Adenoviral Expression of Vascular Endothelial Growth Factor-C Induces Lymphangiogenesis in the Skin

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Abstract—The growth of blood and lymphatic vasculature is mediated in part by secreted polypeptides of the vascular endothelial growth factor (VEGF) family. The prototype VEGF binds VEGF receptor (VEGFR)-1 and VEGFR-2 and is angiogenic, whereas VEGF-C, which binds to VEGFR-2 and VEGFR-3, is either angiogenic or lymphangiogenic in different assays. We used an adenoviral gene transfer approach to compare the effects of these growth factors in adult mice. Recombinant adenoviruses encoding human VEGF-C or VEGF were injected subcutaneously into C57Bl6 mice or into the ears of nude mice. Immunohistochemical analysis showed that VEGF-C upregulated VEGFR-2 and VEGFR-3 expression and VEGF upregulated VEGFR-2 expression at 4 days after injection. After 2 weeks, histochemical and immunohistochemical analysis, including staining for the lymphatic vessel endothelial hyaluronan receptor-1 (LYVE-1), the vascular endothelial marker platelet–endothelial cell adhesion molecule-1 (PECAM-1), and the proliferating cell nuclear antigen (PCNA) revealed that VEGF-C induced mainly lymphangiogenesis in contrast to VEGF, which induced only angiogenesis. These results have significant implications in the planning of gene therapy using these growth factors. (Circ Res. 2001;88:623–629.)

Key Words: angiogenesis □ immunohistochemistry □ viruses □ vessels □ revascularization

Control of the vascular system by modulation of growth factor signaling is essential in attempts to treat diseases such as ischemic cardiovascular disease and cancer.1-3 Perhaps the most important family of growth factors involved in the regulation of angiogenesis is the vascular endothelial growth factor (VEGF) family, which includes VEGF, VEGF-B, VEGF-C, VEGF-D, Orf virus–encoded VEGF-E, and the placenta growth factor.4,5 These ligands bind to VEGF receptors (VEGFR)-1, VEGFR-2, and VEGFR-3 with partially overlapping receptor specificities. Both VEGF-C and VEGF-D bind VEGFR-2 and VEGFR-3 but are differentially regulated in cells and in tissues.6-9 The affinity of VEGF-C and VEGF-D toward their receptors is regulated by proteolytic processing; the affinity of the mature, proteolytically processed forms toward VEGFR-3 is =40 times higher than the affinity toward VEGFR-2.6,10 The importance of VEGF-3 signals in the vascular system is indicated by targeted mutagenesis of the VEGF-3 gene, which results in embryonic lethality despite the presence of an intact VEGFR-2.11 The VEGF-3 gene knockout leads to a disruption of the remodeling of primitive embryonic vasculature into a hierarchy of large and small vessels and results in cardiovascular failure of the embryos. However, in normal adult tissues, VEGF-3 is largely absent from blood vessel endothelia and remains predominantly expressed in the lymphatic endothelium.9,12,13

Although a variety of angiogenic responses have been shown to be induced by adenoviral expression of VEGF in different mouse tissues,14 the biological functions of VEGF-C in normal adult tissues are thus far less clear. Overexpression of VEGF-C or VEGF in the skin under the keratin 14 promoter induced hyperplasia of lymphatic vessels or angiogenesis, respectively.15-17 In addition, recombinant VEGF-C was angiogenic in the early chick chorioallantoic membrane, but it induced exclusively lymphangiogenesis in the differentiated chorioallantoic membrane.18,19 Furthermore, both VEGF and VEGF-C were angiogenic when expressed from a transfected plasmid vector in a rabbit model of hindlimb ischemia.20 VEGF-C expression may thus in general lead to lymphangiogenesis, whereas in early embryonic stages or when overexpressed in ischemic tissues, it may stimulate angiogenesis.

The results showing that VEGF-C can induce both angiogenic and lymphangiogenic responses in various settings of gene delivery have raised important questions about the specificity of VEGF-C–induced vascular effects in normal
adult tissues. Although in at least some conditions, the goal of proangiogenic gene therapy may be to regenerate all components of the vascular system, in other conditions, such as in secondary lymphedema, only lymphangiogenesis may be desired. In fact, the development of specific lymphangiogenic gene therapy would be an important development for example for the tens of thousands of patients who suffer from lymphedema secondary to axillary evacuation of the lymph nodes or for the millions of patients who develop the disease after filariasis. To resolve questions about the angiogenic versus lymphangiogenic specificity of VEGF-C, we have investigated in the present study the effects of VEGF-C gene transfer on the skin vasculature of adult mice compared with gene transfer of VEGF and β-galactosidase in the same setting.

Materials and Methods

Generation of Recombinant Adenoviruses Encoding the VEGFs

For the construction of an adenovirus vector encoding VEGF-C, the full-length human VEGF-C cDNA (GenBank accession No. X94216) was cloned under the cytomegalovirus promoter in the pcDNA3 vector (Invitrogen). The SV40-derived polyadenylation signal of the vector was then exchanged for that of the human growth hormone gene, and the transcription unit was inserted into the pAd BgII site23 as a BamHI fragment. Replication-deficient recombinant E1–E3–deleted adenoviruses were produced in human embryonic kidney 293 cells and concentrated by ultracentrifugation as previously described.22 Recombinant adenoviruses encoding VEGF(C) and β-galactosidase were constructed as previously described.22–26 Adenoviral preparations were confirmed to be free from helper viruses, lipopolysaccharide, and bacteriological contaminants.26

Construction, Expression, and Purification of VEGFR Ig Fusion Proteins

The expression plasmids encoding human VEGFR-1-Ig and VEGFR-3-Ⅲ were constructed by polymerase chain reaction-amplifying the first three Ig homology domains of the extracellular portions of VEGFR-1 and VEGFR-3 with the primer pairs 5′-CTCCGGATCTCTCTAGTTACGAGCTCAAAATT-3′ (BamHI site underlined)5′-GATGAGATCTTCTTATCATATATGCACTGA-3′ (BglII site underlined) and 5′-CTCTTAGATTCCTCTTTATCATATATGCACTGA-3′/5′-GATGAGAGATCTTCTTATCATATATGCACTGA-3′, respectively. The products were cloned into the BglII site of the pMT/BiP·V5·HisC vector (Invitrogen), and the cDNA coding for the Fc-tail of human IgG1 was cloned in frame with the VEGFR Ig homology domains in the same vector. The expression plasmids were cotransfected with the pCOS·Hyg selection plasmid (Invitrogen) into Drosophila S2 cells, and stable cell pools were selected in 150 μg/mL hygromycin B (Calbiochem). The expression of the Ig fusion proteins was induced with 500 μg/mL CuSO₄ in serum-free DES medium (Invitrogen) and after 4 days, they were purified from the conditioned medium by protein A affinity chromatography (Amersham Pharmacia). VEGFR-2-Ig was obtained from R&D Systems (catalogue No. 357-KD).

Expression of Recombinant Adenoviral VEGF-C, VEGF, and β-Galactosidase

Cells (293 EBNA) grown in 10% FCS were transfected with pREP7 (Invitrogen) expression vectors encoding VEGF(C) or VEGF(C), using the calcium phosphate precipitation method or infected by incubation with 2×10⁶ pfu/10⁷ cells (multiplicity of infection=20) of the respective adenoviruses in serum-free medium for 1 hour. The medium was then changed to medium containing 10% FCS, the cells were incubated overnight, and metabolically labeled with [35S]-methionine and cysteine (Promix, Amersham) for 6 hours. The media were collected, and labeled VEGF proteins were precipitated using soluble VEGFR-Ig domain fusion proteins. Before VEGF-C precipitation using VEGFR-2-Ig, endogenous VEGF was removed from the supernatants by preadsorption using anti-VEGF monoclonal antibodies (R&D catalogue No. MAB293). The bound proteins were precipitated with protein G Sepharose, washed three times in PBS, dissolved in Laemmli sample buffer, and analyzed by 12.5% or 15% SDS-PAGE. Gels were then dried and analyzed by phosphorimaging and autoradiography.

Analysis of the Adenovirus-Encoded Transcripts

In Vivo

Adenovirus (2×10⁸ pfu) encoding VEGF, VEGF-C, or β-galactosidase was injected into the tail veins of two C56/Bl6 mice. The mice were sacrificed 4 days later and RNA was extracted from the livers (RNAeasy Kit, Qiagen). Total RNA (15 μg) was subjected to Northern blotting and hybridization with a mixture of 32P-labeled cDNAs specific for VEGF (nucleotides 57 to 639, GenBank accession No. NM003376), VEGF-C (nucleotides 495 to 1661, GenBank accession No. X94216), or LacZ (nucleotides 529 to 977 pbScript SK+, Stratagene).

All experimental procedures involving laboratory animals were approved by the Helsinki University Ethical Committee and by the Provincial State Office of Southern Finland (permit No. HY 312).

Immunohistochemistry and Morphometry

Recombinant adenovirus or buffer (2×10⁸ pfu) was injected subcutaneously into the backs of C56/Bl6 mice or into the ears of NMRI nude (nu/nu) mice (Harlan). The mice were sacrificed at various time points after injection. Skin from the site of injection was fixed in 4% paraformaldehyde and embedded in paraffin, and 6-μm sections were stained using monoclonal antibodies against VEGFR-2,27 VEGFR-3,28 or polyclonal antibodies against the lymphatic marker LYVE-1, a receptor for hyaluronan and a homologue to the CD44 glycoprotein,29 or mouse platelet–endothelial cell adhesion molecule-1 (PECAM-1) (BD Pharmingen, catalogue No. 01951D), the mouse homologue of the human vascular endothelial antigen CD31. Sections were also stained using polyclonal antibodies against laminin.30 The tyramide signal amplification (TSA) kit (NEN Life Sciences) was used to enhance staining. Negative controls were done by omitting the primary antibodies. Double staining of sections was carried out by first staining sections for proliferating cell nuclear antigen (PCNA) (ZYMED, catalogue No. 93-1143) and subsequently for LYVE-1 and PECAM-1 as detailed above. The results were viewed with an Olympus AX80 microscope and photographed. For quantification, the vessels in the sections were counted using square grids (area=0.16 mm², ×200 magnification), and the mean and probability value were calculated using the Student’s t test. Eight visual fields were quantified in sites of active angiogenesis or lymphangiogenesis in five different ears injected with AdVEGF-C or AdVEGF. For controls, 15 to 20 visual fields in five different ears injected with AdLacZ were quantified. For morphometric quantification of vessel volume, quantitative densitometry of 70 to 80 vessels in 8 to 10 visual fields was performed according to Weibel’s principles using a CAS200 (Becton-Dickinson) automated image analyzer and the proprietary software. Blood vessels were visualized and photographed in situ using a Leica MZ APO microscope.

Results

Expression of VEGF-C and VEGF by Recombinant Adenoviruses In Vitro

To confirm that adenoviral gene transfer of VEGF-C results in secretion of polypeptides that bind to their receptors, 293 EBNA cells were infected with the respective adenoviruses. Cells infected with the VEGF-C adenovirus (AdVEGF-C) produced major polypeptides of ~29/31 kDa that bound to the VEGF-3-Ig fusion protein (Figure 1A,
bonded homodimers and bind to VEGFR-1 and VEGFR-2. The expression of VEGF polypeptides that form disulfide-confirmed that adenoviral gene transfer of VEGF results in previously reported.6

The liver of an uninfected mouse showed no signal. Expression of Adenovirally Encoded VEGF-C and VEGF In Vivo The expression of VEGF-C and VEGF adenoviruses in vivo was tested by injecting the viruses into the tail veins of C56/Bl6 mice. Because most of the gene expression after intravenous injection of recombinant adenovirus occurs in the liver,31 we extracted RNA from the liver and analyzed it by Northern blotting and hybridization with a combination of probes specific for the adenoviral inserts. As can be seen in Figure 1C, the adenoviruses efficiently express mRNAs of 4.5 and 2.4 kb, encoding VEGF and VEGF-C, respectively, whereas somewhat lower amounts of mRNA of 6.0 kb encoding β-galactosidase were produced by the control virus. The liver of an uninfected mouse showed no signal.

**AdVEGF-C and AdVEGF Stimulate VEGFR Expression**

The effects of the adenoviruses in vivo were tested by subcutaneous injection into mouse skin and by analyzing skin sections 4 days later by immunohistochemistry for the VEGF-C receptors VEGFR-2 and VEGFR-3 and for the vascular marker PECAM-1. As can be seen from Figure 2A and from the enclosed insets at higher magnification, adenoviral expression of VEGF-C for 4 days induced the expression of VEGFR-2 and VEGFR-3 in endothelial cells of blood vessels (containing erythrocytes), whereas VEGF gene transfer induced the expression of VEGFR-2 but not VEGFR-3 (Figure 2D). In contrast, the blood vessels in mice injected with AdLacZ (Figure 2B) or PBS (Figure 2C) did not stain for VEGFR-2 or VEGFR-3; only the lymphatic vessels were positive for VEGFR-3 in these mice. Analysis after 2 weeks showed an inflammatory response in all adenovirus-injected samples from the C57/Bl6 mice, confounding immunohistochemical analysis (data not shown). For this reason, we continued our studies in the immunocompromised athymic mice.

Lymphangiogenic and Angiogenic Responses to the Adenoviruses

Five ears of three nu/nu mice were injected with each of the adenoviruses. Shown in Figure 3 are AdVEGF-C, AdVEGF, or AdLacZ injection sites of mouse ears photographed in situ.

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**Figure 1.** Expression of VEGF-C and VEGF<sub>165</sub> by the recombinant adenoviruses in vitro and in vivo. A and B, Receptor binding by adenovirally produced VEGF-C and VEGF in vitro. VEGFR Ig fusion proteins were used to precipitate polypeptides from the media of metabolically labeled 293EBNA cells infected with AdVEGF-C, AdVEGF, or AdLacZ, as indicated. Plasmid controls are indicated as pREP for empty vector backbone, pVEGF for the vector encoding VEGF-C, and pVEGF-C for the vector encoding VEGF-C, and pVEGF for the vector encoding VEGF. Analysis by SDS-PAGE is shown under reducing and nonreducing (NR) conditions (the exposure in the lower panel in A was about twice as long as the exposure in other panels). Molecular size markers in the figure are indicated in kilodaltons, and arrows indicate bands representing the precipitated VEGF polypeptides. C, Analysis of adenovirus-encoded RNAs in the livers of infected mice. About 15 μg of total RNA extracted from livers of two mice injected with the indicated recombinant adenoviruses was subjected to Northern blotting and hybridization with a mixture of the corresponding cDNA probes. The first lane contains RNA extracted from the liver of an untreated mouse. The blot was stripped and reprobed for ubiquitin mRNA to confirm equal loading. The sizes of the different RNAs are indicated in kilobases on the right.

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The mature 21/23-kDa species was the predominant VEGF-C form that bound to VEGFR-2-Ig (Figure 1A, bottom), as previously reported.6

In an experiment similar to the one outlined above, we also confirmed that adenoviral gene transfer of VEGF results in the expression of VEGF polypeptides that form disulfide-bonded homodimers and bind to VEGFR-1 and VEGFR-2.
3 days after the injection. As can be seen from this figure, VEGF induced the formation of enlarged, tortuous vessels (Figure 3B, arrows) in contrast to VEGF-C (Figure 3A) or β-galactosidase (Figure 3C), which did not seem to affect at least the larger blood vessels.

The adenovirus-injected ears were processed for immunohistochemistry and stained for PECAM-1 and the lymphatic-specific antigen LYVE-1. As can be seen from the LYVE-1 staining shown in Figures 4A and 4B, AdVEGF-C transfer induced the formation of LYVE-1–positive hyperplastic lymphatic vessels (arrows), which did not stain for laminin, a component of the basal laminae of blood vessels (data not shown), whereas AdVEGF (Figure 4D) or AdLacZ (Figure 4C) did not have any effects on the lymphatic vessels. In contrast, AdVEGF induced the formation of blood vessels (Figures 4E and 4F, arrows) whereas the AdLacZ (Figure 4G) did not have any effects on the blood vasculature. The effects of AdVEGF-C on blood vessels were more difficult to evaluate because of the strong lymphangiogenic response. However, there was a small increase of PECAM-1–positive vessels in the AdVEGF-C–injected ears (see Figures 4H and 5B). Some of these may represent newly formed, very weakly PECAM-1–positive lymphatic vessels (Figure 4H, asterisk).
Quantitative Analysis of the Adenovirus-Induced Lymphatic and Blood Vessels

As can be seen from the results of counting the LYVE-1–positive and strongly PECAM-1–staining vessels with lumens in Figure 5A, AdVEGF-C induced an ~4-fold increase ($P<0.01$) of lymphatic vessel density (Figure 5A) whereas VEGF induced a 2-fold increase ($P<0.01$) of blood vessel density (Figure 5B). The combination of AdVEGF and AdVEGF-C did not significantly ($P>0.5$) potentiate either of these responses. VEGF-C increased the total volume of the LYVE-1–positive vessels by 7.5-fold ($P<0.01$) (Figure 5C), whereas VEGF increased the volume of the blood vessels by 5.7-fold ($P<0.01$) (Figure 5D).

Endothelial Cell Proliferation in Lymphangiogenesis Induced by VEGF-C

As can be seen in Figure 6A and at higher magnification in Figures 6B and 6C, sequential staining for both LYVE-1 and PCNA revealed that the lymphatic vessels in AdVEGF-C– injected ears contained proliferating lymphatic endothelial cells. For example, the lymphatic endothelial cells surrounding a small arteriole in Figure 6C stain for PCNA (closed arrowhead), whereas the blood vascular endothelial cells do not (open arrowhead). Figure 6D shows PCNA-positive nuclei in the wall of a blood vessel in an ear injected with...
VEGFR-2. In our in vivo assay in normal dermis, this could form, which binds VEGFR-3 but only very weakly to vessels and angiogenesis, as described earlier.14,24 Conversely, adenoviral gene transfer of VEGF induces VEGFR-2 and VEGFR-3 expression in blood vessels. In contrast, adenoviral gene transfer of VEGF induced VEGFR-2 upregulation in the endothelial cells of blood vessels and angiogenesis, as described earlier.14,24

The vessel density in foci of lymphatic vessel formation in the ears infected with AdVEGF-C increased ~4-fold in comparison to ears injected with AdVEGF, AdLacZ, or buffer control as measured by quantification of LYVE-1–positive vessels. The lack of smooth muscle cells around the vessels and erythrocytes within the vessels generated in 2 weeks was in accordance with the lymphatic vessel morphology. Furthermore, these vessels did not stain for laminin, a component of the basal laminae (data not shown). The density of strongly PECAM–1–positive vessels in the ears infected with AdVEGF increased ~2-fold compared with ears infected with AdVEGF-C, AdLacZ, or buffer. It may also be noted that LYVE-1 expression was not upregulated in blood vessels in AdVEGF-induced angiogenesis (eg, see Figure 3A). Thus, the response to AdVEGF-C was primarily lymphangiogenic, whereas very little angiogenesis was seen, unlike in the experiments in which plasmid expression vectors were used in ischemic rabbit muscle.20

In cell culture, the majority of the adenovirally produced VEGF-C consisted of the partially processed 29/31-kDa form, which binds VEGFR-3 but only very weakly to VEGFR-2.6 In our in vivo assay in normal dermis, this could be the predominant form, whereas in ischemic tissue the 21-kDa form of VEGF-C, which has a higher binding affinity toward VEGFR-2, may predominate because of increased expression of VEGF-C processing enzymes in the latter. A major difference between our assay conditions and those used in experiments using ischemic hindlimb as a target for plasmid delivery is the presence of abundant amounts of endogenous VEGF induced by hypoxia in the latter. However, at least in our initial experiments, simulation of such conditions by coinjection of AdVEGF and AdVEGF-C did not result in a substantial potentiation of the angiogenic response.

The mechanisms of lymphangiogenesis in adult tissues have not been elucidated. The generation of lymphatic vessels could in principle require endothelial cell sprouting from or splitting of preexisting lymphatic vessels or blood vessels, in situ differentiation of endothelial cells, or recruitment and lymphatic differentiation of endothelial precursor cells, as has been described in other models.32–34 In embryos, lymphatic vessels are mainly formed by the process of sprouting from certain venous structures, although in the avian species, mesenchymal precursor cells called lymphangioblasts also exist.35,36 We do not yet know the mechanisms of lymphangiogenesis in the adult, but the present results are compatible with the process of sprouting lymphatic vessels from preexisting ones and perhaps splitting of such enlarged lymphatic vessels that we observed in the AdVEGF-C–treated ears. The upregulation of VEGFR-2 and VEGFR-3 in blood vessels in response to VEGF-C raises the interesting possibility that endothelial cells in blood vessels could also participate in lymphangiogenesis by the process of migration and transdifferentiation. Such upregulation of both VEGF-C receptors in the blood vascular endothelium should also be considered when using gene therapy in the setting of tissue ischemia.

It has been shown that the angiogenic response induced by AdVEGF is a highly dynamic process involving the initial formation of mother vessels and endothelial glomeruloid bodies.14 Thus, our analysis at the 2-week time point does not reveal the kinetics of possible transient blood vessel responses. The responses to VEGF-C in blood vessel endothelia, which upregulate both receptors for VEGF-C, remain to be characterized. Therapeutic angiogenesis ultimately requires the induction of entire vascular structures consisting of arteries, veins, and lymphatics. Thus, proangiogenic therapy could consist of different growth factors that cover the entire genetic program for the induction of new vessels.37 Our studies in transgenic mouse embryos and newborn mice have revealed that the developing lymphatic vasculature is dependent on VEGF-C for survival signals and when the embryonic tissues are deprived of such signals by blocking both VEGF-C and VEGF-D, the forming lymphatic vessels regress by specific lymphatic endothelial apoptosis (T. Makinen et al, unpublished observations, 2000). Therefore, further studies are needed to determine the long-term effects of the transient viral expression of VEGF-C, whether this results in permanent and functional lymphatic vasculature and whether stable changes of the blood vasculature can also be observed.

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