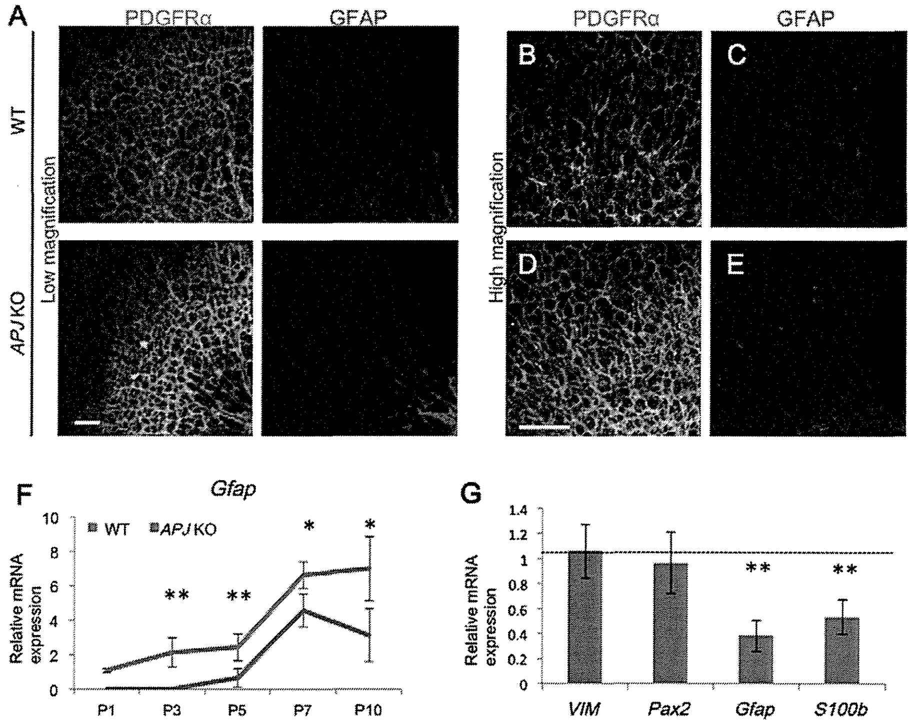

Fig. 2. Suppression of astrocyte maturation in *APJ* KO developing retina. (**A**) Retinal astrocytes stained for PDGFRα (green) and GFAP (red) in P5 WT and *APJ* KO mice. (**B-E**) High-magnification views of retinal astrocytes around the migrating front of the vascular network area as shown in Fig. 1F. Note the weak positivity for GFAP in overgrown astrocytes in *APJ* KO mice. (**F**) Quantitative RT-PCR (qPCR) analysis of *Gfap* expression using isolated RNA from FACS-sorted PDGFRα$^+$ cells at various retinal stages (n=3, *P<0.05, **P<0.01). (**G**) qPCR analysis of retinal astrocyte marker expression with RNA isolated from sorted PDGFRα$^+$ cells of P5 retina. Data represent relative mRNA expression from *APJ* KO mice as compared with WT mice set as unity (n=3, **P<0.01). Dotted line indicates level of WT. Error bars indicate s.d. Scale bars: 100 μm.

the endothelial network-forming area than did WT mice at P5 (Fig. 3D). Moreover, comparing sorted retinal PDGFRα$^+$ astrocytes revealed greater *Vegfa* mRNA expression in *APJ* KO than in WT mice (Fig. 3E). VEGF expression is known to be regulated by hypoxia via hypoxia inducible factor 1α (HIF1α). It has been reported that suppression of retinal vascular growth by VEGF-Trap injections primarily leads to VEGF upregulation, GFAP downregulation, and dense network formation in retinal astrocytes (Uemura et al., 2006). Moreover, West et al. have clearly demonstrated that hypoxia inhibits the maturation of astrocytes, resulting in VEGF upregulation, using models for retinopathy of prematurity (West et al., 2005). Currently, it is widely accepted that hypoxia is crucial for the regulation of astrocyte maturation. Therefore, it is possible that the hyperproliferation of ECs observed in *APJ* KO mice is caused by hypoxia induced by impaired vessel outgrowth. Indeed, compared with WT mice, slightly stronger Hypoxyprobe-1 signals were observed in the avascular area of the vascular front (asterisks in Fig. 4A,B) and the hypovascular areas in the middle of the vascular network (the areas enclosed by the dashed lines in Fig. 4A) in *APJ* KO mice. Although the levels of *Hif1a* mRNA were not significantly different in the whole retinas of WT and *APJ* KO mice (supplementary material Fig. S3), nuclear translocation of HIF1α, indicating its state of activation, was

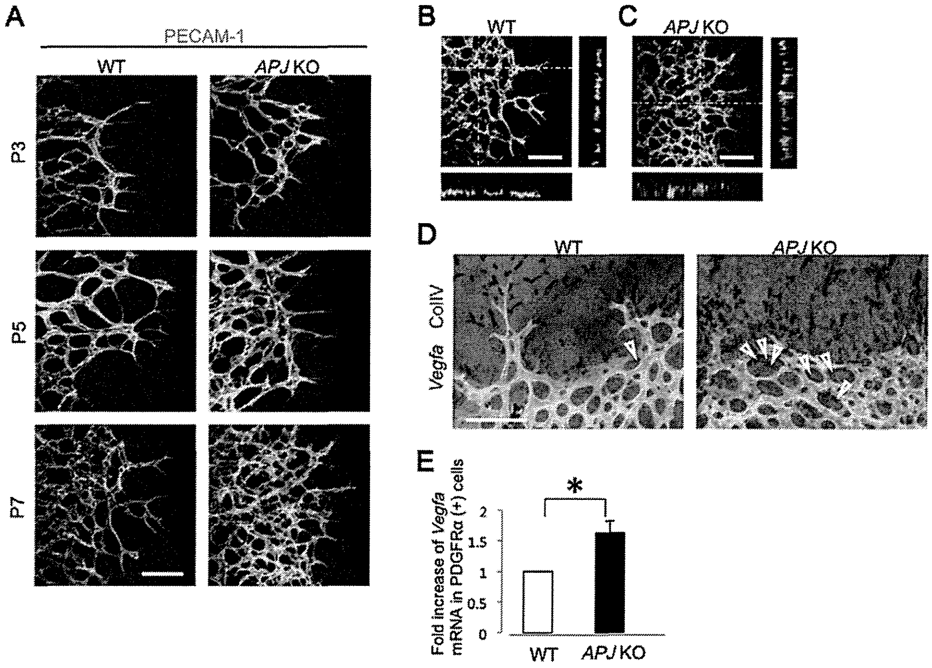

Fig. 3. Aberrant overgrowth of ECs in *APJ* KO mice. (**A**) Whole-mount anti-PECAM1 immunostaining of the developing retina around the vascular front of P3, P5 and P7 WT and *APJ* KO mice. (**B**,**C**) Confocal microscopy images of PECAM1$^+$ ECs in P7 WT (B) and *APJ* KO (C) mouse retinas. z-stack images show a denser EC layer in *APJ* KO than in WT retina. (**D**) In situ hybridization (ISH) for *Vegfa* combined with IHC for collagen IV in the vascular front. Note the increase of *Vegfa* mRNA in *APJ* KO retina. Arrowheads indicate upregulation of *Vegfa* mRNA even in the vascular area. (**E**) qPCR analysis of *Vegfa* mRNA expression in retinal PDGFRα$^+$ astrocytes from P5 retinas of WT and *APJ* KO mice (n=3, *P<0.05). Error bars indicate s.d. Scale bars: 100 μm.

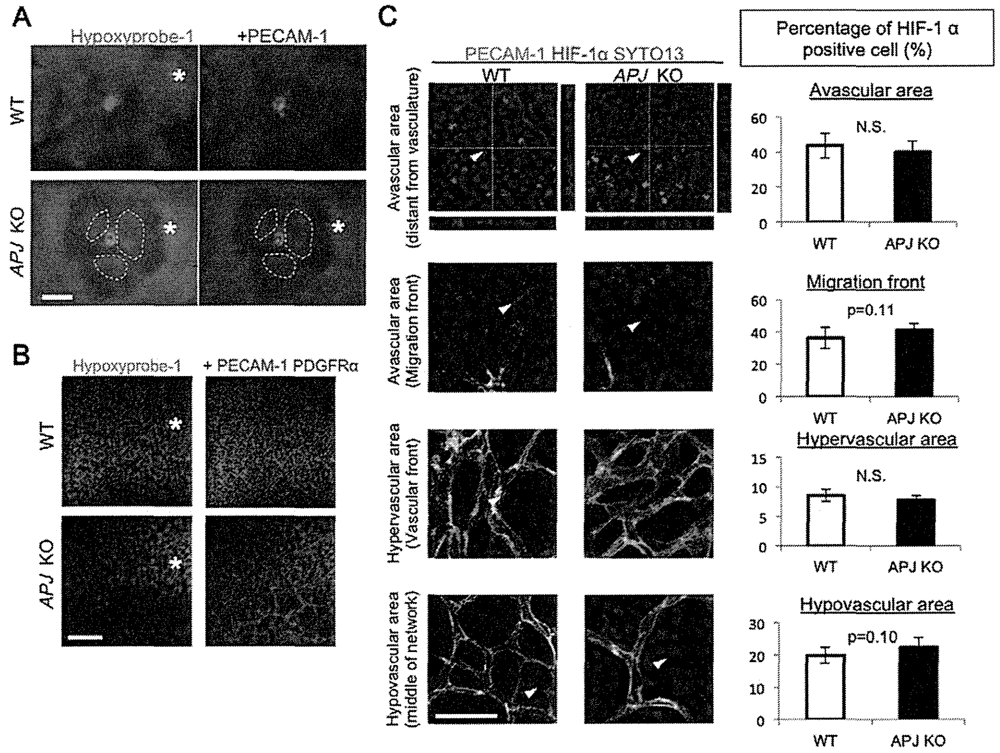

Fig. 4. Evaluation of hypoxic status in *APJ* KO mice. (**A**) Low-magnification images of hypoxic status in *APJ* KO mouse retina. Detection of PECAM1 (red) and Hypoxyprobe-1 (green) in P5 WT and *APJ* KO retinas. Asterisks indicate avascular areas of the vascular front and the areas demarcated by dashed lines indicate the hypovascular areas in the middle of the vascular network. (**B**) Higher magnification images of hypoxic status showing PECAM1 (red), PDGFRα (blue) and Hypoxyprobe-1 (green) in P5 WT and *APJ* KO retinas. (**C**) Nuclear translocation of HIF1α protein in *APJ* KO mice. Retinas of WT and *APJ* KO mice were dissected at P5 and whole-mount immunostaining was performed using anti-PECAM1 (green) and anti-HIF1α (red) antibodies and analyzed in different areas. Arrowheads indicate nuclear positivity for HIF1α. *z*-stack image showing localization of HIF1α in nuclei stained with SYTO13 (blue). (Right) Percentages of nuclear HIF1α^+ cells in the areas described were quantitatively evaluated. Four random FOV in the vascularized area were examined per retina (*n*=6). N.S., not significant. Error bars indicate s.d. Scale bars: 500 μm in A; 100 μm in B; 50 μm in C.

slightly enhanced in areas where more intense Hypoxyprobe-1 signals were observed in the *APJ* KO mice (Fig. 4C). However, the difference in HIFα nuclear translocation in WT and *APJ* KO mice was not statistically significant.

These data suggest that the VEGFA overexpression observed in astrocytes from *APJ* KO mice and the partial dense vascular network formation are dependent on hypoxia as a primary effect of APJ deficiency. However, compared with other models using VEGF-Trap (Uemura et al., 2006) or retinopathy of prematurity (West et al., 2005), in which blood vessel formation in the retina is completely abolished and strong hypoxia is induced, the degree of vascular defects and hypoxia observed here in *APJ* KO mice was not severe. Therefore, we consider that not only hypoxia but also other mechanisms underlie the maturation of astrocytes affected by APJ.

It is possible that APJ is expressed on astrocytes and that this, rather than its absence from ECs, affects the growth of immature astrocytes directly. However, we were unable to detect APJ expression on PDGFRα^+ astrocytes, whereas it was present on ECs (supplementary material Fig. S2). Moreover, we assessed whether the overgrowth of astrocytes is affected by aberrant growth of retinal ganglion cells. As shown in Fig. 5A, radially migrated well-organized retinal ganglion cells were present in *APJ* KO mice to the same extent as in WT mice. Expression of *Pdgfa* mRNA in retinal tissue was not increased in *APJ* KO mice relative to WT mice (Fig. 5B).

Next, we tested whether moderate, but not severely, delayed angiogenesis in the retina, as observed in *APJ* KO mice, affects astrocyte proliferation in WT mice by neutralizing VEGF using injections of soluble (s) FLT1 (VEGFR1). We started to neutralize VEGF from P3 and assessed its effects on vascular formation at P5, as severe vascular defects were induced when VEGF was neutralized from P0, as previously reported (Uemura et al., 2006). As shown in Fig. 5C, treatment with sFLT1 according to this schedule retarded the outgrowth of blood vessels to a similar extent to that observed in *APJ* KO mice. Although a partial dense astrocyte sheet was observed (Fig. 5C, arrow), *z*-stack images suggested that the thickness of the astrocyte layer was almost the same in PBS-treated or sFLT1-treated mice (Fig. 5D). Furthermore, increases in the total number and proliferation of astrocytes were not observed (Fig. 5E-H). These data suggest that molecular cues that are absent owing to the lack of APJ in ECs affect overgrowth by immature astrocytes.

Exogenous apelin induces the expression of GFAP in retinal astrocytes

Based on this result that a lack of APJ on ECs affects the outgrowth of immature astrocytes, we next examined whether apelin is involved in astrocyte differentiation and proliferation in vivo. Immunohistochemical analysis revealed that GFAP expression on astrocytes at P5 was enhanced following intraocular injection of apelin into WT mice at P3 (Fig. 6A). We confirmed upregulation

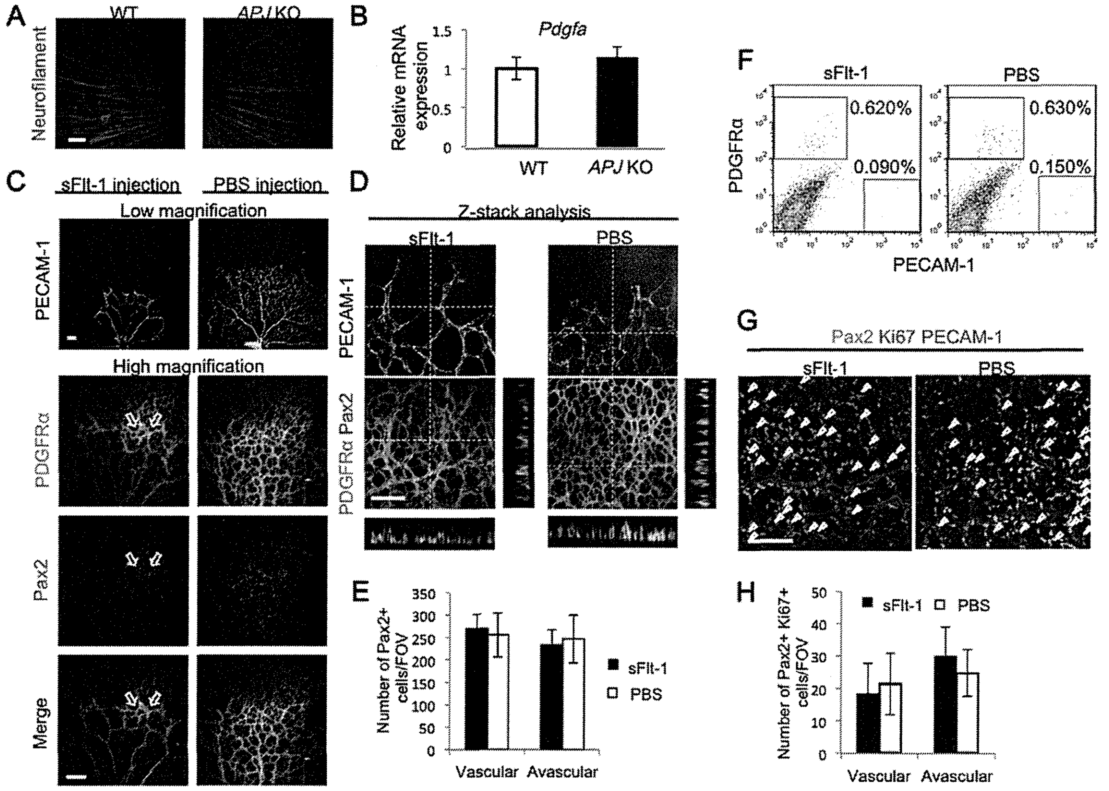

Fig. 5. Evaluation of neuronal cell development in the absence of APJ and its effects on proliferation of astrocytes mediated by retardation of vascular development. (**A**) The morphology of retinal ganglion cells in P3 WT and *APJ* KO mouse retinas. Retinas were stained with anti-neurofilament antibody. (**B**) qPCR analysis of *Pdgfa* mRNA expression in P5 WT and *APJ* KO retinas. (**C-G**) Effect of vascular retardation on astrocyte development in the retina assessed by intraocular injection of soluble (s) FLT1 or PBS (control). (C) Retinas were stained with antibodies against PDGFRα (green), PAX2 (red) and PECAM1 (white) at P5, 48 hours after treatment with sFLT1 or PBS. Although sFLT1 retarded vascular outgrowth, this degree of vascular defectiveness did not induce substantially abnormal networks of astrocytes at the vascular front with the exception of slight dense astrocyte network formation (arrows in C). (D) *z*-stack imaging showing no differences in the thickness of the glial cell layer or in the number of PAX2$^+$ cells between PBS- and sFLT1-treated mice. (E) Quantification of PAX2$^+$ astrocytes in the vascular and avascular areas. (F) Flow cytometry analysis of P5 retina from PBS- and sFLT1-treated mice (*n*=8). The number of PECAM1$^+$ cells decreased with sFLT1 treatment but the number of PDGFRα$^+$ cells did not change. (G) Proliferation status of astrocytes in P5 retinas from PBS- and sFLT1-treated mice. Retinas were stained with antibodies against PAX2 (green), KI67 (magenta) and PECAM1 (blue). Arrowheads indicate PAX2$^+$ KI67$^+$ astrocytes in vascular areas of P5 retinas from PBS- and sFLT1-treated mice. (**H**) Quantification of PAX2$^+$ KI67$^+$ astrocytes in the vascularized and non-vascularized retinal areas. Four random FOV per retina were examined (*n*=5). Error bars indicate s.d. Scale bars: 100 μm.

of *Gfap* mRNA in sorted PDGFRα$^+$ astrocytes from retinal tissues (Fig. 6B). Contrary to expectations, however, additional apelin in the WT retina did not alter blood vessel formation (Fig. 6A,C).

Next, we assessed whether apelin affected overgrowth by astrocytes in *Apln* KO mice. As in *APJ* KO mice, hyperproliferation of PDGFRα$^+$ PAX2$^+$ astrocytes was observed in *Apln* KO mice at P5 (Fig. 6D). Such astrocytes were weakly positive for GFAP (data not shown). Similar to the experiment shown in Fig. 6A, *Apln* KO mice at P3 were given intraocular injections of apelin and retinal gliogenesis was observed at P5. This demonstrated that apelin prevented the hyperproliferation of astrocytes that would otherwise result from the lack of apelin (Fig. 6D,E). Moreover, the capillary density in the migrating front of the vascular network was decreased in *Apln* KO mice injected intraocularly with apelin (Fig. 6D,F).

Because we failed to detect APJ expression in astrocytes, it is possible that ECs produce maturation factors for astrocytes when they are stimulated by apelin. We added supernatants from 24-hour apelin-stimulated cultures of cells of the bEnd3 EC line derived from mouse brain to primary cultures of retinal cells from WT mice at P1 (Fig. 7A). We did not detect a direct effect of apelin on the induction of GFAP expression by astrocytes, but these culture supernatants enhanced its expression in retinal cells. Candidate factors for inducing GFAP positivity in astrocytes are LIF and ciliary neurotrophic factor (CNTF), which are both members of the IL6 family (Kishimoto et al., 1995). We investigated the expression of IL6 family cytokines in PECAM1$^+$ ECs directly sorted from the retina of *APJ* KO mice or WT mice at P5. We could not detect IL6, oncostatin M, cardiotrophin 1 or IL11 in ECs from WT or *APJ* KO mice, and CNTF expression was similar in ECs from both sources. By contrast, LIF expression was markedly lower in *APJ* KO than in WT mice (Fig. 7B). Transcription of *LIF* was upregulated transiently upon stimulation of human umbilical vein ECs (HUVECs) with apelin (Fig. 7C). These data suggest that stimulation of ECs by apelin induces production of LIF in an APJ-dependent manner, which then influences astrocyte maturation.

Overgrowth of immature astrocytes resulting from a lack of APJ in ECs is abrogated by LIF injection

On the basis of the above results, we suggest that a lack of apelin/APJ system activity in ECs induces overgrowth of immature astrocytes followed by inhibition of their maturation,

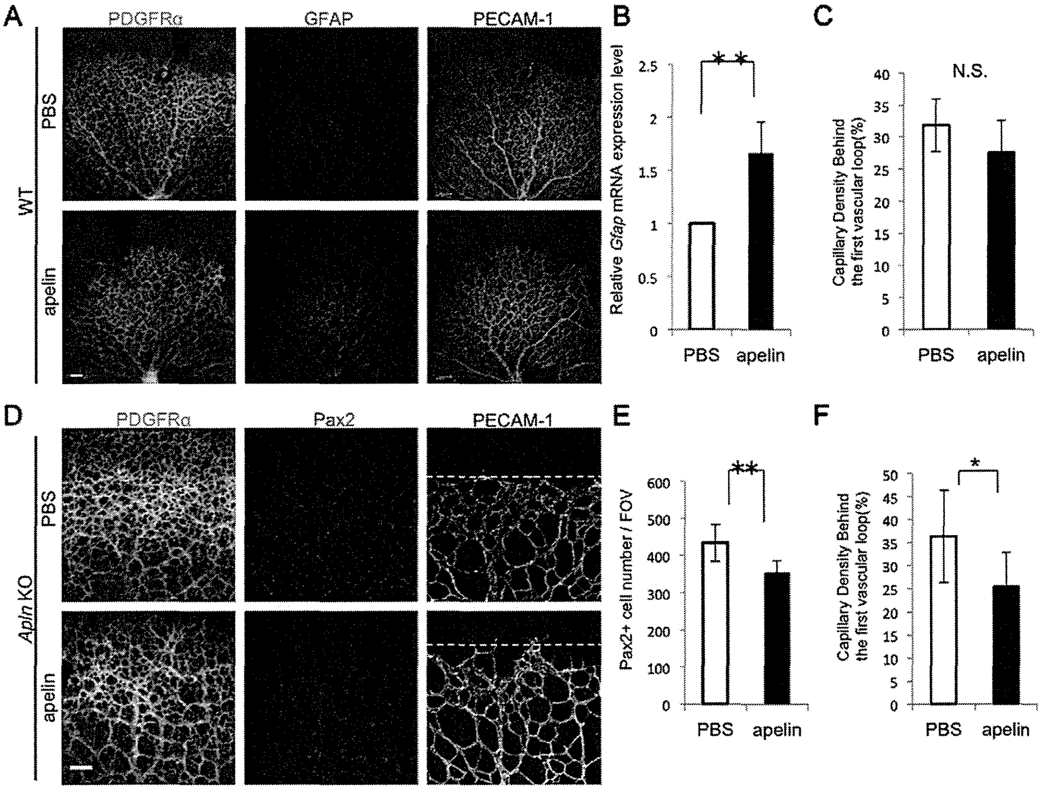

Fig. 6. Exogenous apelin-13 induces the expression of GFAP in retinal astrocytes. (**A-C**) Effect of apelin-13 in WT mouse retina. (A) Retinas were stained with antibodies against PDGFRα, GFAP and PECAM1 at P5, 48 hours after intraocular injection with PBS or apelin-13. (B) qPCR analysis of *Gfap* using mRNA from FACS-sorted PDGFRα$^+$ cells of P5 retina (**P<0.01). (C) Capillary density behind the first vascular loop after injection with apelin in WT mouse retina (n=6). N.S., not significant. (**D-F**) Rescue of aberrant overgrowth of astrocytes observed in *Apln* KO mice by intraocular injection of apelin-13. (D) Retinas were immunostained for PDGFRα, PAX2 and PECAM1 at P5, 48 hours after intraocular injection of PBS or apelin-13. (E) Quantitative evaluation of PAX2$^+$ astrocytes. Six random FOV in the retina were examined (n=6, **P<0.01). (F) Apelin reduces the capillary density from the vascular front in *Apln* KO mice (n=6, *P<0.05). The yellow dashed lines (D) demarcate the area (the first vascular loop) for which vascular density was calculated (C,F). Error bars indicate s.d. Scale bars: 100 μm.

resulting in aberrant EC network formation. Because LIF is upregulated upon stimulation of APJ by apelin in ECs, and because LIF is widely accepted as a maturation factor for astrocytes (Bonni et al., 1997; Mi et al., 2001), we injected LIF into *APJ* KO mice to assess whether maturation of astrocytes inhibits overgrowth of ECs as well as astrocytes. Intraocular injection of LIF into *APJ* KO mice at P3 resulted in a reduction of the number of PDGFRα$^+$ astrocytes and improved the formation of dense sheets of astrocytes (Fig. 7D). Moreover, weakly GFAP-positive astrocytes became strong GFAP expressors. Furthermore, staining with anti-PECAM1 antibody indicated that aberrant overgrowth of ECs was not induced. Quantitative evaluation of the number of astrocytes (confirmed by PAX2 staining) revealed that the hyperproliferation observed in the vascular area was reduced, but that LIF injection did not influence the number of astrocytes in the avascular area where no overgrowth had previously been observed (Fig. 7E). It is accepted that immature weakly GFAP-positive astrocytes induce proliferation of ECs but that this is gradually reduced as their level of GFAP expression increases (Kubota et al., 2008; West et al., 2005). This was suggested to be caused by the expression of VEGF in immature astrocytes. We assessed *Vegf* mRNA expression in retinal PDGFRα$^+$ astrocytes from *APJ* KO mice at P5. We found that LIF injection attenuated *Vegf* transcription (Fig. 7F), suggesting induction of astrocyte maturation.

DISCUSSION

Using a model of retinal angiogenesis, we have identified a possible mechanism by which maturation of astrocytes is induced as angiogenesis is finalized and newly developed blood vessels are consolidated. This entails apelin stimulation of APJ in ECs and subsequent LIF production, which induces maturation of weakly to strongly GFAP-positive astrocytes, which then enter quiescence. Because weakly GFAP-positive astrocytes act as proangiogenic accessory cells for ECs by producing VEGF and proliferate vigorously in response to PDGFA produced by ganglion cells, when LIF production is decreased due to the lack of apelin or APJ, the resulting aberrant overgrowth of immature astrocytes induces hyperproliferation of ECs. We propose that apelin/APJ activation in ECs is a trigger for finalization of blood vessel formation, indirectly mediated by the induction of astrocyte maturation.

We previously reported that although APJ is not expressed on ECs in the steady state after birth, in adulthood ischemia induces transient APJ expression in ECs mediated by stimulation with VEGF (Kidoya et al., 2008). In the retina, from the onset of retinal angiogenesis in newborn mice, network-forming ECs also transiently express APJ, which is downregulated after the establishment of the retinal endothelial network at P12 (Saint-Geniez et al., 2003). It has been reported using ISH that apelin is produced in tip cells, which might then induce proliferation of the stalk cells migrating behind them (del Toro et al., 2010). Apelin is secreted as peptides of 13 or 36 amino

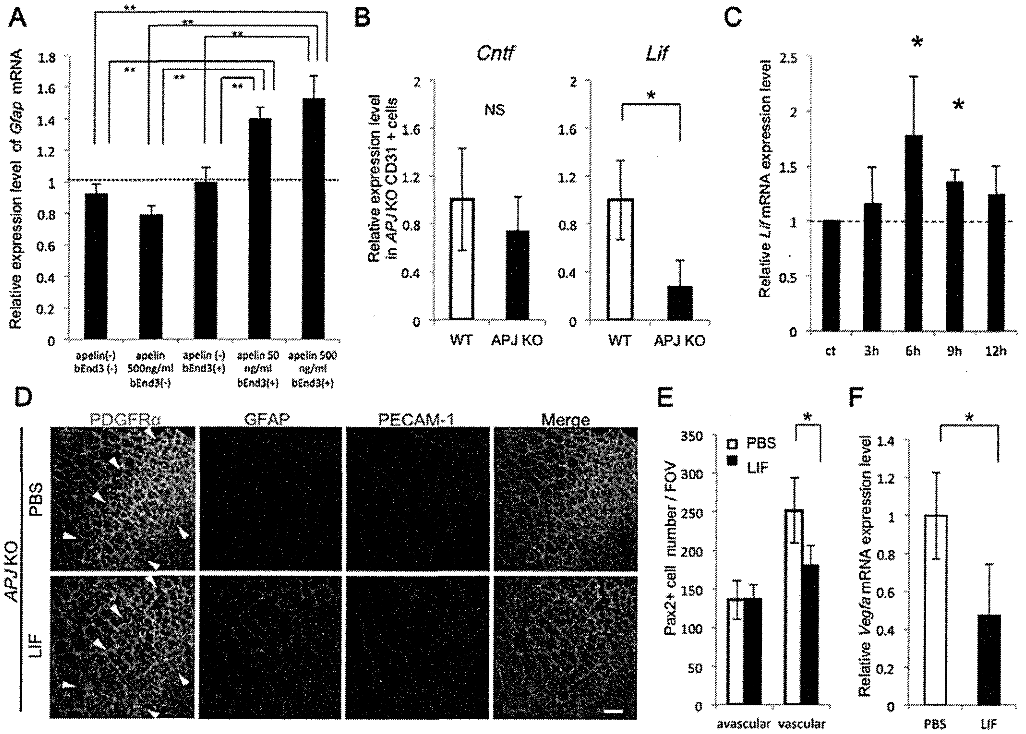

Fig. 7. Overgrowth of immature astrocytes resulting from the lack of APJ in ECs is prevented by LIF. (**A**) Effect on astrocyte GFAP positivity of medium conditioned by bEnd3 ECs stimulated with 50 ng/ml or 500 ng/ml apelin. Total RNA was extracted from dissociated retinal cells 24 hours after treatment with conditioned medium and qPCR analysis was performed to examine the expression of *Gfap* mRNA. $**P<0.01$. (**B**) qPCR analysis of *Cntf* and *Lif* using RNA isolated from FACS-sorted PECAM1$^+$ ECs of P6 mouse retinas ($n=4$, $*P<0.05$; N.S., not significant). (**C**) qPCR analysis of *LIF* mRNA expression in HUVECs. Total RNA was extracted from HUVECs stimulated with 50 ng/ml apelin for 0-12 hours ($n=3$, $*P<0.05$). (**D-F**) Effects of LIF on aberrant outgrowth of ECs and astrocytes. (D) Retinas of P5 *APJ* KO mice were dissected 48 hours after intraocular injection of PBS or LIF and stained with antibodies against PDGFRα, GFAP and PECAM1. LIF inhibited astrocyte proliferation (surrounded by arrowheads) and induced upregulation of GFAP even ahead of the sprouting edge. Scale bar: 100 μm. (E) Quantitative evaluation of the number of PAX2$^+$ astrocytes in vascular or avascular areas of *APJ* KO retina after treatment with PBS or LIF ($n=3$, $*P<0.05$). (F) qPCR analysis of *Vegfa* mRNA expression in sorted PDGFRα$^+$ cells of P5 PBS- or LIF-treated *APJ* KO retinas ($n=3$, $*P<0.05$). Error bars indicate s.d.

acids. It is possible that apelin affects ECs that are continuously expressing APJ in the retina, not only locally but also in a wider context. While apelin in the retina has been reported to have proangiogenic properties (del Toro et al., 2010), we previously reported that it also acts as a maturation factor for newly developing blood vessels. It induces the assembly of ECs, and thus promotes the formation of larger blood vessels (Kidoya et al., 2008). It also stabilizes the junction protein VE-cadherin and thus inhibits vascular hyperpermeability induced by VEGF or inflammatory stimuli (Kidoya et al., 2010). Therefore, diverse functions for apelin during angiogenesis have been postulated. VEGF has strong proangiogenic activity, but also induces the production of vasohibin 1, which has anti-angiogenic activity (Watanabe et al., 2004). This implies that proangiogenic factors might also concurrently induce anti-angiogenic factors in ECs as part of a negative-feedback regulatory mechanism. LIF production from ECs upon activation of APJ might also be involved in such a negative-feedback system during angiogenesis. Based on the phenotype of *Apln* KO or *APJ* KO mice, we conclude that apelin facilitates angiogenesis by inducing proliferation of ECs, but subsequently indirectly finalizes angiogenesis by furthering the maturation of astrocytes in the retina. Therefore, delay of capillary outgrowth from the optic nerve head, and the suppression of vascular network formation, are primarily defects induced by the lack of APJ or apelin. The partial hypervascularity subsequently observed in the migrating front of the vascular network-forming area is, indirectly, a secondary deficit caused by insufficient maturation of astrocytes.

We previously reported that TIE2 activation by ANG1 in ECs is one pathway of apelin production (Kidoya et al., 2008). Consistent with ANG1 regulating the enlargement of blood vessels, we found that apelin also induces enlarged blood vessels by promoting the assembly of ECs. Based on these findings, we reported apelin as a factor for constructing enlarged blood vessels and that it acts as a downstream regulator of the ANG1/TIE2 system. We initially focused on enlargement of blood vessels in retinas from *APJ* KO mice. However, *APJ* KO mice showed moderate defects of vascular network formation in their retinas and we could not clearly compare vascular diameters because of delayed blood vessel formation in these mice.

ANG1 production is usually induced in mural cells, which are located beside both tip cells and stalk cells. With respect to mural cell localization, WT and *APJ* KO mice were indistinguishable (supplementary material Fig. S4). Therefore, ANG1 might affect both tip cells and stalk cells. Because apelin mRNA is expressed predominantly in tip cells in the retina (del Toro et al., 2010; Strasser et al., 2010), these might possess a specific machinery for apelin production, which could be affected by ANG1. However, mechanisms regulating apelin production in tip cells have not been elucidated. It has previously been reported that ANG1 is produced by astrocytes upon re-oxygenation after ischemia and has been suggested to play an important role in the barrier function associated with tight junction proteins (Lee et al., 2003). We previously reported that apelin also induces stabilization of VE-cadherin in ECs, as described above (Kidoya et al., 2010). Therefore, further studies of the relationship between ANG1 and apelin and of the additional involvement of other mechanisms regulating apelin production in tip cells as influenced by mural cells or astrocytes are required.

In the brain, neural precursor cells (NPCs) generate neurons and subsequently glia. This switch is crucial for determination of the number of neurons and glia. Mechanisms regulating the differentiation of glia from NPCs, such as how and where the commitment to the glial lineage is made, have been extensively analyzed (Freeman, 2010; Rowitch and Kriegstein, 2010). However, regulation of astrocyte differentiation from immature to mature cells in vivo is not well characterized. One line of evidence suggests that oxygen levels control astrocyte differentiation, i.e. inadequate vascularity in the retina induces hypoxia, resulting in the suppression of astrocyte differentiation (West et al., 2005). Reciprocally, well-organized vascular formation triggers maturation of astrocytes under normoxia. Deficiency of APJ also induces hypoxia because of insufficient outgrowth of blood vessels; such hypoxia may then induce hypervascularity caused by VEGF upregulation and release from immature astrocytes. It is possible that maturation arrest of astrocytes might be secondary to the lack of APJ; however, we found that expression of LIF, an astrocyte maturation factor, is induced in ECs by stimulation with apelin. Because LIF expression is reduced in *APJ* KO mice, these data suggest that complex mechanisms, such as hypoxia and attenuation of LIF, underlie the suppression of astrocyte maturation in *APJ* KO mice.

Although it has been reported that LIF secreted by ECs induces astrocyte maturation (Kubota et al., 2008; Mi et al., 2001), how LIF is induced in ECs in vivo has not been determined. Our present data suggest that LIF production mediated by activation of APJ in ECs by apelin is one of the programmed processes regulating maturation of astrocytes in vivo, which facilitates well-organized vascular and astrocyte network formation in the retina. However, it has been reported that *Lif* KO mice show overall hypervascularity in their retinas (Kubota et al., 2008) and this phenotype is different from that of *APJ* KO mice because hypervascularity was restricted to the migrating front of the vascular network area in these latter mice. GFAP positivity in astrocytes at areas other than the migrating front of the vascular network did not differ between WT and *APJ* KO mice (Fig. 2A). This suggests the existence of mechanisms other than the apelin/APJ system for astrocyte maturation and indicates that further investigation is required to achieve a full understanding of the molecular mechanisms of blood vessel and astrocyte maturation.

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Competing interests statement
The authors declare no competing financial interests.

Supplementary material
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ORIGINAL ARTICLE

The apelin/APJ system induces maturation of the tumor vasculature and improves the efficiency of immune therapy

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Immature and unstable tumor vasculature provides an aberrant tumor microenvironment and leads to resistance of tumors to conventional therapy. Hence, normalization of tumor vessels has been reported to improve the effect of immuno-, chemo- and radiation therapy. However, the humoral factors, which can effectively induce maturation of tumor vasculature, have not been elucidated. In this study, we found that the novel peptide apelin and its receptor APJ can induce the morphological and functional maturation of blood vessels in tumors. This apelin-induced tumor vascular maturation enhances the efficacy of cancer dendritic cell-based immunotherapy and significantly suppresses tumor growth by promoting the infiltration of invariant natural killer T cells into the central region of the tumor and thereby robustly inducing apoptosis of tumor cells. Additionally, we showed APJ expression to be enhanced in the tumor endothelium in comparison with normal-state endothelial cells. These findings provide a new target for tumor vascular-specific maturation, which is expected to improve the efficacy of conventional cancer therapies.

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Introduction

Agents targeting the tumor vasculature have been used for antitumor therapy in various preclinical and clinical studies (Gasparini *et al.*, 2005; Heath and Bicknell, 2009). The function of vascular endothelial growth factor (VEGF)-family ligands and their receptors in tumor angiogenesis has been well established, and serves as a logical target for antiangiogenic cancer therapy (Lohela *et al.*, 2009).The anti-VEGF monoclonal antibody, bevacizumab, neutralizes all isoforms of human VEGF (Gerber and Ferrara, 2005). Combining bevacizumab with chemotherapeutic agents appears to result in modest survival benefit in patients with metastatic colorectal cancer (Hurwitz *et al.*, 2004). This antitumor effect of bevacizumab was assumed to be due to its disruption of VEGF, and it was expected to directly suppress endothelial cell (EC) growth and inhibit tumor angiogenesis. However, Jain and co-workers recently showed that anti-angiogenic therapy causes 'normalization' of aberrant tumor vasculature and thus induces the formation of functional mature vasculature (Jain, 2005). This normalization of the tumor vasculature is effective for combination antitumor therapies, because mature vasculature and increased blood flow to tumors can promote the delivery of antitumor therapeutics to tumor cells (Dickson *et al.*, 2007). Therefore, investigating the role played by endogenous vascular maturation factors during the angiogenesis process could help in the development of a new antitumor therapy.

Apelin, a secreted peptide, has been identified as the endogenous ligand of the G-protein-coupled cell-surface receptor APJ (Tatemoto *et al.*, 1998). Apelin and APJ mediate a wide range of physiological actions, including angiogenesis (Cox *et al.*, 2006; Eyries *et al.*, 2008; Kasai *et al.*, 2008; Kidoya *et al.*, 2008), heart contractility, blood pressure regulation (Dai *et al.*, 2006) and other effects (Sorhede Winzell *et al.*, 2005; Lambrecht *et al.*, 2006; Lago *et al.*, 2007). Apelin and APJ are expressed on ECs of newly developing blood vessels during angiogenesis (Kidoya *et al.*, 2008), and it has been reported that apelin expression is induced by hypoxia in ECs (Eyries *et al.*, 2008). *In vitro* analyses revealed that apelin stimulates the proliferation, migration and tube formation of ECs (Kasai *et al.*, 2004; Masri *et al.*, 2004). Recently, we reported that apelin-deficient mice have narrow blood vessels, but in contrast, apelin-overexpressing mice have enlarged blood vessels. Apelin induces larger cords of ECs, mainly mediated by cell–cell aggregation, resulting in the formation of enlarged blood vessels (Kidoya *et al.*, 2008). These enlarged blood vessels are stable, and vascular permeability was reduced (Kidoya *et al.*, 2010). Taken together, these data support the notion that the apelin/APJ pathway has an important role in vascular maturation, especially for regulating the caliber of blood vessels to facilitate lumen enlargement (Kasai *et al.*, 2008; Kidoya *et al.*, 2008).

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Invariant natural killer T (iNKT) cells are implicated in the control of autoimmunity (Singh *et al.*, 2001), resistance to tumors (Shin *et al.*, 2001; Smyth *et al.*, 2002) and protection against infectious agents (Kakimi *et al.*, 2000). The iNKT cells are characterized by the co-expression of natural killer (NK) receptor and T-cell receptor (TCR), which is encoded in humans by Vα24-JαQ gene segments and in mice by homologous Vα14-Jα281 sequences (Taniguchi *et al.*, 2003). iNKT cells are activated by a specific glycolipid antigen α-galactosylceramide (αGalCer) presented on CD1d (Kawano *et al.*, 1997; Brossay *et al.*, 1998; Spada *et al.*, 1998). Activated iNKT cells also induce cell death in tumor cells by the expression of a wide variety of cell death-inducing effector molecules, including perforin, Fas ligand and tumor necrosis factor-related apoptosis-inducing ligand, in a manner similar to other cytotoxic cells such as NK cells and CD8 cytotoxic T cells (Nieda *et al.*, 2001). Furthermore, activation of iNKT cells induces a rapid release of cytokines, including interleukin-4, interleukin-12 and interferon-γ (IFN-γ) (Smyth *et al.*, 2002).

We previously reported that intravenous injection of αGalCer-pulsed dendritic cells (DCs) induced the activation of murine iNKT cells *in vivo*, and eradicated established metastatic tumor foci in models of mouse liver and lung metastasis (Shin *et al.*, 2001). Based on these observations in murine models, several clinical trials of intravenous injection of αGalCer-pulsed DCs have been performed (Nieda *et al.*, 2001; Motohashi *et al.*, 2009). In these studies, the interventions had limited clinical efficacy in advanced cancer patients, although iNKT cell-specific systemic immune responses had been induced in a large population of the patients. We hypothesized that optimal delivery of effector cells to the target tissues is necessary to improve the efficacy of this immunotherapy. Therefore, we performed a clinical trial using intra-arterial infusion of activated iNKT cells for patients with advanced head and neck cancer (Kunii *et al.*, 2009), and a significant tumor reduction was observed in some patients after direct infusion of iNKT cells to the tumor-feeding arteries.

In the present study, we analyze the expression and function of the apelin–APJ system in the tumor vasculature and examined the therapeutic effects of apelin-mediated tumor vascular normalization. Moreover, we also studied the effects of combination therapy with tumor vascular normalization by apelin and cancer immunotherapy by activated DC transplantation in the mouse tumor model.

Results

Apelin and APJ are highly expressed in tumor ECs

We previously reported temporal expression of APJ in ECs during angiogenesis in embryos and during the process of recovery from ischemic states (Kidoya *et al.*, 2008, 2010). To determine whether apelin and APJ are expressed in a cell type-specific manner in ECs of tumor vessels, we evaluated the expression of vascular apelin and APJ in growing syngeneic mouse tumors by real-time PCR and immunohistochemical analyses. In real-time PCR analysis, we used CD31+ CD45− ECs obtained from the heart, skin or tumors of mice by fluorescence-activated cell sorting sorting. Compared with normal tissue ECs, APJ was more highly expressed in ECs from colon26 murine colon adenocarcinoma and Lewis lung carcinoma (LLC) (Figure 1a).

Immunohistochemical analysis of tumor tissue derived from colon26 murine colon cancer revealed that apelin and APJ are specifically expressed in the tumor vasculature (Figures 1b and c). Apelin and APJ expression was not observed in all tumor vessels, but about 13% of vessels were APJ-positive and about 27% of vessels were apelin-positive (Figure 1d). By analyzing the relationship between location or caliber of vessels and APJ expression, many APJ-positive ECs were observed in the large-caliber blood vessels in the peripheral region (Figure 1e). We also detected apelin and APJ protein expression in LLC tumor tissue blood vessels by immunohistochemical staining (Figures 1f and g). In these tumors, most ECs co-expressed apelin and APJ as reported previously (Kälin *et al.*, 2007) (data not shown). These data indicated that apelin and APJ are highly expressed in tumor blood vessels.

Apelin induces blood vessel enlargement in tumors and inhibits tumor growth

To analyze the effects of apelin on the morphology of blood vessels, we first observed the growth of blood vessels in tumors. Colon26 mouse colon cancer cells stably transfected with the apelin expression vector (Figure 2a) were inoculated under the skin of BALB/c mice to form tumors. Overexpression of apelin greatly inhibited the growth of colon26 tumors in all three cell lines derived from distinct clones (Figure 2b). In agreement with a previous report that apelin induced enlarged blood vessels in the dermis of apelin Tg mice (Kidoya *et al.*, 2010), the caliber of blood vessels observed in tumors formed by colon26 cells transduced with apelin was enlarged compared with control colon26 tumors (Figures 2c–e). This enlargement of tumor vessels is not dependent on tumor size, because the lumen size of the vessels was different even for tumors of the same volume (300 mm^3) (Supplementary Figure 1; day 8 for colon26/vector, day 10 for colon26/apelin). However, there is little difference between density of blood vessels in apelin-expressing tumor and control tumor (date not shown). Blood vessel enlargement by apelin was also observed in tumors developed from PC3 human prostate cancer cells (Figures 2f–h) and B16 mouse melanoma cells (data not shown). This indicated that the action of apelin on the change in the caliber of blood vessels is not a specific response to colon26 cells.

It is well known that the size of newly developed blood vessels is affected by mural cell adhesion to ECs during the maturation process of blood vessel formation (Gerhardt and Betsholtz, 2003). Usually, the blood vessels observed in tumors are not well covered with mural cells. In order to determine whether apelin is

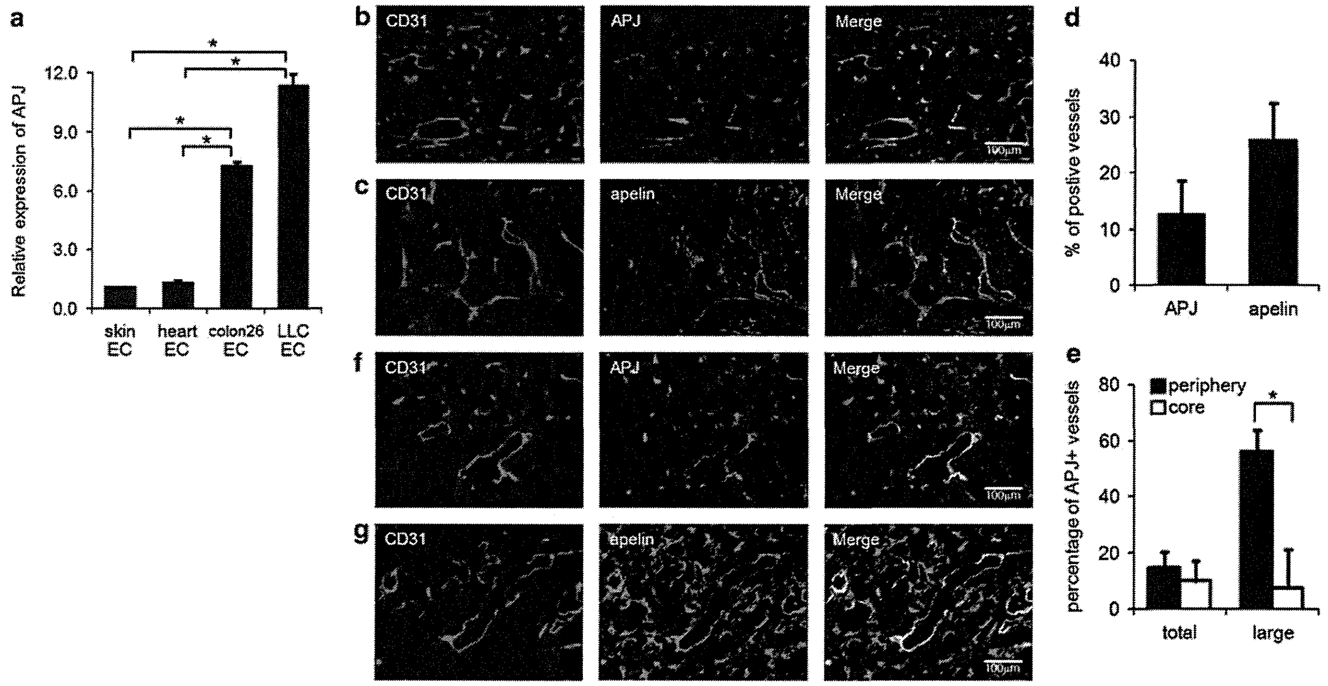

Figure 1 Analysis of apelin and APJ expression in ECs of the tumor vasculature. (**a**) Quantitative real-time PCR analysis of APJ mRNA expression in CD31+CD45− ECs derived from mouse skin and heart, and colon26 or LLC tumors 12 days after implantation. $*P<0.01$. (**b**, **c**) Immunohistochemical staining of sections from colon26 tumors using anti-CD31 (red) and anti-APJ (green) antibodies (**b**) or anti-apelin (green) antibodies (**c**). The scale bar indicates 100 μm. (**d**) Quantification of the ratio of tumor vessels expressing apelin or APJ. The data represent the ratio of apelin- or APJ-positive vessels versus apelin- or APJ-negative vessels as determined by immunohistochemical analysis. (**e**) Quantification of the size of APJ-positive blood vessels and their localization in colon26 tumors by immunohistochemical analysis. $*P<0.01$. (**f**, **g**) Immunohistochemical staining of tumor sections from LLC tumors using anti-CD31 (red) and anti-APJ (green) antibodies (**f**), or anti-apelin (green) antibodies (**g**). The scale bar indicates 100 μm.

involved in muscularization resulting in enlargement of blood vessels, tumor sections were stained with an anti-smooth muscle actin antibody. As shown in Figure 2i, the preexisting vessels around tumor were well muscularized, but mural cells did not adhere to the ECs of enlarged blood vessels in colon26 tumors expressing apelin. This suggested that the induced enlargement of blood vessels by apelin occurs independently of mural cells.

Apelin induces the formation of functional, non-leaky, mature vessels

Recent reports indicate that anti-angiogenic cancer therapy often converts the immature blood vessels in tumors to more a normal functional vascular network (Jain, 2005; Dickson *et al.*, 2007). As shown Figure 2b, apelin-mediated maturation of the tumor vasculature suppressed tumor growth. Therefore, we examined whether the apelin-induced enlargement of blood vessel also contributes to functional blood vessel normalization. Because the tumor vasculature is generally immature and leaky, oxygen cannot reach the center of the tumor tissue, leading to hypoxia. However, the hypoxic status of the center of tumor tissues was moderated in the tumors formed by the colon26 cells transduced with apelin (Figures 3a and b). Moreover, fluorescence-conjugated 100 mM dextran effectively infiltrated to the center of tumor tissues in apelin-expressing colon26 tumors (Figures 3c and d). These results indicate that the apelin-mediated enlargement of tumor vessels also induced the functional maturation of the blood vessels.

We then analyzed the phenotype of the CD31+ CD45− ECs isolated from apelin-expressing or control colon26 tumors. In the apelin-transduced tumors, the expression level of EC-related genes VCAM1, Flk1, Flt1 and APJ was increased (Figures 3e and f). Furthermore, consistent with our previous report, expression of the EC junction proteins VE-cadherin and Claudin5 was upregulated (Figure 3f). Therefore, we speculated that the increased vascular stability observed in the apelin-expressing tumors is due to these changes in the EC phenotypes.

Functional analysis of αGalCer-pulsed mature BMDCs

Tumor vessel vascular normalization has been reported to enhance the therapeutic effects of anticancer drugs, radiotherapy and immunotherapy (Willett *et al.*, 2006). Therefore, we examined whether induction of functional normalization of blood vessels induced by apelin improved the efficacy of cancer immunotherapy. In addition, we hypothesized that vascular normalization would improve the migration of antitumor effector cells to the tumor site. Furthermore, we believed that