Vascular Endothelial Growth Factor and Angiopoietin-1 Stimulate Postnatal Hematopoiesis by Recruitment of Vascularogenic and Hematopoietic Stem Cells

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Abstract

Tyrosine kinase receptors for angiogenic factors vascular endothelial growth factor (VEGF) and angiopoietin-1 (Ang-1) are expressed not only by endothelial cells but also by subsets of hematopoietic stem cells (HSCs). To further define their role in the regulation of postnatal hematopoiesis and vasculogenesis, VEGF and Ang-1 plasma levels were elevated by injecting recombinant protein or adenoviral vectors expressing soluble VEGF165, matrix-bound VEGF189, or Ang-1 into mice. VEGF165, but not VEGF189, induced a rapid mobilization of HSCs and VEGF receptor (VEGFR)2 circulating endothelial precursor cells (CEPs). In contrast, Ang-1 induced delayed mobilization of CEPs and HSCs. Combined sustained elevation of Ang-1 and VEGF165 was associated with an induction of hematopoiesis and increased marrow cellularity followed by proliferation of capillaries and expansion of sinusoidal space. Concomitant to this vascular remodeling, there was a transient depletion of hematopoietic activity in the marrow, which was compensated by an increase in mobilization and recruitment of HSCs and CEPs to the spleen resulting in splenomegaly. Neutralizing monoclonal antibody to VEGFR2 completely inhibited VEGF165, but not Ang-1–induced mobilization and splenomegaly. These data suggest that temporal and regional activation of VEGF/VEGFR2 and Ang-1/Tie-2 signaling pathways are critical for mobilization and recruitment of HSCs and CEPs and may play a role in the physiology of postnatal angiogenesis and hematopoiesis.

Key words: vascular endothelial growth factor • angiopoietin-1 • angiogenesis • hematopoiesis • tyrosine kinase receptors

Introduction

In the adult, the majority of hematopoietic stem cells (HSCs) and circulating endothelial precursor cells (CEPs; references 2–4) reside in the bone marrow (BM). However, upon stimulation with various cytokines, HSCs and CEPs can be mobilized to the peripheral circulation and colonize other hematopoietic organs, such as the spleen. In addition, BM failure states secondary to BM fibrosis (myelofibrosis) or certain metastatic neoplastic diseases are associated with relocalization of HSCs from BM to extramedullary hematopoietic macroenvironments, including the spleen resulting in splenomegaly (5). However, the exact identities of the chemocytokines responsible for the mobilization and the mechanism of extramedullary recruitment of BM–derived HSCs and CEPs are not well established.

Given the common prenatal origin of CEPs and HSCs from hemangioblasts, both hematopoietic and vasculogenic cells share several survival and chemotactic signaling path-
ways. The tyrosine kinase receptors, VEGFR2 (Flk-1, KDR; reference 6) and Tie-2 (7), whose expression was originally shown to be restricted to vascular cells, are also shared by subsets of HSCs. Angiopoietin-1 (Ang-1), the natural ligand for Tie-2 (8), in conjunction with VEGF, modulates various aspects of angiogenesis such as remodeling (9–12) and vascular permeability (13). Furthermore, Ang-1 and VEGF exert a synergistic effect in promoting the survival of hematopoietic progenitor cells in the developing aorta-gonad-mesonephros (14, 15). In addition to conveying signals that regulate cell proliferation, VEGF and Ang-1 also promote chemotaxis and chemokinesis of endothelial cells (11, 12). Since VEGF plasma levels are elevated in the circulation during tumor growth (16) and BM failure states (17), we hypothesized that angiogenic factors may play a role in the pathogenesis of postnatal hematopoietic dysfunction and splenomegaly. In this regard, we speculated that acute or chronic regional overexpression of angiogenic factors, such as VEGF and Ang-1, may regulate hematopoiesis by promoting the extramedullary mobilization and recruitment of HSCs and CEPs.

Adenoviral (Ad) vectors are ideal vectors for the high level expression of angiogenic factors with chemokinetic potential because they allow for regional expression of a given chemokine for durations long enough to exert their physiological effect. The intravenous injection of Ad vectors into SCID mice results primarily in the localization of the Ad vectors to the extramedullary organs, including liver and, to a smaller degree, spleen. Therefore, to mimic physiological conditions of sustained plasma release of VEGF and Ang-1, we delivered Ad vectors expressing Ang-1 and isoforms of VEGF (including soluble VEGF165 and matrix-bound VEGF165) to extramedullary organs of immunocompromised SCID mice. In this regard, Ad vectors are ideal vectors for the expression of factors with chemokinetic potential because they allow for regional expression at high titers long enough to exert their physiological effect.

We demonstrate that plasma elevation of VEGF and/or Ang-1 results in the mobilization of HSCs and CEPs. Combined elevation of VEGF and Ang-1 resulted in remodeling of the BM vasculature with concomitant splenomegaly. These studies suggest that temporal and regional activation of VEGF/VEGFR2 and Ang-1/Tie-2 signaling pathways are critical for mobilization and recruitment of HSCs and CEPs and may play a role in the pathogenesis of hematopoietic dysfunction and physiology of postnatal angiogenesis and hematopoiesis.

Materials and Methods

Animals. Immunodeficient age- (8 wk), weight- (>20 g), and sex-matched SCID mice (on BALB/c background) were purchased from the The Jackson Laboratory and maintained in filtered air Thorensen units. All mice received the Ad vector expressing VEGF165 (AdVEGF165; 1.5 × 10^9 PFU) and/or the AdAng-1 (10^9 PFU), the AdNull vector (no transgene; 10^9 PFU), or the AdVEGF189 vector (2 × 10^9 PFU) in a volume of 100 µl, by single intravenous administration on day 0. Each study involved three to four animals. Age-matched female BALB/c and C57BL/6 mice were used in CFU-S assay/allogeneic peripheral blood cell transplantation as recipients.

Ad Vectors. AdVEGF165 and AdVEGF189 are Ad5-derived E1a-, E3-deficient (E1a-E3-E4+) vectors with an expression cassette in the E1a region containing the murine VEGF165 cDNA/human VEGF189 cDNA driven by the CMV major immediate/early promoter/enhancer. The control vector, AdNull, is similar in design except that it contains no transgene in the expression cassette. AdAng-1 is constructed using the Adeno-Quest™ system from Quantum Biotechnology, Inc. Full-length cDNAs encoding an engineered version of human Ang-1 called Ang-1* were cloned into shuttle vector pQBI-AdCMV5 green fluorescent protein. Linearized plasmid and viral long-arm DNA were cotransfected into 293 cells as described previously (18).

Immunoassays of Cytokines. Murine VEGF plasma levels were evaluated using commercial ELISA (R&D Systems) following the manufacturer’s instructions. Human plasma Ang-1 levels were also measured using a sensitive ELISA (Regeneron).

Peripheral Blood Analysis. Initially every 2–3 d and later on a weekly basis, retroorbital blood was collected with capillary pipettes (Unopette; Fisher Scientific). Platelets, total white blood cells (WBCs), and granulocytes (polymorphonuclear leukocytes) were counted using a Neubauer hemocytometer (Fisher Scientific). Differential leukocyte counts were obtained by examination of blood smears from each mouse stained with Wright-Giemsa stain (200 cells counted/slide). The plasma samples were collected, stored at −80°C, and assessed later by immunoassay for murine VEGF and human Ang-1.

Flow Cytometry. A total of 10^4 to 10^5 cells were incubated for 30 min at 4°C with the following FITC- or PE-conjugated mAbs: H-2K^d-FITC (AF6-88.5; BD Pharmingen); CD11b-FITC (M1/70; BD Pharmingen); and H-2K^d-FITC (SF-1-1.1; BD Pharmingen). DC101 (VEGFR2)–FITC (ImClone Systems) was developed and characterized as described previously (19). Propidium iodide (Becton Dickinson) was dissolved at 3 mM in PBS and used at 30 µM. The cells were analyzed by two-color flow cytometry using a Coulter Elite flow cytometer (Beckman Coulter).

Spleen and BM Analysis. BM was obtained by flushing both femoral bones with 3 ml of cold (4°C) IMDM containing 20% FCS. Manual leukocyte differentials were performed on Wright-Giemsa–stained cytospin preparations of BM cells and spleenocytes. The number of megakaryocytes in randomly chosen femoral BM and spleen samples was determined using 400X magnification field light microscopy.

Progenitor Assay. PBMCs were collected from orbital plexus and isolated after centrifugation over a discontinuous gradient using lympholyte-M. PBMCs (10^6 cells) were plated in triplicate in 1 ml of 0.8% methylcellulose containing 30% FCS, 1% l-glutamine, 2.5% hemin, 0.05 mM 5-ME, IL-3 (50 ng/ml; R&D Systems), c-kit ligand (20 ng/ml; Immunix), and erythropoietin (2 U/ml; Sandoz) in 35-mm suspension culture dishes. Scoring was performed with an inverted microscope (40X) on day 7. Cells from PBMCs obtained from AdVEGF165- and/or AdAng-1–treated mice were seeded in the colony assays and four CFU types were scored: CFU-GM, BFU-E, CFU-M, and CFU-Mix, 3, 5, 14, 28 d after the onset of treatment. CEPs present in the mobilized PBMCs were quantified as described previously (4, 20). Freshly isolated PBMCs obtained from mice treated with AdVEGF and/or AdAng-1 on days 3 and 14 were cultured in endothelial growth medium (M199; Gibco BRL) supplemented with 20% fetal bovine serum (HyClone), endothelial cell growth factor (30 µg/ml), fibroblast growth factor (FGF) (5 ng/
ml, human recombinant basic FGF; Sigma-Aldrich), heparin (5 U/ml), penicillin (100 U/ml), streptomycin (100 µg/ml), and fungizone (0.25 µg/ml). These cells were placed on 12-well gelatin-coated plates. After 2–3 wk, the endothelial colonies were identified by metabolic uptake of Dil-acetylated-LDL (Dil-Ac-LDL; PerImmune, Inc.) by incubating the wells with 1 µg/ml of human Dil-Ac-LDL for 5 h and visualized by fluorescence microscopy. For von Willebrand factor (vWF) staining, cells were rinsed with HBSS and fixed immediately with ethanol for 10 min. Dil-Ac-LDL-vWF+ colonies formed in the first 3 d after vector administration were scored as early outgrowth endothelial colonies, whereas endothelial colonies formed after 14 d of culture were considered as late-outgrowth colonies (CFU-ECs).

CFU-S Assay. Mobilized PBMCs were obtained from days 3, 5, 7, 14, 21, and 28 after the onset of treatment with various Ad vectors. For each data point, three recipient mice were irradiated with 9 Gy from a 137Cs γ-ray source at a dose rate of ∼0.90 Gy/min to prevent the production of endogenous spleen colonies. Irradiated mice were injected intravenously via the tail vein with 10^8 PBMCs within several hours after the completion of irradiation. The mice were killed 12 d later, and their spleens were removed and fixed in Bouin’s solution. The number of macroscopic spleen colonies was then scored.

Repopulating Assay. After vector administration, the peripheral blood from SCID mice was collected on day 7. PBMCs (10^6 cells) were transfected into lethally irradiated (9.5 Gy) recipient C57BL/6 mice. As a control, PBMCs (10^6 cells) from AdNull-treated SCID mice were transfected into irradiated C57BL/6 mice by intravenous injection at day 0. Chimerism was determined by FACS® analysis (donor SCID mice, H-2K^b; recipient C57BL/6 mice, H-2K^b). The chimeric mice were killed at 90, 120, and 150 d after transplantation and BM mononuclear cells (BMMCs) were stained for flow cytometry analysis with H-2K^b–FITC (donor type). The representative percentages of positive cells were determined in the peripheral blood. Control mice were injected with 10^7 PFU of AdNull vector. Compared with AdNull-treated mice, AdVEGF165-treated mice had a fourfold increase in WBCs on day 3, returning to the level of AdNull-treated mice by 5 wk after injection (Fig. 1 A). In contrast, administration of AdAng-1 into SCID mice resulted in only a small increase in WBCs, peaking at day 17 and returning to control levels by 7 wk. However, the combination of AdVEGF165 and AdAng-1 resulted in a synergistic sevenfold increase in WBCs 5 d after vector administration. As expected, injection of AdVEGF189, which results in production of matrix-bound VEGF189, did not result in leukocyte mobilization.

Populations of blast-like cells that are usually localized to the BM were detected at high levels in the peripheral circulation of the AdVEGF165- and/or AdAng-1–treated mice. These cells displayed scant cytoplasm and large nuclei, reminiscent of BM-derived immature hematopoietic progenitor and precursor cells (Fig. 1 B). Compared with AdNull-treated mice, AdVEGF165– and AdVEGF165 plus AdAng-1–treated mice had a dramatic increase in the WBC percentage of blast-like cells (Others; Fig. 1 B) and monocytes during days 2–14, returning almost to baseline 3 wk after the start of treatment (Fig. 1 C). The intravenous administration of AdAng-1 to SCID mice also resulted in increased circulation of blast-like cells, peaking at day 16 and returning to baseline on day 49 (Fig. 1 C). There were no significant changes in the leukocyte levels of AdNull-treated mice.

AdVEGF165 and AdAng-1 Induced Mobilization of Hematopoietic Progenitor Cells with Stem Cell Potential. The administration of AdVEGF165 induced mobilization of hematopoietic progenitors to the peripheral circulation. These progenitors comprised colony-forming units (CFU-Cs) such as CFU-M, CFU-GM, BFU-E, and CFU-Mix (CFU-GEMM). Compared with AdNull-treated mice, at days 3 and 5 the majority of the mobilized CFU-Cs consisted of CFU-GM (P < 0.005). CFU-GMs peaked at day

Results

AdAng-1 and AdVEGF165 but Not AdVEGF189 Promote Mobilization of Hematopoietic Cells. Intravenous administration of Ad vectors expressing VEGF165 (AdVEGF165, 1.5 × 10^8 PFU) resulted in a peak VEGF plasma level (1,640 ± 233 pg/ml) 24 h after injection and a return to pretreatment level on day 35. Doses >1.5 × 10^8 PFU of AdVEGF165 were significantly toxic and resulted in the death of the treated mice (data not shown). There were no signs of toxicity in mice treated with AdNull vectors at doses up to 10^9 PFU. In AdAng-1–treated mice (10^9 PFU), plasma levels of Ang-1 peaked on day 3 after injection (74.1 ± 0.7 ng/ml), returning to the pretreatment level after 8 wk. Plasma VEGF and Ang-1 were not detectable in AdNull-treated mice.

To examine the effects of acute and chronic elevation of circulating VEGF165 or Ang-1 levels in the mobilization of CEPs and HSCs, SCID mice were injected intravenously with AdVEGF165 (1.5 × 10^8 PFU) and/or AdAng-1 (10^8 PFU), or AdVEGF189 (2 × 10^8 PFU). Subsequently, the number of leukocytes, hematopoietic progenitor cells, and HSCs were determined in the peripheral blood. Control mice were injected with 10^7 PFU of AdNull vector. Compared with AdNull-treated mice, AdVEGF165–treated mice had a fourfold increase in WBCs on day 3, returning to the level of AdNull-treated mice by 5 wk after injection (Fig. 1 A). In contrast, administration of AdAng-1 into SCID mice resulted in only a small increase in WBCs, peaking at day 17 and returning to control levels by 7 wk. However, the combination of AdVEGF165 and AdAng-1 resulted in a synergistic sevenfold increase in WBCs 5 d after vector administration. As expected, injection of AdVEGF189, which results in production of matrix-bound VEGF189, did not result in leukocyte mobilization.

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and returned to baseline levels by day 28 (Fig. 2 A). The remaining leukocytes mobilized to the peripheral blood consisted of mature cells including monocytes.

Administration of AdAng-1 promoted a delayed but significant mobilization of CFU-Cs to the peripheral blood. Compared with AdNull or AdVEGF165, at day 14 after injection, AdAng-1–mobilized CFU-Cs comprised predominantly CFU-M (*P = 0.005). The numbers of CFU-Cs returned to control levels on day 28. The combination of both AdVEGF165 and AdAng-1 enhanced the mobilization of CFU-Cs (**P < 0.05).

The number of mobilized pluripotent hematopoietic cells with stem cell potential, capable of forming spleen colonies (CFU-S), was measured by injecting AdVEGF165 and/or AdAng-1 or, as control, AdNull-mobilized PBMCs into lethally irradiated syngeneic mice (Fig. 2 B). Administration of AdVEGF165 induced a 20-fold increase in peripheral blood CFU-S 14 d after injection. Coinjection of both AdVEGF165 and AdAng-1 had a synergistic effect on the number of mobilized CFU-S. Administration of AdNull did not result in the mobilization of CFU-S.

The number of mobilized pluripotent hematopoietic cells with BM-repopulating capacity was also determined by allogeneic transplantation of VEGF165– and/or Ang-1–mobilized PBMCs into lethally irradiated mice. Injection of either AdVEGF165 and/or AdAng-1, but not AdNull, resulted in mobilization of HSCs that were able to engraft and rescue lethally irradiated mice. All mice transplanted with 10^6 PBMCs from AdNull-treated mice died within 18 d (Fig. 2 D). However, 56% of the mice transplanted with PBMCs from AdVEGF and AdAng-1, 45% of AdVEGF, and 22% of AdAng-1–treated mice survived beyond 150 d. These data suggest that overexpression of VEGF165 and Ang-1 results in mobilization of pluripotent hematopoietic cells with stem cell potential from BM to the peripheral circulation.
AdVEGF165 and AdAng-1 Induce the Mobilization of CEPs. We have shown that a subset of mobilized circulating VEGFR2+ PBMCs contain a unique population of marrow-derived endothelial cells, namely CEPs (2, 4). AdVEGF165 caused mobilization of CEPs to the peripheral blood on days 2, 5, and 7, with a return to control levels by day 14 (Fig. 3A). Administration of AdVEGF165 and AdAng-1 into SCID mice resulted in increased levels of circulating VEGFR2+ CD11b+ cells, 7 d (15.3 ± 2.5%) and 14 d (11.1 ± 4.1%) after the start of treatment (Fig. 3B). Mobilized CEPs can be distinguished from mature endothelial cells by their capacity to form late-outgrowth colonies (CFU-ECs) (20). In contrast to mature endothelial cells, which form early outgrowth colonies, CEPs form rapidly proliferating endothelial colonies 3–4 wk after initiation of culture. Incubation of mobilized VEGFR2+ PBMCs with VEGF and FGF-2 (basic FGF) on collagen-coated plastic dishes resulted in the generation of early and late outgrowth DiI-Ac-LDL1 endothelial cells (CFU-ECs; Fig. 3C and D). The majority of the colonies formed (Fig. 3E, F, and G) were composed of late outgrowth endothelial cells, suggesting that VEGF and Ang-1 promote the mobilization of BM-derived CEPs.

Prolonged Plasma Elevation of VEGF165 and Ang-1 Results in Cellular and Vascular Remodeling of BM and Spleen. The sustained chronic elevation of VEGF165 and Ang-1 within 1 wk resulted in the initial stimulation of hematopoiesis with increased BM cellularity and proliferation of ery-
Figure 3. AdVEGF<sub>165</sub> and Ang-1 promote mobilization of CEPs with late outgrowth potential. (A) Mobilized PBMCs were isolated from AdVEGF<sub>165</sub>- and/or AdAng-1- or AdNull-treated SCID mice on days 0–28 and stained with FITC-conjugated anti-VEGFR2 (clone DC101) mAb and propidium iodide. (A) 10<sup>4</sup> cells were analyzed on a Beckman Coulter Elite flow cytometer, and representative percentages of positive populations in PBMCs are shown. (B) The percentages of mobilized circulating VEGFR2<sup>+</sup>CD11b<sup>-</sup> cells from AdVEGF<sub>165</sub>- and/or AdAng-1- or AdNull-treated SCID mice (n = 3) are shown from days 0–28. For quantification of CEPs with late outgrowth potential, mobilized PBMCs were obtained from AdVEGF<sub>165</sub>- and/or AdAng-1 or AdNull-treated SCID mice on days 0–21 and plated in the presence of endothelial growth medium (reference 13) on collagen/fibronectin-coated plastic dishes. Endothelial colonies (CFU-ECs) were identified by vWF immunostaining and metabolic labeling with Dil-Ac-LDL. (C) CFU-ECs proliferated 2 wk after the start of culture (mean ± SEM). Colonies that formed within the first 3 d (early outgrowth) and colonies formed 14 d (late outgrowth) after vector administration were quantified by vWF and Dil-Ac-LDL labeling. (D) The majority of CFU-EC proliferated 3 wk after the start of culture, forming focal Dil-Ac-LDL<sup>+</sup> endothelial monolayers as seen at 14 (E), 20 (F), and 25 d (G).
thyroid, myeloid, and megakaryocytic lineages compared with BM of AdNull-treated SCID mice (Fig. 4, A and B). However, by 2–3 wk there was a gradual decrease in BM cellularity and remodeling of the BM architecture with concomitant profound splenomegaly of AdVEGF- and AdAng-1–treated SCID mice. Histological examination of the BM at day 14 demonstrated progressive increase in sinusoidal space and proliferation of capillaries (Fig. 4 C). By day 60, at a time when the plasma levels of VEGF and Ang-1 returned to baseline, the overall BM cellularity and vascularity returned to baseline levels (Fig. 4 D). These BM architectural changes were much less pronounced when either VEGF or Ang-1 was overexpressed.

Given that SCID mice have an abnormal splenic structure, evaluation of the splenic cellular architecture after injection with VEGF or Ang-1 is not feasible. Therefore, immunocompetent BALB/c mice were injected subcutaneously with 100 ng of recombinant VEGF on a daily basis for 2 wk. After

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2 wk, at the time when there was a relative decrease in BM cellularity (1.9 ± 0.3 × 10⁶/femur from VEGF-treated mice compared with 2.5 ± 0.1 × 10⁶/femur for normal BALB/c mice, \( P < 0.01 \)), there was a remarkable increase in spleen size (Fig. 4, E and F). Compared with the control group (Fig. 4 H), there was increased cellularity and follicular hyperplasia in the spleen of VEGF-treated group (Fig. 4 G; 0.3 ± 0.2 × 10⁶ compared with 2.4 ± 0.3 × 10⁶ for normal BALB/c mice, \( P < 0.005 \)). Splenomegaly and follicular hyperplasia were reversed after cessation of treatment.

**Mobilization of Leukocytes by AdVEGF165 Is Mediated Primarily through VEGFR2 Signaling.** Murine VEGFR2 (Flk-1), which is expressed on subsets of HSCs and CEPs, mediates signals that may not only promote proliferation but also stimulate chemotaxis of endothelial cells. Therefore, we postulated that the primary mechanism whereby VEGF induces mobilization of HSCs and CEPs is through activation of VEGFR2. Injection of a neutralizing mAb to murine VEGFR2 (clone DC101) 2 d after AdVEGF165 injection significantly blocked VEGF165-induced mobilization of leukocytes (Fig. 5, A and B) and CFU-Cs (Fig. 5 C) to the peripheral circulation. However, DC101 failed to inhibit Ang-1–induced migration of HSCs, suggesting that Ang-1–delayed mobilization of HSCs and CEPs requires Tie-2 signaling and is therefore independent of the VEGFR2/VEGF signaling pathway.

**Discussion**

In this report, we have demonstrated that the elevation of VEGF165 and/or Ang-1 plasma levels by Ad vectors results in robust mobilization of CEPs and hematopoietic progenitors and HSCs (CFU-S, marrow repopulating cells) to the peripheral circulation. Although VEGF165 alone could also induce splenomegaly and increase BM cellularity, the sustained elevation of both VEGF165 and Ang-1 was essential to induce significant remodeling of BM vascular architecture, with concomitant mobilization to the extramedullary organs, resulting in profound splenomegaly. Elevation of Ang-1 alone did not affect the size of the

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**Figure 5.** Neutralizing mAb to VEGFR2 inhibits mobilization of leukocytes and hematopoietic progenitor cells induced by AdVEGF165 but not AdAng-1. (A) SCID mice were inoculated with AdVEGF165 (1.5 × 10⁹ PFU) or AdNull (10⁹ PFU) on day 0. Half of the AdVEGF165-treated mice received 800 µg of anti-VEGFR2 (DC101) mAb at 2-d intervals starting from day 2. Total WBCs are expressed as the mean ± SEM (n = 8). ○, AdVEGF165; ▲, AdVEGF165 + DC101; ■, AdNull. (B) SCID mice inoculated with AdVEGF165 (1.5 × 10⁹ PFU) and AdAng-1 (10⁹ PFU) received 800 µg of anti-VEGFR2 (DC101) at 2-d intervals starting from day 0. AdAng-1 (10⁹ PFU) inoculated SCID mice were used as a control. Total WBCs were quantified using a Neubauer hematocytometer. All data are expressed as the mean ± SEM (n = 8). △, AdAng-1; ●, AdVEGF165 + AdAng-1 + DC101; ■, AdVEGF165 + AdAng-1; ◆, AdNull. (C) PBMCs from AdAng-1 alone, AdVEGF165 + AdAng-1 (treated or untreated with DC101), or AdNull-treated mice were seeded into the colony assays and four types of CFU (CFU-GM, BFU-E, CFU-M, and CFU-GEMM) were scored at 3, 5, 14, and 28 d after the onset of treatment. All data are expressed as the mean ± SEM (n = 4). Data points achieving statistical significance are shown. * \( P < 0.005 \).
spleen or cellularity of the BM, suggesting that combined signaling through VEGFR2/VEGF and Ang1/Tie-2 signaling pathways plays a key role in the regulation of organ-specific hematopoietic activity.

The overexpression of VEGF165 induces a rapid (24–48 h) mobilization of CEPs and HSCs, suggesting that the effect of VEGF165 is mediated through a chemokinetic process. However, plasma elevation of Ang-1 requires at least 7 d to induce mobilization of CEPs and HSCs. The physiological effect of VEGF is most likely not mediated through BM endothelial cell leakiness since studies have shown that Ang-1 prevents VEGF-induced vascular permeability (13, 18). In this regard, Ang-1 should have inhibited the VEGF-induced mobilization of the HSCs and CEPs. In contrast, Ang-1 promoted the mobilization of HSCs and CEPs and synergized with VEGF in augmenting its effect. Collectively, these data suggest that VEGF alone or in combination with Ang-1 induce mobilization by directly interacting with stem cells or promoting remodeling of the BM vasculature. It is conceivable that Ang-1 may alter the adhesion molecule repertoire of BM endothelial cells or HSCs, resulting in enhanced mobilization. Alternatively, Ang-1 may sustain or promote the survival of Tie-2+ HSCs and CEPs, inducing cell cycle shifts that may favor their mobilization to the peripheral circulation.

VEGF has been shown to exert its pleiotropic effects on endothelial cells through its receptors VEGFR1 and VEGFR2. VEGFR2 has been shown to be the principal mitogenic receptor for VEGF (21, 22), whereas VEGFR1 conveys signals for vascular remodeling. However, VEGFR1 is expressed by various mature hematopoietic cells, including dendritic and monocytic cells (23, 24), whereas VEGFR2 is expressed by HSCs and CEPs (4). Therefore, VEGF165-induced mobilization of mature cells such as monocytes may be mediated through VEGFR1, whereas mobilization of HSCs is most likely mediated through VEGFR2 (6). Neutralizing mAb to VEGFR2 inhibited VEGF165-induced mobilization and splenomegaly, suggesting that interaction of VEGF165 with VEGFR2 is essential for mobilization and recruitment of HSCs. Delayed mobilization in response to elevation in circulating Ang-1 is most likely induced by interaction with either Tie-2+ on the stem cells (19) or because of remodeling of the BM microenvironment.

Most in vivo experiments assessing the chemoattractant properties of VEGF165 have been performed with injection of recombinant VEGF165. However, given that the half-life of VEGF165 in the circulation is only several minutes, it has been difficult to evaluate the role of chronic VEGF165 release, as it may occur during tumor growth and metastasis or myelodysplastic syndromes. Likewise, recombinant Ang-1 is unstable and previous studies using Ang-1 protein have failed to demonstrate a functional endpoint (21). It is suggested that in contrast to VEGF165, whereby injection of recombinant protein can induce mobilization of stem cells, Ang-1 protein does not have enough biochemical stability to exert any biological effect. Furthermore, given the delayed mobilization seen with Ang-1 treatment, injection of AdAng-1 into SCID mice as opposed to immunocompetent mice was the only means of sustaining the level of Ang-1 long enough in vivo to observe its effects. Therefore, the use of Ad vectors as regional delivery vehicles for VEGF165 and Ang-1 provides ideal tools for studying the role of these angiogenic factors in mobilization and recruitment of HSCs and CEPs. In addition, given that VEGF165 is matrix bound, Ad vectors producing VEGF165 provide an ideal mechanism to deliver this matrix-bound isoform of VEGF regionally to the extramedullary hematopoietic microenvironments such as the liver.

We show that long-term overexpression of both VEGF165 and Ang-1 is essential to induce a initial increase in BM cellularity followed by remodeling of the BM architecture, with depletion of sinusoidal spaces of hematopoietic cells and a parallel increase in BM vascularization and splenomegaly. These results suggest that regional expression of VEGF165 and Ang-1 in extramedullary organs may act synergistically to modulate postnatal hematopoiesis by inducing extramedullary shifts in hematopoiesis or remodeling of vascular architecture of sinusoidal BM endothelial cells. Recently, it has been shown that plasma VEGF levels are significantly elevated in myelodysplastic syndromes (17), where the BM microenvironment is damaged by fibrotic tissue. This raises the possibility that elevation of VEGF may serve as one of the primary adaptive responses to compensate for BM myelofibrosis, by promoting the relocalization and recruitment of HSCs to other hematopoietic microenvironments such as the spleen, resulting in splenomegaly.

Mobilization of CEPs to the peripheral circulation may play a critical role in regulating postnatal angiogenesis and vasculogenesis. Based on the data presented here, high levels of VEGF produced by tumors may result in the mobilization of BM-derived CEPs to the peripheral circulation and enhance their recruitment into the tumor vasculature. Given that CEPs may also contribute to vascular healing, overexpression of VEGF165 may promote the peripheral blood mobilization and recruitment of CEPs to the injured vascular bed, thereby accelerating wound healing.

As evidenced by the relative plasma levels of Ang-1 and VEGF, higher levels of Ang-1 are necessary to induce mobilization of HSCs and CEPs. Indeed, at doses >1.5 × 10⁸ PFU of AdVEGF165, elevations of plasma VEGF were associated with significant toxicity and resulted in the death of the treated mice. Ang-1 does not exert any major physiological effect at the lower doses (5 × 10⁸ PFU); however, when administered at higher doses (10⁹ PFU) it had a potent synergistic effect with VEGF in mobilizing HSCs and CEPs. These differences in the dose response may be due to the variable receptor densities or differential physiological effects of the VEGF receptors and Tie-2. It is also conceivable that expression of VEGFR2 (Flk-1) on HSCs and CEPs is significantly higher than Tie-2.

These data set forth a novel paradigm for efficient mobilization of HSCs and CEPs to the peripheral circulation. This strategy facilitates recovery of large numbers of pluripotent HSCs and CEPs, which may be used for transplantation or treatment of a wide variety of genetic and malig-
nant disorders. Whether transplantation of mobilized CEPs in conjunction with mobilized HSCs will exert a synergistic effect to enhance engraftment and reconstitution of hematopoiesis is the subject of future studies.

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