Th2 cytokines on the permeability of keratinocytes. We recently demonstrated that IL-4 down-regulated the cell surface expression of an adhesion molecule, E-cadherin, whereas IFN-γ up-regulated its expression [7]. This finding suggested that IL-4 and IFN-γ may modify the permeability of keratinocyte. In the present study, we examined the effects of IFN-γ and IL-4 on the trans-epithelial electrical resistance (TER) and the flux of 40 kDa FITC-dextrans across a cultured keratinocyte sheet.

2. Results

2.1. IFN-γ increased the TER of the keratinocyte sheet

We first examined the effects of IFN-γ and IL-4 on the TER of the keratinocyte sheet. The TER values represent the permeability of water-soluble ions. IFN-γ significantly increased the electrical resistance in a dose- and time-dependent manner (Fig. 1). In particular, the values of TER after treating the cultured sheet with 2 ng/ml of IFN-γ were approximately three times higher than those of the medium control, suggesting that IFN-γ profoundly inhibited the permeability of ions through the keratinocyte sheet. In contrast, IL-4 did not affect the TER (Fig. 1).

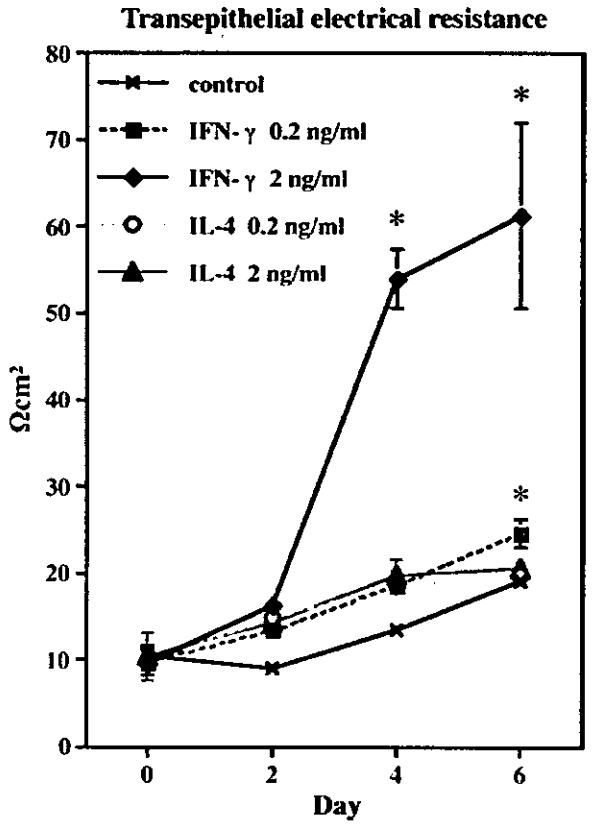

Fig. 1. The TER was measured across the confluent HaCaT keratinocyte sheet every second day using a Millicell-ERS epithelial voltohmmeter. IFN-γ significantly increased the TER in a dose- and time-dependent manner. In contrast, IL-4 did not affect the TER. The values indicated are means ± SD ($n = 4$). *$p < 0.01$ compared with the control.

2.2. Down-regulation of the flux of FITC-dextran through the keratinocyte sheet by IFN-γ and its up-regulation by IL-4

Next, we examined whether IFN-γ or IL-4 may modify the permeability of high molecular weight material through the keratinocyte sheet using 40 kDa FITC-dextran. As shown in Fig. 2, IFN-γ significantly decreased the flux of FITC-dextran in a dose-dependent fashion compared to the medium control (81.3% inhibition at 2 ng/ml of IFN-γ). In sharp contrast, IL-4 dose-dependently up-regulated the flux of FITC-dextran (92.3% up-regulation at 2 ng/ml of IL-4).

2.3. Desmoglein-3 expression was up-regulated by IFN-γ, but was down-regulated by IL-4

Desmoglein-3 is one of the major intercellular adhesion molecules between keratinocytes. Therefore, we investigated whether the expression of desmoglein-3 is modulated by IL-4 or IFN-γ. The expression of desmoglein-3 was dramatically up-regulated by IFN-γ and was down-regulated by IL-4 (Fig. 3).

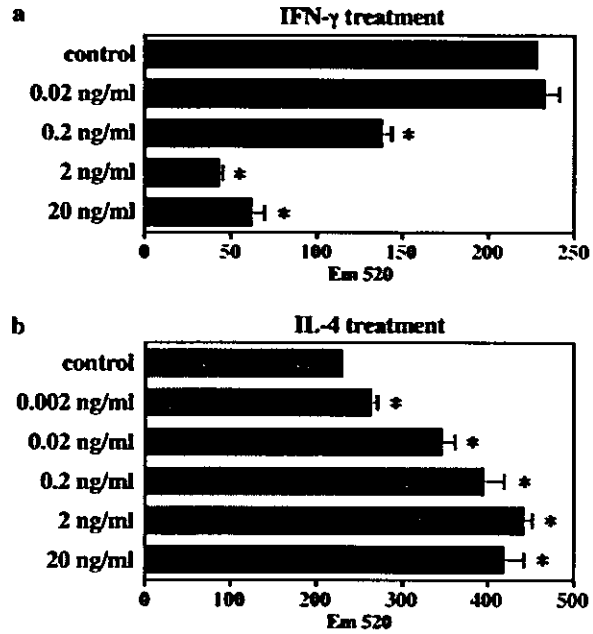

Fig. 2. The flux of 40 kDa FITC-dextrans was measured using a fluorometer (excitation, 492 nm; emission, 520 nm). IFN-γ dose-dependently inhibited the permeability of FITC-dextran, whereas IL-4 enhanced its permeability. The values indicated are means ± SD ($n = 4$). *$p < 0.01$ compared to the control.

3. Discussion

TER and the flux assay have been demonstrated to be a suitable in vitro models to determine the permeability of water-soluble ions and solutes containing various molecular weight materials, respectively [8,9]. FITC-labeled dextrans with a molecular weight of 40 kDa, which are similar in molecular weight to plasma albumin, were utilized in the flux assay as a tracer. In this study, we demonstrated a significant increase in TER and a significant decrease in the flux of dextran by IFN-γ, suggesting that IFN-γ may reduce the permeability of both ions and high molecular weight material through the keratinocyte sheet. In contrast, IL-4 significantly enhanced the permeability of dextran. We did not detect an effect of IL-4 on the TER of the keratinocyte sheet. Interestingly, Ahdieh et al. recently investigated the permeability of cultured lung epithelial cells and found that IL-4 treatment resulted in a 70–75% increase in permeability, as assessed by electrophysiological and mannitol flux measurements. In contrast, IFN-γ markedly reduced the permeability [10]. However, the means that IFN-γ and IL-4 modify the permeability are unknown.

Ye et al. have reported that the expression of IL-1 and its receptor plays a pivotal role in permeability homeostasis in the epidermis [2]. IFN-γ and IL-4 may alter the IL-1/IL-1 receptor signaling system. In fact, IFN-γ augments IL-1 production [11]. The expression of adhesion molecules may be related to the permeability of keratinocytes. Trautmann et al. demonstrated a reduced expression of E-cadherin in areas of spongiosis in acute eczematous dermatitis. They also showed that the induction of keratinocyte apoptosis is accompanied by a rapid cleavage of E-cadherin [12]. Recently, we found that IL-4 down-regulated the cell surface expression of E-cadherin, whereas IFN-γ up-regulated its expression [7]. In the present study, we showed that the expression of desmoglein-3 was also enhanced by IFN-γ but was inhibited by IL-4. The modification of these intercellular adhesion molecules occurred earlier than the permeability change and required higher concentrations of cytokines, however, it may be partly responsible for the permeability of keratinocytes.

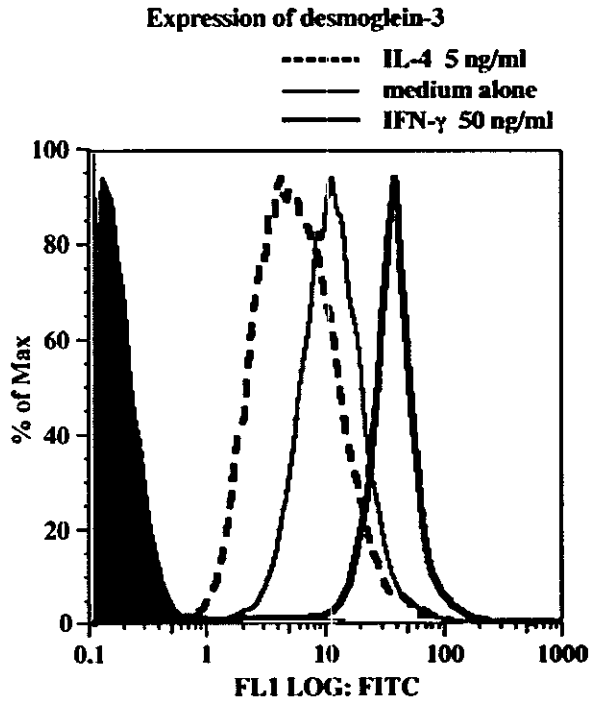

Fig. 3. Keratinocytes were cultured with IFN-γ (50 ng/ml), IL-4 (5 ng/ml) or medium alone for 48 h and the expression of desmoglein-3 was analyzed by flow cytometry. IFN-γ augmented the expression of desmoglein-3, while IL-4 decreased its expression.

4. Material and methods

4.1. Cell culture

HaCaT keratinocytes (a kind gift from Dr. N.E. Fusening in Heidelberg) were maintained in Dulbecco's modified Eagle medium (DMEM) supplemented with 10% fetal bovine serum (FBS), 100 IU/ml penicillin, and 100 μg/ml streptomycin (GIBCO BRL, Rockville, MD/USA). Using a two-layer well culturing system, cells were plated at a confluent density, at about 3×10^5 cells/cm^2, on 12-mm membrane culture inserts (0.6 cm^2; Millipore Corp., Bedford, MA/USA) in a 24-well plate. After an overnight incubation for cell attachment, we added various concentrations of IFN-γ (0.02–20 ng /ml) or IL-4 (0.002–20 ng/ml) into the outer layer culture medium, and further cultured the cells for up to 6 days. Assays for the permeability of keratinocyte sheets were performed as described below.

4.2. Measurement of the TER

The TER was measured using a Millicell-ERS epithelial voltohmmeter (Millipore), as described previously [13]. The TER values were calculated by subtracting the contribution of the bare filter and medium and multiplying by the surface area of the filter. The TER represents the transepithelial permeability of the water-soluble ions. A higher value of TER means a lower permeability of ions. These data were analyzed using the Student's t test. A p value of less than 0.01 was considered to be statistically significant. The experiment was repeated at least three times in quadruplicate.

4.3. Measurement of flux of FITC-dextran

The cells were cultured at confluence with or without various concentrations of IFN-γ or IL-4 for 6 days on culture insert. The flux was measured as described previously [13]. In brief, the culture medium was replaced with P buffer (10 mM Hepes, pH 7.4, 1 mM sodium pyruvate, 10 mM glucose, 3 mM $CaCl_2$, 145 mM NaCl), and 1 mg/ml FITC-dextran (40 kDa: Sigma, St. Louis, MO/USA) was added to the outer wells. At 120 min after the addition of FITC-dextran into the outer chambers, the media from the inner wells were collected, and the flux of FITC-dextran was measured with a fluorometer RF-1500 (Shimadzu, Tokyo, Japan). The flux of FITC-dextran represents the permeability of the solutes with high molecular weight material beyond the keratinocyte sheet. These data were analyzed using the Student's t test. A p value of less than 0.01 was considered to be statistically significant. The experiment was repeated at least three times in quadruplicate.

4.4. Flow cytometry

The HaCaT keratinocytes were cultured in the presence or absence of IL-4 (5 ng/ml) or IFN-γ 50 ng/ml) for 48 h. Cells were detached from the plates using trypsine–EDTA and were incubated with mouse anti-desmoglein-3 antibody (Zymed, San Francisco, California, USA) or isotype-matched control antibody (Zymed) for 30 min on ice. After washing, the cells were incubated with FITC-conjugated goat anti-mouse IgG antibody (Molecular Probes, Eugene, OR). The stained cells were analyzed by flow cytometry (EPIX-XL, Coulter, Fullerton, CA).

Acknowledgements

This work was supported in part by grants from Koga Hideya Funds and Grants-in-Aid for Scientific Research from the Ministry of Education, Science and Culture, Japan (Nos. 08770015, 09770010 and 11770008).

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THE JOURNAL OF BIOLOGICAL CHEMISTRY
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Vol. 279, No. 48, Issue of November 26, pp. 50537–50554, 2004
Printed in U.S.A.

Vascular Endothelial Growth Factor- and Thrombin-induced Termination Factor, Down Syndrome Critical Region-1, Attenuates Endothelial Cell Proliferation and Angiogenesis*[S]♦

Received for publication, June 10, 2004, and in revised form, September 17, 2004
Published, JBC Papers in Press, September 23, 2004, DOI 10.1074/jbc.M406454200

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Activation and dysfunction of the endothelium underlie many vascular disorders including atherosclerosis, tumor growth, and inflammation. Endothelial cell activation is mediated by many different extra-cellular signals, which result in overlapping yet distinct patterns of gene expression. Here we show, in DNA microarray analyses, that vascular endothelial growth factor (VEGF) and thrombin result in dramatic and rapid up-regulation of Down syndrome critical region (DSCR)-1 gene encoding exons 4–7, a negative feedback regulator of calcium-calcineurin-NF-AT signaling. VEGF- and thrombin-mediated induction of DSCR-1 involves the cooperative binding of NF-ATc and GATA-2/3 to neighboring consensus motifs in the upstream promoter. Constitutive expression of DSCR-1 in endothelial cells markedly impaired NF-ATc nuclear localization, proliferation, and tube formation. Under *in vivo* conditions, overexpression of DSCR-1 reduced vascular density in matrigel plugs and melanoma tumor growth in mice. Taken together, these findings support a model in which VEGF- and thrombin-mediated induction of endothelial cell proliferation triggers a negative feedback loop consisting of DSCR-1 gene induction and secondary inhibition of NF-AT signaling. As a natural brake in the angiogenic process, this negative pathway may lend itself to therapeutic manipulation in pathological states.

The endothelium is highly malleable cell layer, constantly responding to changes within the extracellular environment and responding in ways that are usually beneficial, but at times harmful, to the organism. Several mediators, including growth factors (*e.g.* vascular endothelial growth factor (VEGF)[1]), cytokines (*e.g.* tumor necrosis factor-α (TNF-α)), and serine proteases (*e.g.* thrombin), activate gene transcription in endothelial cells, resulting in changes in hemostatic balance, increased leukocyte adhesion, loss of barrier function, increased permeability, migration, proliferation, and successive angiogenesis. The tight control of these processes is essential for homeostasis; endothelial cell activation, if excessive, sustained, or spatially and temporally misplaced, may result in vasculopathic disease. Under normal conditions, the activation signal may be terminated by negative feedback inhibition of downstream transcriptional networks. Such a mechanism has been well established for TNF-α (1–4). In contrast, little is known about the major self-regulatory processes involved in VEGF and thrombin signaling.

VEGF is an endothelial cell-specific mitogen, and chemotactic agent, which is involved in wound repair, angiogenesis of ischemic tissue, tumor growth, microvascular permeability, hemostasis, and endothelial cell survival (5, 6). VEGF binds to two receptor-type tyrosine kinases, Flt-1 and Flk-1/KDR (7, 8). A third receptor, neuropilin, has been identified, but its role in VEGF signaling has not been fully elucidated (9). The VEGF receptors have been shown to activate a number of different intracellular signaling pathways, including PKC (10), PI3K and Akt/PKB (11), MEK1/2 (12), p38 MAPK (13), and phospholipase C (14).

Thrombin is a multifunctional serine protease that is involved not only in mediating the cleavage of fibrinogen to fibrin in the coagulation cascade but also in activating a variety of cell types, including platelets and endothelial cells. Thrombin signaling in the endothelium may result in a multitude of phenotypic changes, including alterations in cell shape, permeability, vasomotor tone, leukocyte trafficking, migration, DNA synthesis, angiogenesis, and hemostasis (15). Thrombin signaling in the endothelium is mediated by a family of seven-transmembrane G-protein-coupled receptors, termed protease activated receptors (PAR) (16). Currently, four members of the PAR family have been identified (PAR-1 to PAR-4). Of the various PAR family members, PAR-1 is the predominant thrombin receptor in endothelial cells (17). Once activated, PAR-1 is linked to a number of signal intermediates that include, but are not limited to, MAPK, protein kinase C, PI3K, and Akt (15, 18).

* This work was supported in part by grants-in-aid from the Ministry of Education, Science, Sports and Culture of Japan (to T. M.) and by the Uehara Memorial Foundation in Japan (to T. M.). The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked "*advertisement*" in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

♦ This article was selected as a Paper of the Week.

[S] The on-line version of this article (available at http://www.jbc.org) contains supplemental Fig. 1 and Tables I and II.

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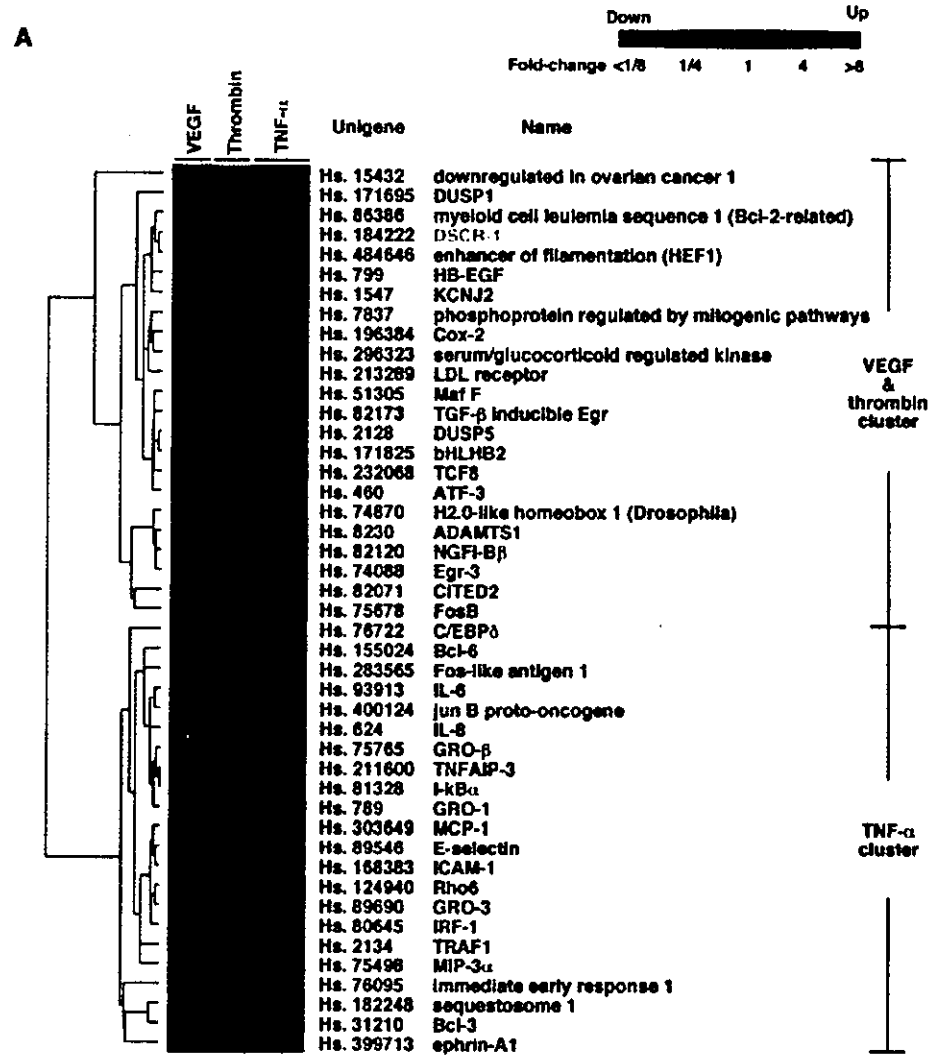
‖ Supported in part by National Institutes of Health Grant HL36028.

[1] The abbreviations used are: VEGF, vascular endothelial growth factor; TNF-α, tumor necrosis factor-α; PAR, protease activated receptor; MAPK, mitogen-activated protein kinase; PI3K, phosphatidylinositol 3-kinase; HUVEC, human umbilical vein endothelial cells; TRAP, thrombin receptor activation peptide; PlGF, placenta growth factor; EGM, endothelial growth medium; Ad, adenovirus; EMSA, electrophoretic mobility shift assay; FACS, fluorescence-activated cell sorter; PBS, phosphate-buffered saline; CsA, cyclosporine A; EGFP, enhanced green fluorescent protein; GAPDH, glyceraldehyde-3-phosphate dehydrogenase; RT, reverse transcription; IRES, internal ribosome entry.



B

the five highest induced genes at 1 h

VEGF-mediated genes	1 DSCR-1 22.3-fold	2 Egr-3 17.0-fold	3 NGFI-Bβ 11.9-fold	4 COX-2 8.1-fold	5 ADAMTS1 7.2-fold
thrombin-mediated genes	1 DSCR-1 17.7-fold	2 FosB 17.5-fold	3 IL-8 10.7-fold	4 COX-2 10.4-fold	5 GRO-β 10.1-fold
TNF-α-mediated genes	1 E-selectin 87.1-fold	2 GRO-β 54.1-fold	3 GRO-1 35.7-fold	4 ICAM-1 24.3-fold	5 GRO-3 22.4-fold

FIG. 1. **DSCR-1 is the most highly induced early response gene in VEGF- and thrombin-treated HUVEC.** *A*, cluster analysis of early response genes (1 h). *B*, the average fold induction of the five most highly induced genes in VEGF-, thrombin-, and TNF-α-treated HUVEC.

Given the overlapping functions of VEGF and thrombin both in terms of signaling pathways activated and phenotypic response, we hypothesized that these two mediators are likely to trigger common transcriptional networks in the endothelium. To identify such factors, we compared DNA microarray analyses of VEGF and thrombin-treated human umbilical vein endothelial cells (HUVEC). We found that under both conditions, the most highly induced gene was DSCR-1. The DSCR-1 gene (also known as MCIP-1), designated as such because it resides within the Down syndrome critical region of human chromosome 21, encodes a protein that binds to and inhibits the catalytic subunit of calcineurin (19). In this report, we show that DSCR-1 acts as a "circuit breaker" in VEGF and thrombin signaling, serving in a negative feedback loop to inhibit endothelial cell proliferation and activation as well as angiogenesis. These results provide new insights into endothelial cell signaling and point to DSCR-1 as a potential therapeutic target for anti-angiogenesis and anti-inflammatory therapy.

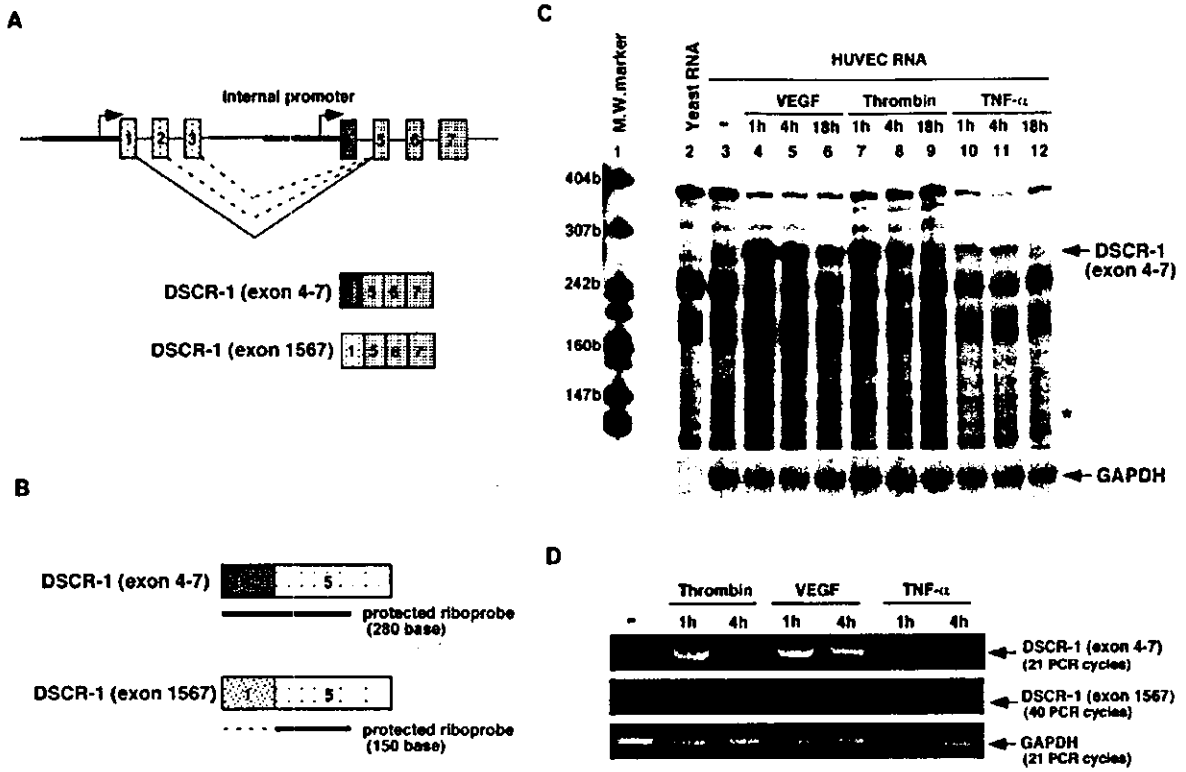


FIG. 2. **DSCR-1 isoform consisting of exons 4–7 was selectively induced with VEGF and thrombin treatments in primary human endothelial cells.** *A*, schematic representation of the human DSCR-1 gene. The mRNA consists of four alternative first exons (*boxes 1–4*) followed by three common exons (*boxes 5–7*). The *broken line* indicates the putative splicing isoforms. Shown are the two major DSCR-1 isoforms, DSCR-1 (exon 4–7) and DSCR-1 (exon 1567). *B*, schematic representation of the riboprobe used to distinguish the two DSCR-1 isoforms in RNase protection assays. The *bold line* indicates the protected fragment and the *broken line* the RNase-digested region. *C*, RNase protection assays were performed with [α-^{32}P]UTP-labeled 361-bp riboprobe as shown in *B* and either 10 μg of yeast RNA (*lane 2*), 10 μg of total RNA from control (*lane 3*), VEGF-treated (*lanes 4–6*), thrombin-treated (*lanes 7–9*), or TNF-α-treated (*lanes 10–12*) HUVEC. The *arrow* indicates the protected fragment (280 bp) from the DSCR-1 (exon 4–7) isoform; the *asterisk* indicates the expected length (130 bp) from the DSCR-1 (exon 1567) isoform. An [α-^{32}P]UTP-labeled human GAPDH riboprobe was hybridized with total RNA as an internal control. *D*, RT-PCR was performed with either DSCR-1 (exons 4–7) or DSCR-1 (exon 1567) isoform-specific primers, using RNA from control (−) and thrombin-, VEGF-, or TNF-α-treated HUVEC and 21- or 40-cycle amplification. GAPDH-specific primers were included as an internal control.

EXPERIMENTAL PROCEDURES

Materials and Cell Culture—VEGF and TNF-α were obtained from Peprotec (Rocky Hill, NJ). Human thrombin, cyclosporine A, and SU1498 were obtained from Calbiochem. Hirudin and thrombin receptor activation peptide (TRAP; SFLLRNPNDKYEPF) were from Wako chemicals (Osaka, Japan). Human placenta growth factorPlGF) was from R&D Systems (Minneapolis, MN). HUVEC were grown in endothelial growth medium-2-MV (EGM-2-MV) BulletKit (Clonetics, San Diego, CA). HUVEC were used within the first eight passages. Mouse B16-melanoma cells (JCRB-0202) were grown in Dulbecco's modified Eagle's medium plus 10% fetal bovine serum.

Microarray Analysis—HUVEC were serum-starved overnight in medium containing EGM-2 and 0.5% fetal bovine serum and then treated with 50 ng/ml VEGF or 1.5 units/ml thrombin. RNA was harvested and purified with Trizol according to manufacturer's protocol (Invitrogen). Preparation of cRNA and hybridization of probe arrays were performed according to the protocols of the manufacturer (Affimetrix, Santa Clara, CA).

RNase Protection Assays and Reverse Transcription-PCR (RT-PCR)—HUVEC were serum-starved in EBM-2 medium containing 0.5% fetal bovine serum. 18 h later, HUVEC were pretreated for 30 min with cyclosporin A or SU1498 at the doses indicated or infected with adenovirus at multiplicity of infection = 40 and then incubated in the absence or presence of either 50 ng/ml VEGF, 1.5 units/ml thrombin, 10 ng/ml TNF-α, or 50–200 ng/ml PlGF. RNase protection assays were performed with a RPA III kit (Ambion) according to the manufacturer's instructions. For RT-PCR, a Superscript First-strand synthesis kit (Invitrogen) was used with 5 μg of total RNA. Forward and reverse primers and amplification cycles as follows: Tissue factor (22 cycles), 5′-TCAGAGTTTTGAACAGGTGGGAACA-3′ (forward) and 5′-TTCTCCTGGCCCATACACTCTACCG-3′ (reverse); E-selectin (22 cycles), 5′-CATGTGGAGCCACAGGACACTGGTCTG-3′ (forward) and 5′-TCTGATTCAAGGCTTTGGCAGCTGCTG-3′ (reverse); angiopoietin-2 (20 cycles), 5′-ACAAATGTATTTGCAAATGTTCACAAA-3′ (forward) and 5′-GAAATCTGCTGGTCGGATCATCATGGT-3′ (reverse); PlGF (20 cycles), 5′-CCGGTCATGAGGCTGTTCCCTTGC-3′ (forward) and 5′-CTCGCTGGGGTACTCGGACACGAC-3′ (reverse); P27 (26 cycles), 5′-CGCAGGAATAAGGAAGCGACCTGC-3′ (forward) and 5′-CGTTTGACGTCTTCTGAGGCCAGGCTT-3′ (reverse); P21 (18 cycles), 5′-AGCAAGGCCTGCCGCCGCCTCTTC-3′ (forward) and 5′-TGACAGGTCCACATGGTCTTCCTC-3′ (reverse); ADAMTS1 (20 cycles), 5′-AGCTTTCTTGCCATCAAAGCTGCT-3′ (forward) and 5′-A ACCTGGATGGTCAAGGGCTCTTT-3′ (reverse); interleukin-8 (23 cycles), 5′-TGTCAGTGCATAAAGACATACTCCA-3′ (forward) and 5′-CTTCTCCACAACCCTCTGCACCCAG-3′ (reverse); ICAM-1 (23 cycles), 5′-GTGCAAGAAGATAGCCAACCAATG-3′ (forward) and 5′-AGGAGTCGTTGCCATAGGTGACTG-3′ (reverse); cyclophilin A (23 cycles), 5′-TTCGTGCTCTGAGCACTGGAGA-3′ (forward) and 5′-GGACCCGTATGCTTTAGGATGAAG-3′ (reverse).

Transfections and Analysis of Luciferase Activity—HUVEC were transfected using FuGENE 6 reagent (Roche Applied Science) as described previously (20). The serum-starved transfected cells were preincubated for 30 min with 1 μM cyclosporine A and then incubated with 50 ng/ml VEGF or 1.5 units/ml thrombin for 6 h.

Electrophoretic Mobility Shift Assays (EMSAs)—Nuclear extracts purification and EMSAs were prepared as described previously (21). To test the effect of antibodies on DNA-protein binding, nuclear extracts were preincubated with antibodies of NF-ATc, NF-ATp (Affinity BioReagents, Golden, CO), GATA-2, -3, or -6 (Perseus Proteomics, Tokyo, Japan) for 30 min at room temperature.

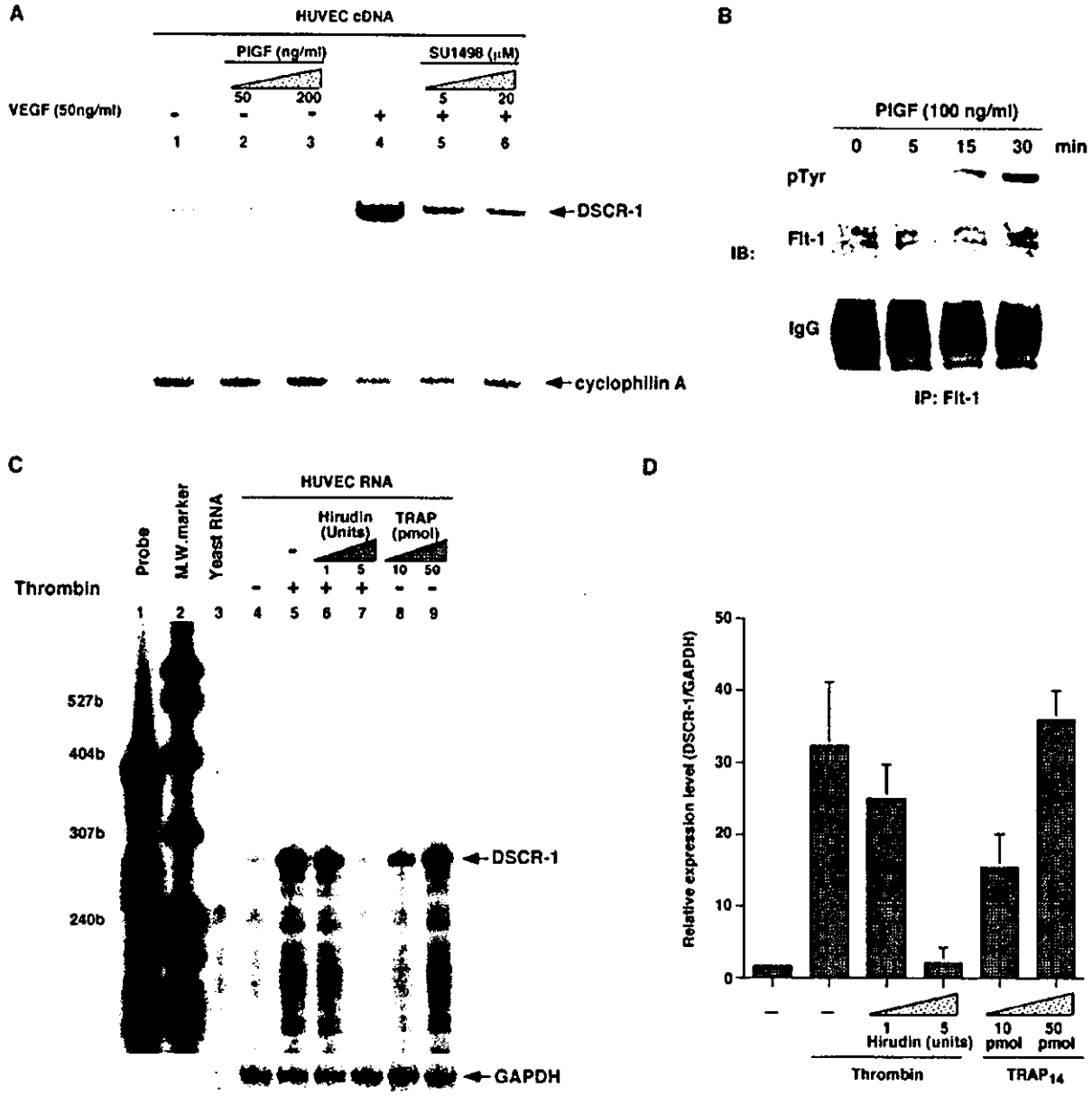


FIG. 3. **VEGF-Flk-1/KDR- and thrombin-PAR1-mediated up-regulation of DSCR-1 mRNA.** *A*, RT-PCR of DSCR-1 in HUVEC treated with 50 ng/ml PlGF (*lane 2*), 200 ng/ml PlGF (*lane 3*), pretreated with 5 μM SU1498 (*lane 5*), 20 μM SU1498 (*lane 6*), and treated in the absence (−) or presence (+) of 50 ng/ml VEGF for 1 h. Cyclophilin A-specific primers were added as an internal control. *B*, immunoprecipitation assays were performed in HUVEC treated with 100 ng/ml PlGF for 0, 5, 15, and 30 min. Total HUVEC lysates were subjected to immunoprecipitation (*IP*) using anti-Flt-1 antibody, then immunoblotted (*IB*) with anti-phosphotyrosine antiboby (*pTyr*). The same blots were stripped and reprobed with anti-Flt-1 antibody (*Flt-1*). IgG is shown as a loading control. *C*, RNase protection assays were performed with either no RNA (*lane 1*, *Probe*), 10 μg of yeast RNA (*lane 3*), or 10 μg of total RNA from control HUVEC (*lane 4*), thrombin-treated HUVEC pretreated in the absence (*lane 5*) or presence of 0.5 and 5 units of hirudin (*lanes 6* and *7*, respectively) or HUVEC treated with 10 or 50 pmol of TRAP (*lanes 8* and *9*, respectively). Human GAPDH was used as an internal control. *D*, quantification of RNase protection assays. Densitometry was used to calculate the ratio of DSCR-1 and GAPDH signals (arbitrary relative expression level). Mean and S.D. values were derived from three independent experiments.

FACS Analysis—Ad-DSCR-1-, Ad-Control-, or Ad-DSCR-1 plus Ad-CA-NFAT-infected HUVEC were scraped, spun down for 5 min at 100 × *g*, re-suspended in PBS containing with 0.2% Triton X, and stained in 25 μg/ml propidium iodide and 50 ng/ml RNase A. Cells were counted on a FACS Calibur using CellQuest software (BD Biosciences), and the percentages of cells in the G_1, S, and G_2/M phases of the cell cycle were determined using ModFit LT software (Verity Software House, Topsham, ME).

Immunolocalization Studies—HUVEC were plated onto glass coverslips (Matsunami Glass, Osaka, Japan) in a 6-well plate at a density of 25,000 cells/slide. The cells were treated in the presence or absence of 1 unit/ml thrombin or 50 ng/ml VEGF for 1 h, fixed in ice-cold 3.7% paraformaldehyde for 10 min, washed with PBS, and subsequently incubated with primary anti-NF-ATc antibody (Affinity BioReagents). Following extensive washes in PBS, the cells were incubated with an Alexa-Fluor 594-labeled secondary antibody (Molecular Probes, Eugene, OR) for 1 h. The slides were then washed in PBS, mounted in Crystal/Mount (Biomeda, Foster City, CA) with Hoechst (Sigma) for identification of nuclear localization, and examined by fluorescence microscopy. The degree of nuclear localization was quantified with NIH image.

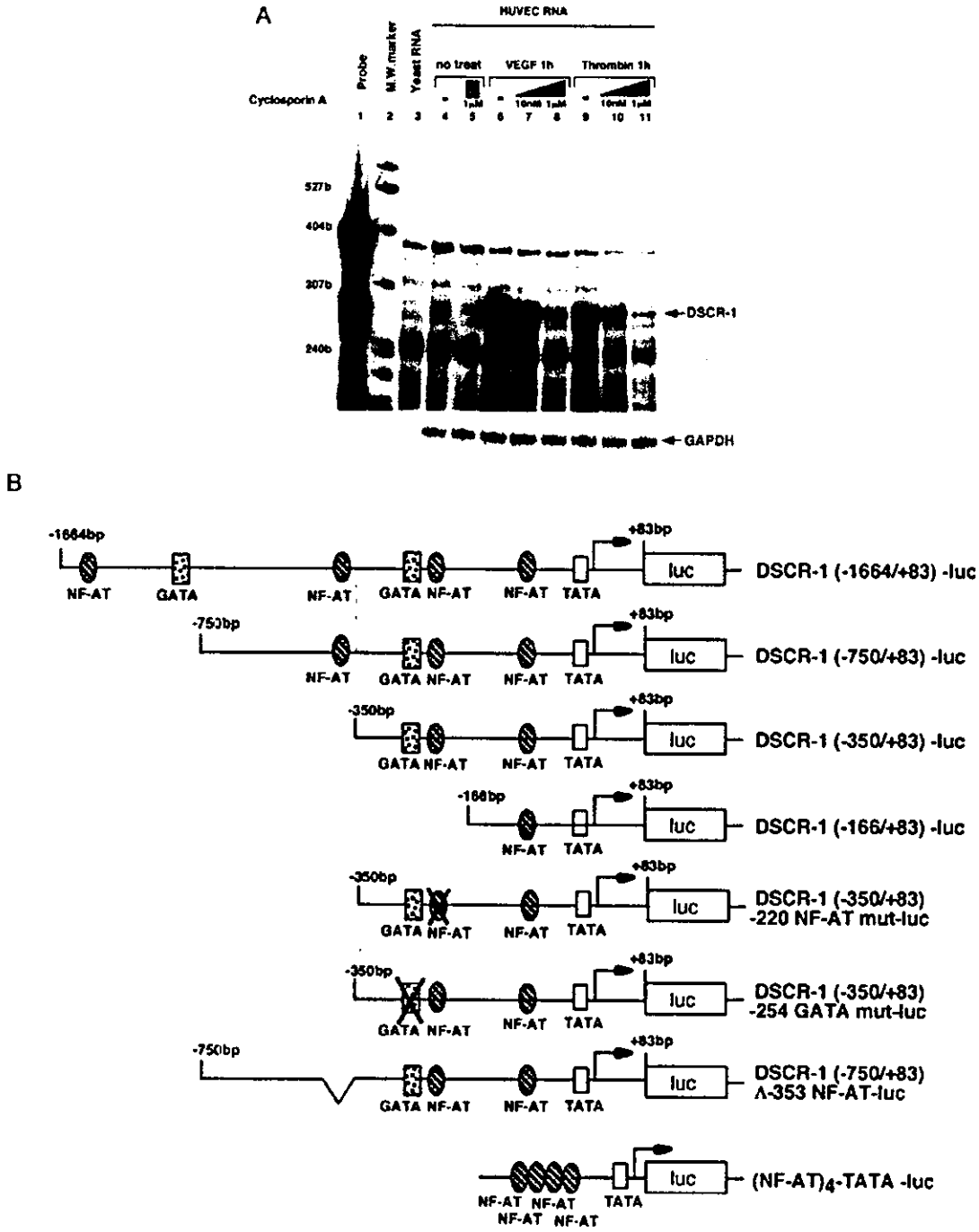
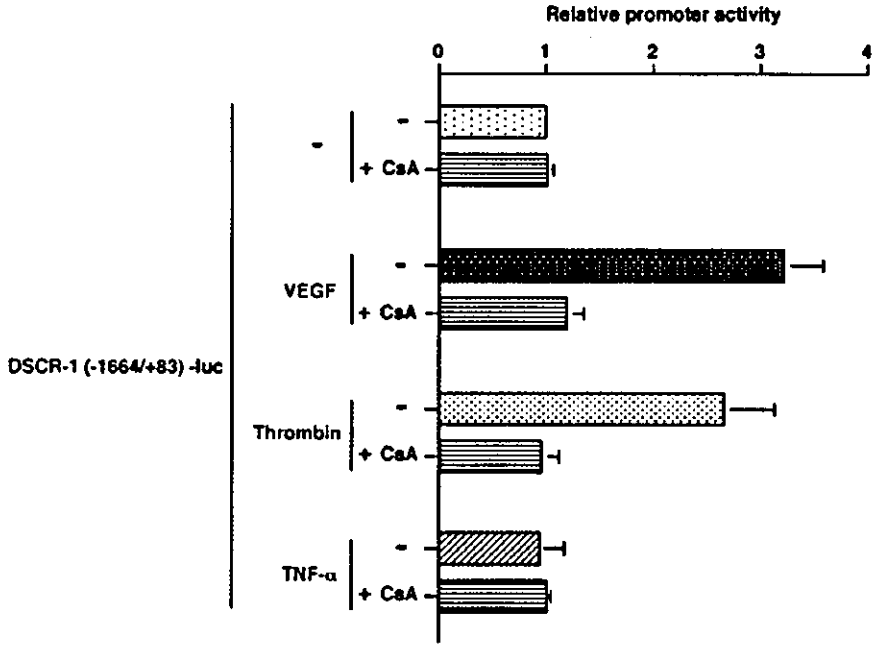


FIG. 4. **The NF-AT and GATA motif is necessary for mediating VEGF and thrombin stimulation of DSCR-1 mRNA and promoter in endothelial cells.** *A*, RNase protection assays were employed with either no RNA (*lane 1, Probe*), 10 μg of yeast RNA (*lane 3*), or 10 μg of total RNA from untreated HUVEC (*lanes 4* and *5*), VEGF-treated HUVEC (*lanes 6–8*), or thrombin-treated HUVEC (*lanes 9–11*), preincubated in the absence (−) or presence of 10 nM CsA (*lanes 7* and *10*) or 1 μM CsA (*lanes 5, 8,* and *11*). GAPDH antisense riboprobe was hybridized with total RNA as an internal control. The results are representative of three independent experiments. *B*, schematic shows the deletion and/or mutant DSCR-1 promoter constructs. *C*, HUVEC were transiently transfected with the DSCR-1 (−1664/+83)-luc plasmid and exposed to 50 ng/ml VEGF, 1.5 units/ml thrombin, or 10 ng/ml TNF-α for 6 h in the absence (−) or presence of 1 μM CsA. The results show the mean and S.D. of luciferase light units (relative to untreated and minus CsA cells) obtained in triplicates from at least three independent experiments. *D* and *E*, HUVEC were transiently transfected with deletion and/or mutant constructs and exposed to 50 ng/ml VEGF or 1.5 units/ml thrombin for 6 h. Each plasmid was co-transfected with pRL-SV40 to normalize for transfection efficiency. Promoter activities were determined relative to the normalized activity from DSCR-1 (−1664/+83)-luc plasmid in untreated cells (*D*) or each untreated control (*E*). *F*, HUVEC were transiently transfected with $(NF\text{-}AT)_4$-TATA-luc plasmid and exposed to 50 ng/ml VEGF, 1.5 unit/ml thrombin, or 10 ng/ml TNF-α for 6 h. *G*, HUVEC were transiently co-transfected with DSCR-1 (−350/+83)-luc and GATA-2 (pMT_2-GATA2), constitutively active NF-ATx (pSRα-CANF-AT), or vector alone (pMT_2 or pSRα), alone or in combination. The means and S.D. values are derived from at least three separate experiments performed triplicate.

C



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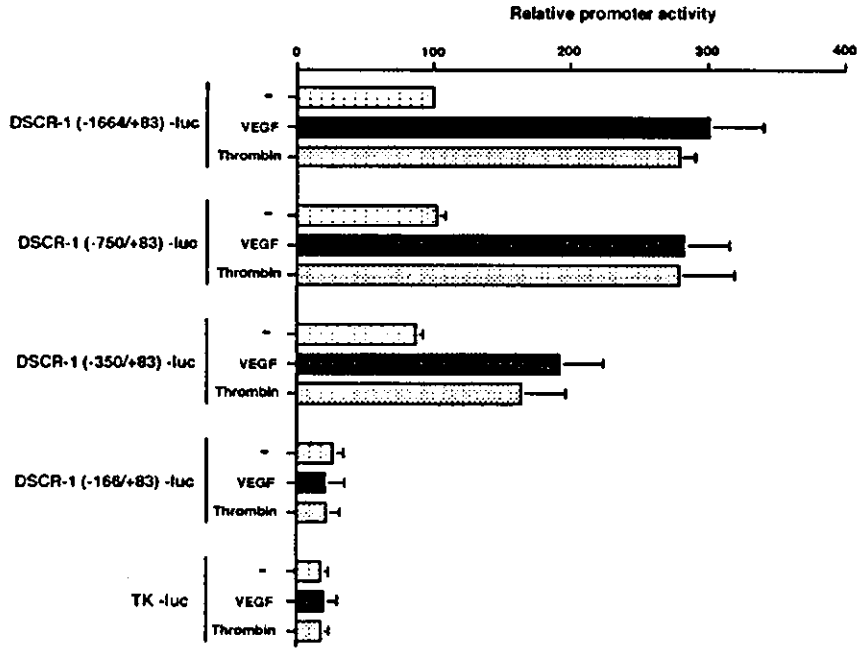
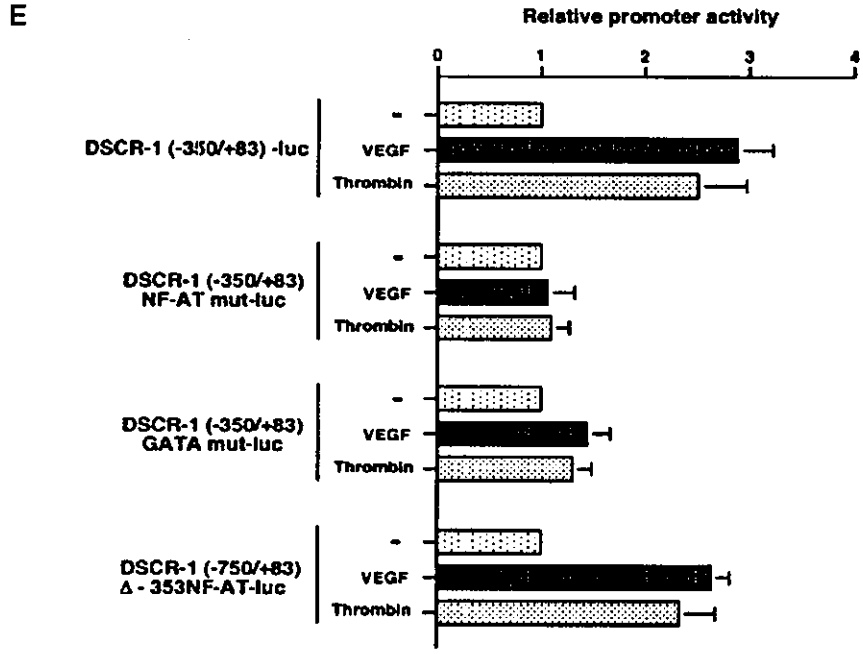
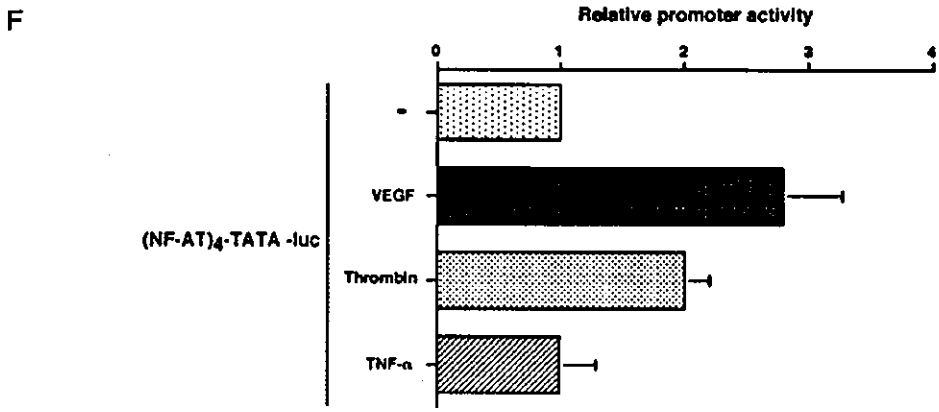


FIG. 4—*continued*

Tube Formation Assays—400-μl aliquots of type-I collagen gel (Koken, Tokyo, Japan) containing EGM-2-MV medium without basic fibroblast growth factor were used as described previously (22). Briefly, HUVEC infected with Ad-Control or Ad-DSCR-1 were seeded at 1×10^5 cells/well and incubated for 24 h in 5% CO_2. The medium was removed, and HUVEC were covered with 400 μl of the gel. Cells were incubated with 1 ml of EGM-2-MV medium in the absence of basic fibroblast growth factor. Two days later, a branched capillary network was visualized under a microscope. Images from at least three different areas in each well were captured by a digital camera under a microscope.

Matrigel Plug Assays—Matrigel (BD Biosciences) containing 50 ng of VEGF and either 10^9 plaque-forming units of Ad-Control, Ad-DSCR-1, or Ad-DSCR-1 plus Ad-CA-NFAT was injected subcutaneously into C57BL6 mice. After 14 days, matrigel plugs were removed for histological sections. Alternatively, the matrigel plugs were





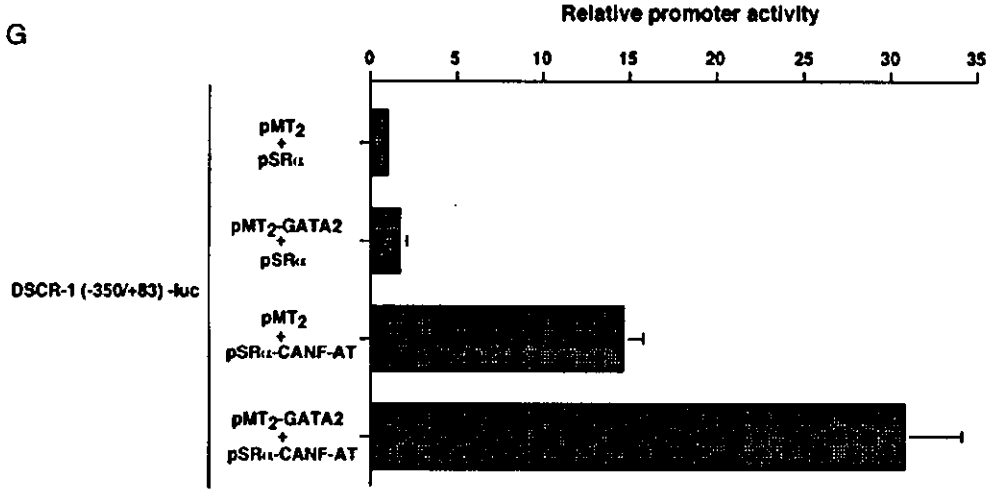


FIG. 4—*continued*

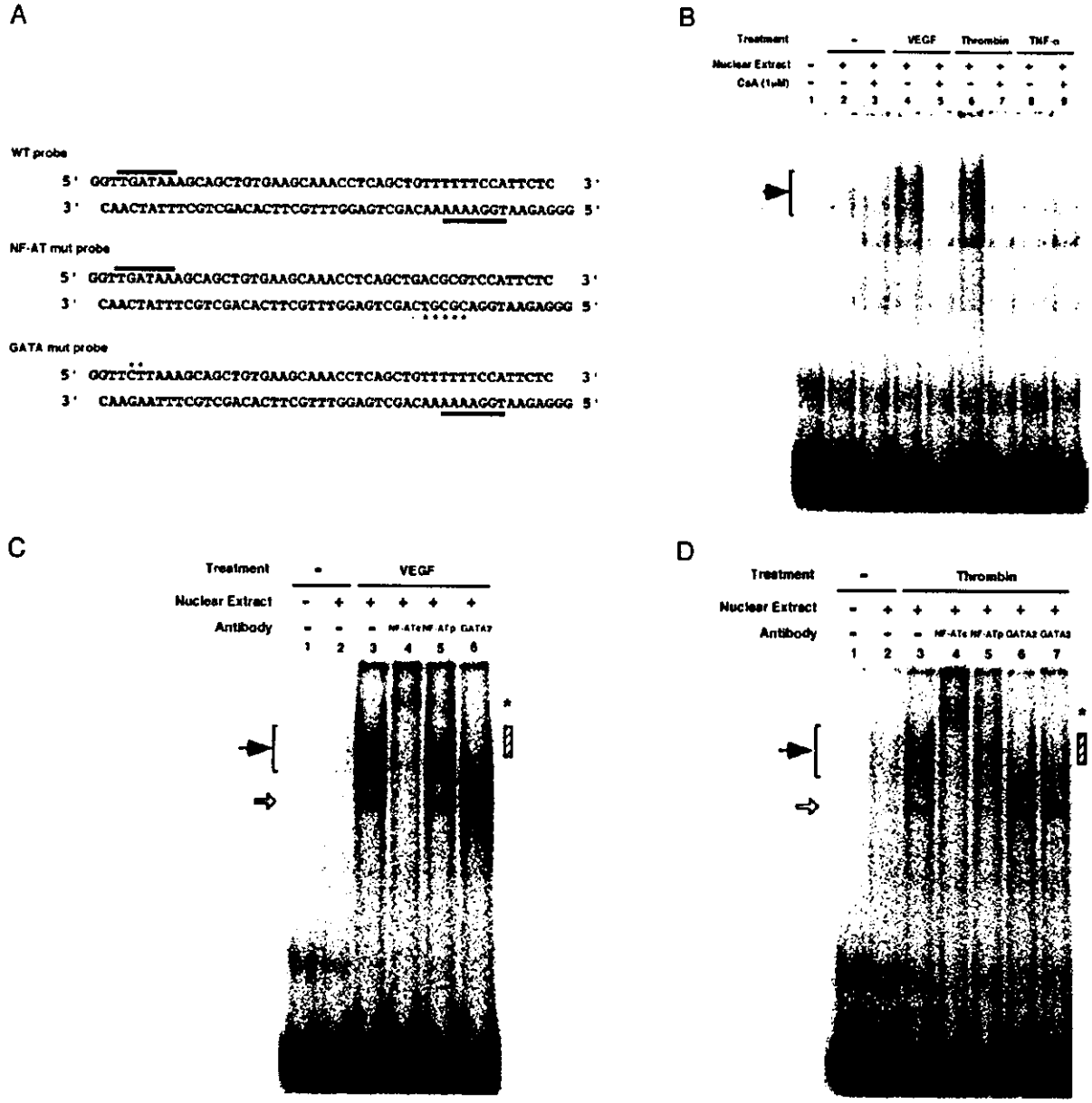


FIG. 5. **VEGF and thrombin response element on the DSCR-1 binds NF-ATc and NF-Atp and GATA-2 and -3.** *A*, schematic representation of the probe sequences used in EMSA. The consensus NF-AT and GATA motifs are *underlined*. The mutated bases are represented by *asterisks*. *B*, EMSAs were performed with ^{32}P-labeled WT probe and nuclear extract from untreated HUVEC (− treatment) (*lanes 2* and *3*) or HUVEC treated with 50 ng/ml VEGF (*lanes 4* and *5*), 1.5 units/ml thrombin (*lanes 6* and *7*), or 10 ng/ml TNF-α (*lanes 8* and *9*), in the absence (−) or presence (+) of 1 μM CsA. The *arrow* indicates the CsA-sensitive DNA-protein complexes. *C* and *D*, nuclear extracts from untreated (*lane 2*) and VEGF (*C*)- or thrombin (*D*)-treated HUVEC were incubated in the absence (*lanes 2* and *3*) or presence of antibodies against NF-ATc (*lane 4*), NF-ATp (*lane 5*), GATA-2 (*lane 6*), or GATA-3 (*D*, *lane 7*). The *asterisks* indicate the supershifted complex. The *hatched rectangles* indicate the inhibited complex. *E*, EMSAs were performed with ^{32}P-labeled NF-AT mutant probe in the absence (*lane 1*) or presence of nuclear extracts from VEGF-treated HUVEC, incubated without (*lane 2*) or with 100-fold molar excess of unlabeled NF-AT mutant (*lane 3, self*) GATA mutant (*lane 4, mut*) or antibodies against GATA-6 (*lane 5*), GATA-3 (*lane 6*), or GATA-2 (*lane 7*). *F*, EMSAs were performed with ^{32}P-labeled GATA mutant probe in the absence (*lane 1*) or presence of nuclear extracts from VEGF-treated HUVEC incubated without (*lane 2*) or with 100-fold molar excess of unlabeled GATA mutant (*lane 3, self*), NF-AT mutant (*lane 4, mut*) or antibodies against NF-ATc (*lane 5*) or NF-ATp (*lane 6*). The *asterisk* indicates the supershifted complex.

weighed and homogenized at 4 °C. The hemoglobin content was assayed with a Drabkin's reagent kit 525 (Sigma) according to the manufacturer's protocol.

Solid Tumor Model—1 × 10^6 logarithmically growing B16-melanoma cells were implanted subcutaneously into the right hind flank of C57BL6 mice. When the tumor reached about 50 mm^3 in volume, it was injected with 5 × 10^9 plaque-forming units of Ad-DSCR-1 or Ad-Control. Tumor volume (mm^3) was determined using length × width × height × 0.52 after caliper measurement.

RESULTS

DSCR-1 Is the Most Highly Induced Gene in VEGF- and Thrombin-treated Primary Human Endothelial Cells—Endo-

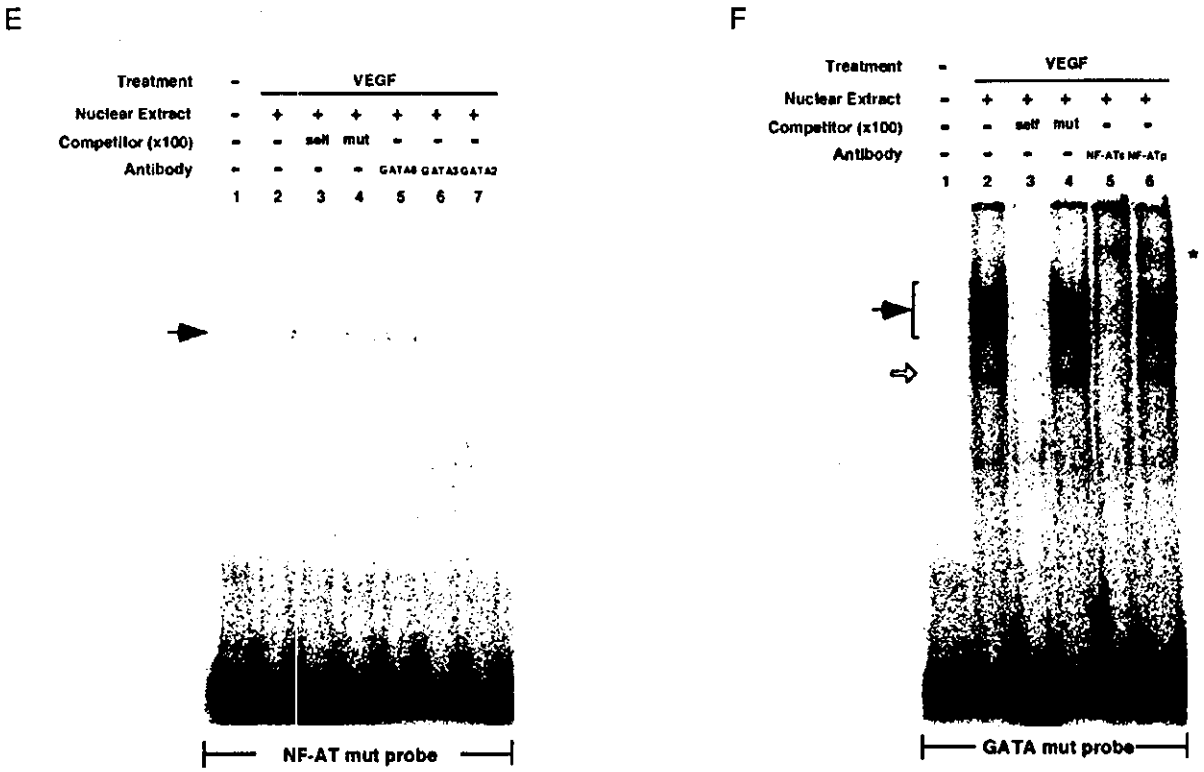


FIG. 5—*continued*

thelial cell activation is not an all-or-none response. Indeed, different extra-cellular mediators engage the endothelium in ways that differ from one signal to the next. A major focus is to study the temporal and spatial dynamics of endothelial cell phenotypes. Using DNA microarrays, we carried out a global survey of mRNA in HUVEC treated in the absence or presence of growth factor (VEGF), serine protease (thrombin), or cytokine (TNF-α). Clustering analyses of the data revealed a far closer relationship between VEGF and thrombin than between other pairings (Fig. 1*A* and supplemental Table I). Of the various transcripts that were responsive both to VEGF and thrombin, DSCR-1 was the most highly induced at the earliest time point. At 1 h, VEGF resulted in 22.3-fold induction of DSCR-1, while thrombin induced DSCR-1 by 17.7-fold (Fig. 1*B*). The effect of VEGF and thrombin was no longer detectable at 24 and 18 h, respectively. Compared with VEGF and thrombin, TNF-α treatment of HUVEC resulted in far less induction of DSCR-1 (3.2-fold at 1 h) (supplemental Table I and data not shown).

VEGF and Thrombin Selectively Induce the DSCR-1 Isoform Consisting of Exons 4–7 in Primary Human Endothelial Cells—The DSCR-1 gene includes seven exons and six introns. The first four exons are alternative and code for four different isoforms (23, 24). A 5′ promoter regulates expression of the first three isoforms, which are derived from alternative splicing. The most common of these contains exons 1, 5, 6, and 7. An intragenic region between exons 3 and 4 contains an alternative promoter which initiates transcription of the fourth isoform (exons 4, 5, 6, and 7) (Fig. 2*A*) (24). To determine which isoform(s) is up-regulated by VEGF and thrombin, we performed RNase protection assays using riboprobes that span either exons 4 and 5 or exons 1 and 5 (Fig. 2*B*). As shown in Fig. 2*C*, the addition of VEGF or thrombin to HUVEC resulted in marked up-regulation of the DSCR-1 isoform encoded by exons 4–7, with maximal levels occurring at 1 h. In contrast, there was no detectable induction of the DSCR-1 isoform encoded by exons 1, 5, 6 and 7 (Fig. 2*C*, *asterisk*). Consistent with the DNA microarray data, TNF-α resulted in comparatively low levels of DSCR-1 induction. To determine whether DSCR encoding exons 1, 5, 6, and 7 is expressed in endothelial cells and to further test its inducibility, RT-PCR assays were performed using isoform-specific primers and cDNA from control or VEGF-, thrombin-, or TNF-α-treated HUVEC. Transcripts were detected only after 40 cycles of amplification and were not affected by the addition of extracellular mediators at 1 or 4 h. By comparison, the isoform encoded by exons 4–7 was detected in thrombin- and VEGF-treated HUVEC after just 21 PCR cycles (Fig. 2*D*). Together, these results suggest VEGF and thrombin and to a far lesser extent TNF-α result in the rapid and selective induction of the DSCR-1 isoform containing exons 4–7.

VEGF and Thrombin Induce DSCR-1 Expression in Primary Human Endothelial Cells via Flk-1/KDR and PAR-1, Respectively—VEGF has two high affinity receptors, Flt-1 and Flk-1/KDR. To determine which receptor mediates VEGF stimulation of DSCR-1, HUVEC were treated with the selective Flt-1 agonist, PlGF, or with VEGF in the absence or presence of the Flk-1/KDR selective inhibitor, SU1498. The addition of 50–200 ng/ml PlGF failed to induce DSCR-1 mRNA (Fig. 3*A*, *lanes 2* and *3*). In contrast, VEGF-mediated induction of DSCR-1 was attenuated by pretreatment with 5 and 20 μM SU1498, by 74.2 and 84.4%, respectively (Fig. 3*A*, *lanes 4–6*). As an internal control for PlGF activity in HUVEC, agonist-treated endothelial cells were assayed for Flt-1 phosphorylation, using immunoprecipitation. As shown in Fig. 3*B*, the addition of 100 ng/ml PlGF resulted in tyrosine phosphorylation of Flt-1. Taken together, these data suggest that VEGF increases DSCR-1 mRNA in endothelial cells through a Flk-1/KDR-dependent mechanism.

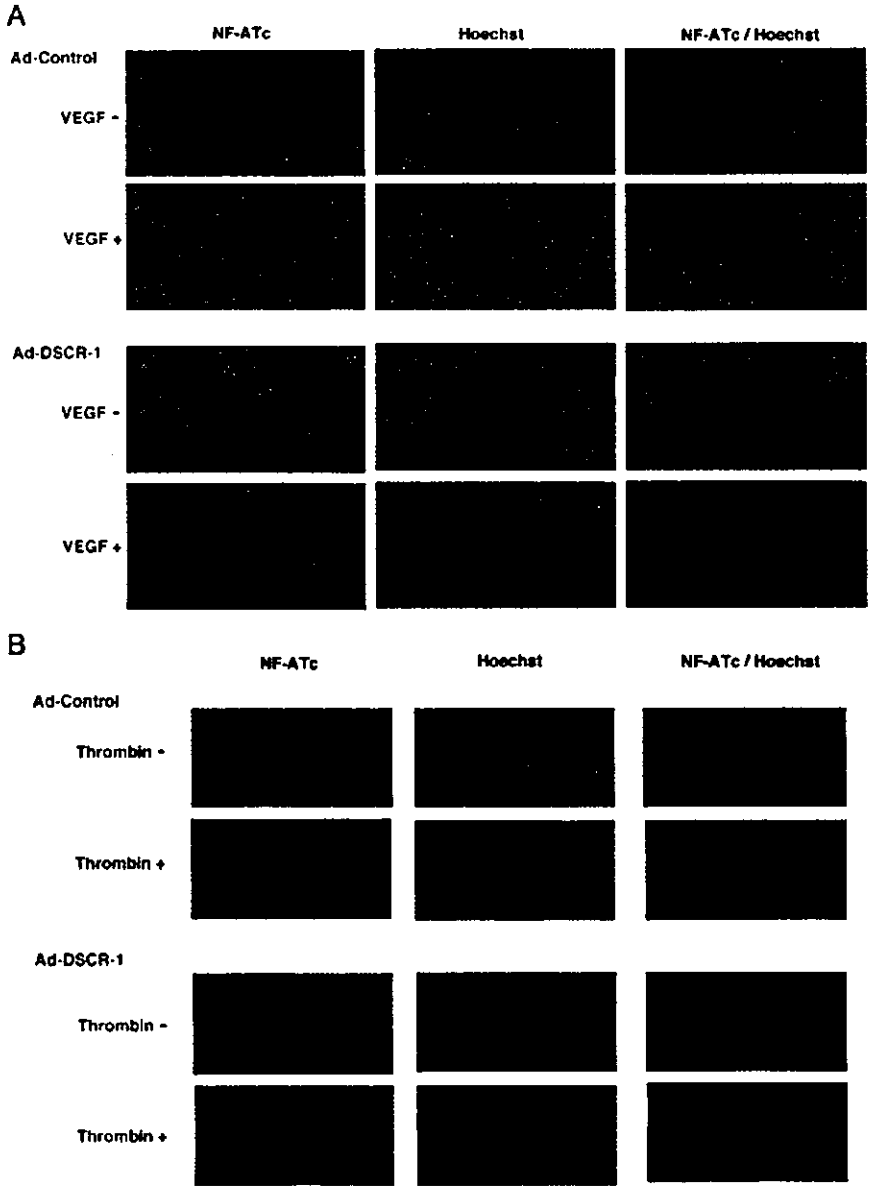


FIG. 6. **DSCR-1 attenuates tube formation and cell cycle progression of primary endothelial cells.** *A* and *B*, HUVEC were infected with either Ad-Control or Ad-DSCR-1 and then serum-starved for 18 h and incubated in the absence or presence of 50 ng/ml VEGF (*A*) or 1.5 units/ml thrombin (*B*) for 1 h. The nuclei were stained with Hoechst. *C*, capillary-like tube formation model. HUVEC were infected with either Ad-Control (*panels a–d*) or Ad-DSCR-1 (*panels e–h*), grown on the collagen gel in the presence (*panels b–d* and *f–h*) or absence (*panels a* and *d*) of VEGF. 48 h later, cells were observed under bright field (40-fold magnification (*panels a*, *b*, *e*, and *f*)) or under fluorescence (40-fold magnification (*panels c* and *g*) or 100-fold magnification (*panels d* and *h*)). The results are representative of three independent experiments. *D*, quantification of tube area. The means and S.D. values were calculated with NIH image from three independent experiments. *E*, FACS analysis of cell cycle in Ad-Control-, Ad-DSCR-1-, and Ad-DSCR-1 plus Ad-CA-NFAT-infected HUVEC, carried out as described under "Experimental Procedures." The results are representative of three independent experiments. *F*, FACS analysis of apoptosis and necrosis in Ad-Control- and Ad-DSCR-1-infected HUVEC: *panel a*, representative result showing M1 (G_1/G_0), M2 (G_2), M3 (S), and M4 (apoptosis and necrosis) fields; *panel b*, the percentage gated in each field.

Thrombin is known to signal through protease-activated receptors (PARs). PAR-1 is the most important thrombin receptor in endothelial cells. To demonstrate a potential role for PAR-1 in mediating the thrombin response, we employed RNase protection assays of HUVEC treated in the presence or absence of TRAP, a 14-amino acid PAR-1 agonist peptide. TRAP resulted in a dose-dependent increase in DSCR-1 mRNA levels. Moreover, thrombin-mediated induction of DSCR-1 was completely blocked by pretreatment with the thrombin-specific inhibitor, hirudin (Fig. 3, *C* and *D*). Taken together, these findings suggest that VEGF and thrombin mediate DSCR-1 induction in endothelial cells via Flk-1/KDR and PAR-1, respectively.

VEGF- and Thrombin-induced DSCR-1 mRNA and Promoter Activity in Primary Human Endothelial Cells via a Calcineurin-dependent Signaling Pathway—Previous studies in non-endothelial cells have demonstrated an important biological role for DSCR-1 as a regulator of calcium-calcineurin-NF-AT signaling (25–27). To determine whether VEGF- and

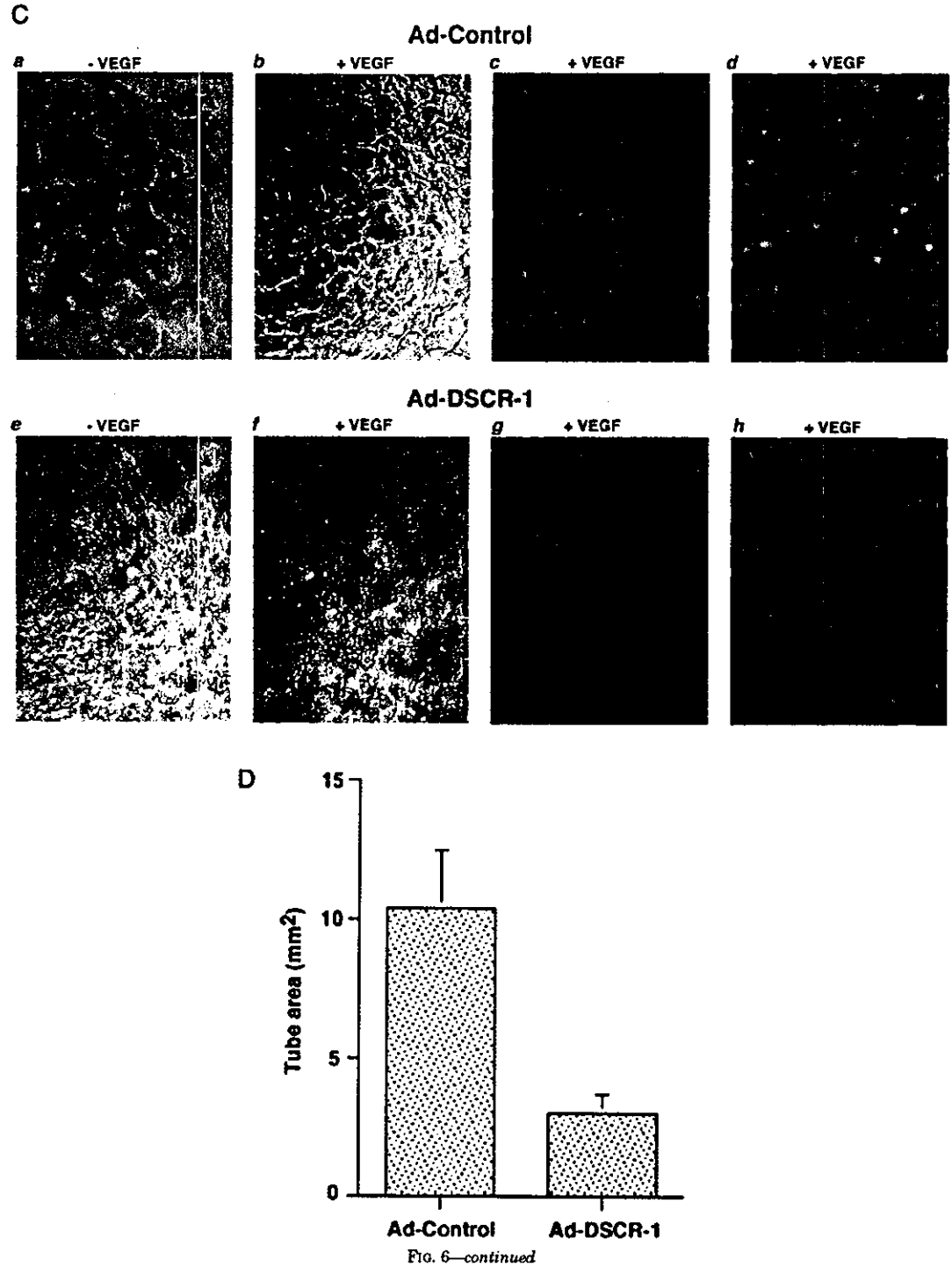


FIG. 6—*continued*

thrombin-mediated induction of DSCR-1 in endothelial cells is similarly dependent on calcineurin, we employed RNase protection assays with the calcineurin inhibitor, cyclosporine A (CsA). VEGF-mediated induction of DSCR-1 was inhibited 64.1% by 10 nM CsA and 93.3% by 1 μM CsA (Fig. 4*A*, *lanes 6–8*). Similarly, thrombin stimulation of DSCR-1 was inhibited by pretreatment with 10 nM and 1 μM CsA (by 72.6 and 93.1%, respectively) (Fig. 4*A*, *lanes 9–11*). Next, we wished to determine whether the DSCR-1 promoter contained information for transducing the VEGF/thrombin-calcineurin-dependent signal. To that end, the human DSCR-1 promoter (−1664 to +83) was isolated and coupled to the luciferase reporter gene (Fig. 4*B*). The resulting DSCR-1-luc plasmid was transiently transfected into HUVEC. As shown in Fig. 4*C*, VEGF and thrombin induced DSCR-1 promoter activity by 3.2- and 2.6-fold, respectively, whereas TNF-α had no such effect. VEGF- and throm-

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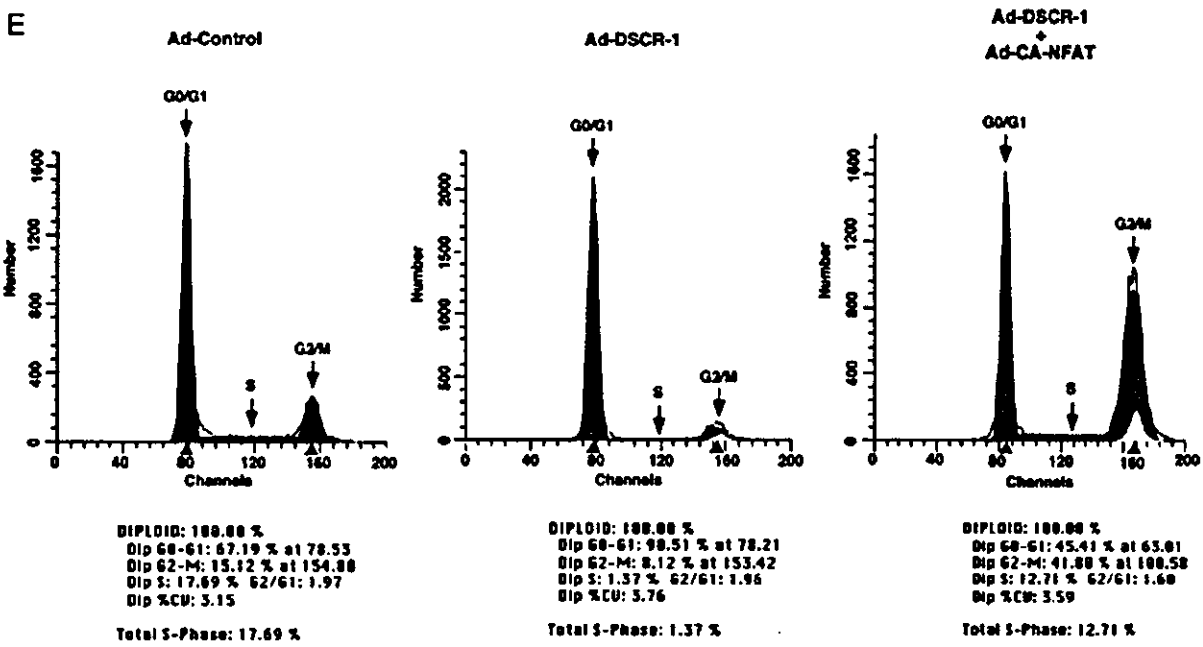

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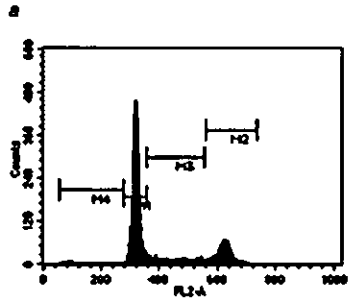

Ad-Control				Ad-DSCR-1			
1 st experiment		2 nd experiment		1 st experiment		2 nd experiment	
Marker	% Gated	Marker	% Gated	Marker	% Gated	Marker	% Gated
M1	75.80	M1	67.57	M1	90.20	M1	88.39
M2	11.90	M2	20.60	M2	7.49	M2	9.80
M3	10.83	M3	11.28	M3	0.81	M3	1.15
M4	0.91	M4	0.68	M4	1.50	M4	0.65

FIG. 6—*continued*

bin-mediated induction of the promoter was inhibited by 1 μM CsA (90.7 and 96.3%, respectively). Taken together, these results indicate that both VEGF-Flk-1/KDR and thrombin-PAR-1 signals induce DSCR-1 mRNA and promoter activity through a calcineurin-dependent pathway.

To delineate the promoter elements responsible for mediating the effects of VEGF and thrombin on DSCR-1 expression, a series of 5'-deletion constructs was generated and transiently transfected into HUVEC (Fig. 4*B*). Most notably, a deletion of the promoter region between −350/−166 resulted in a loss of response to VEGF and thrombin (Fig. 4*D*). The region contains neighboring consensus NF-AT and GATA motifs located at positions −220 and −254, respectively. To assess the role of each of these DNA elements in mediating VEGF and thrombin stimulation of DSCR-1, a point mutation of either the NF-AT or GATA motif was introduced and the resulting construct transfected into HUVEC. Each mutation profoundly blocked VEGF/thrombin-mediated the induction (Fig. 4, *E* and *F*). To test the capacity of NF-AT and GATA factors to transactivate the DSCR-1 promoter, we carried out co-transfections in HUVEC with DSCR-1-luc and NF-AT and/or GATA expression plasmids. As shown in Fig. 4*G*, co-transfection of constitutive active NF-AT resulted in marked transactivation of promoter activity (14.6-fold). Co-transfection of GATA-2 resulted in weak but significant induction of promoter activity (1.71-fold). Importantly, GATA-2 and NF-AT interacted synergistically to induce the promoter by 30.8-fold.

VEGF and Thrombin Promote Binding of NF-ATc, NF-ATp, GATA-2, and GATA-3 to the DSCR-1 Promoter—To study the effect of VEGF and thrombin on NF-AT and GATA DNA-protein interactions, we carried out EMSA using radiolabeled oligonucleotide probes that spanned one or both consensus motifs. In the first set of experiments, a radiolabeled wild-type probe, containing the closely aligned GATA and NF-AT binding sites (Fig. 5*A*), was incubated with nuclear extracts derived from HUVEC treated in the absence or presence of VEGF, thrombin, or TNF-α. In control untreated cells, EMSA revealed a specific DNA-protein complex (Fig. 5*B*, *arrow*). Importantly, the addition of VEGF or thrombin, but not TNF-α, resulted in marked increase the DNA binding activity, an effect that was abrogated by pretreatment of cells with 1 μM CsA (Fig. 5*B*, compare *lanes 4, 6, and 8* with *lanes 5, 7, and 9*). These DNA-protein complexes were inhibited by the addition of 100-fold molar excess of the unlabeled self-competitor, but not by the same concentration of the unlabeled NF-AT mutant competitor, or unlabeled GATA mutant competitor (supplemental Fig. 1).

To determine the identity of proteins in the VEGF- and

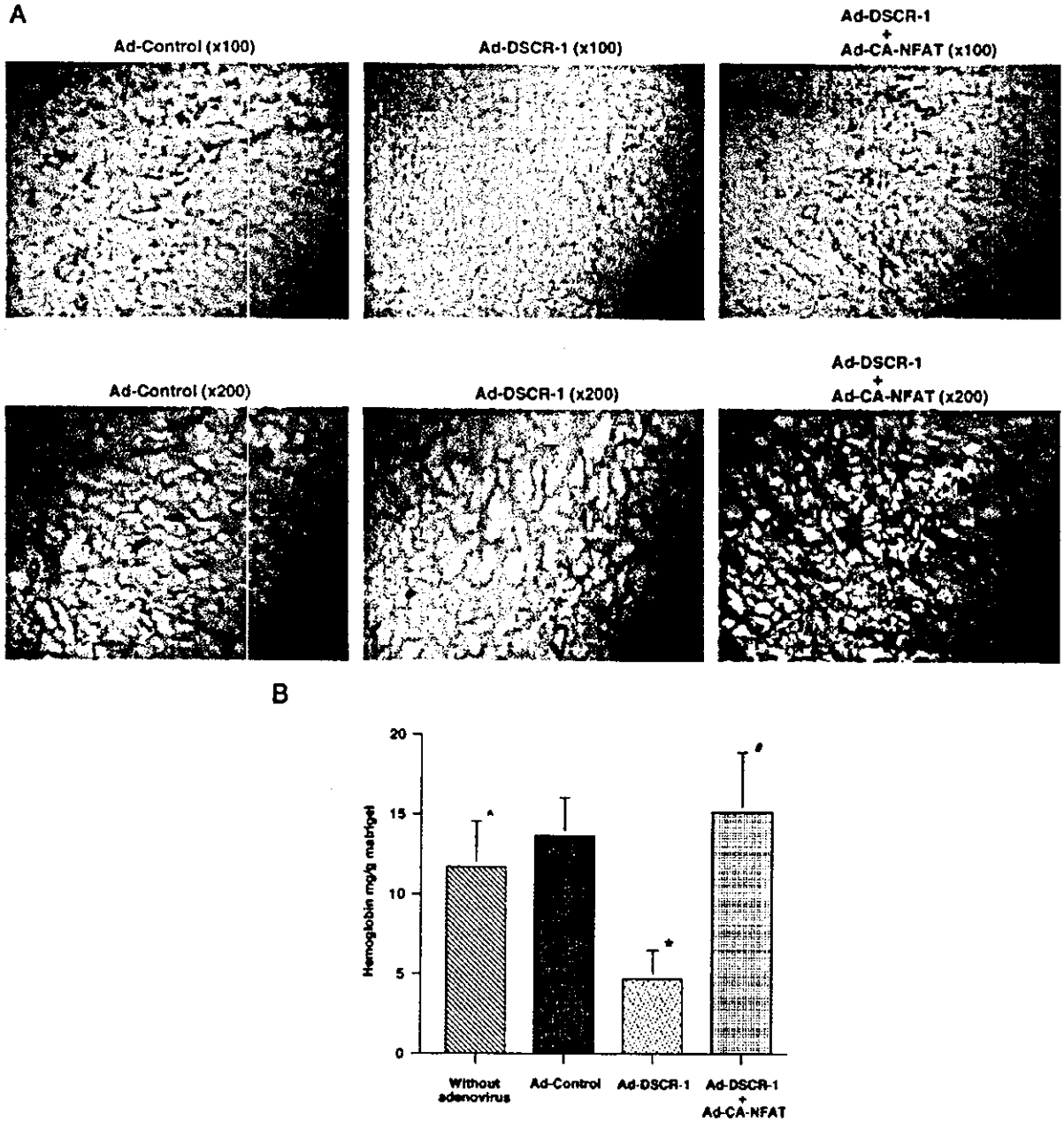

FIG. 7. **DSCR-1 attenuates matrix neo-vascularization and tumor-progression in mice.** *A*, matrigel containing 50 ng of VEGF and either 10^9 plaque-forming units of Ad-Control, Ad-DSCR-1, or Ad-DSCR-1 plus Ad-CA-NFAT was injected subcutaneously into C57BL6 mice. After 14 days, matrigel plugs were removed for analysis of new vessel formation by histological sections and hemoglobin assays. Optical magnifications were ×100 (*upper panels*) and ×200 (*lower panels*). The data are representative of seven independent experiments. *B*, hemoglobin in the matrigel plugs was measured using the Drabkin's reagents and normalized by the weight of matrigel. Data are expressed as means and S.D., $n = 5$. *, $p < 0.01$ compared with Ad-Control and Ad-DSCR-1. #, $p < 0.001$ compared with Ad-DSCR-1 and Ad-DSCR-1 and Ad-DSCR-1 plus Ad-CA-NFAT. [caret], $p > 0.5$ (not significant) compared with Ad-Control and uninfected control mice. *C*, DSCR-1 reduces B16-melanoma growth in mice. Tumor growth was reduced at 4 days (9.1-fold; $p < 0.04$), 6 days (7.7-fold; $p < 0.04$), and 8 days (7.4-fold; $p < 0.04$) by injection of Ad-DSCR-1. *D*, gross tumors representative of Ad-Control or Ad-DSCR-1 injected groups immediately after resection. *E*, tumor mass after 14 days following Ad-Control or Ad-DSCR-1 administrations. Data are expressed as means and S.D., $n = 5$. *, $p < 0.031$ compared with Ad-Control. *F*, representative sections of B16-melanoma at the edge (*panels a* and *c*) and center (*panels b* and *d*) of the tumor.

thrombin-inducible binding complex, the binding reactions were preincubated with anti-NF-ATc, anti-NF-ATp, anti-GATA-2, or anti-GATA-3 antibodies. The addition of an anti-NF-ATc antibody resulted in a strong supershift of the binding complex (Fig. 5, *C* and *D*, *lane 4*, *asterisks*), whereas anti-NF-ATp antibody resulted in a comparatively weak supershift (Fig. 5, *C* and *D*, *lane 5*). Preincubation with anti-GATA-2 or GATA-3 antibodies resulted in decreased intensity of DNA binding activity (Fig. 5*C*, *lane 6*, and *D*, *lanes 6* and *7*, *hatched rectangles*).

To more clearly assess GATA DNA-protein interactions, a radiolabeled probe containing the NF-AT mutant (Fig. 5*A*) was

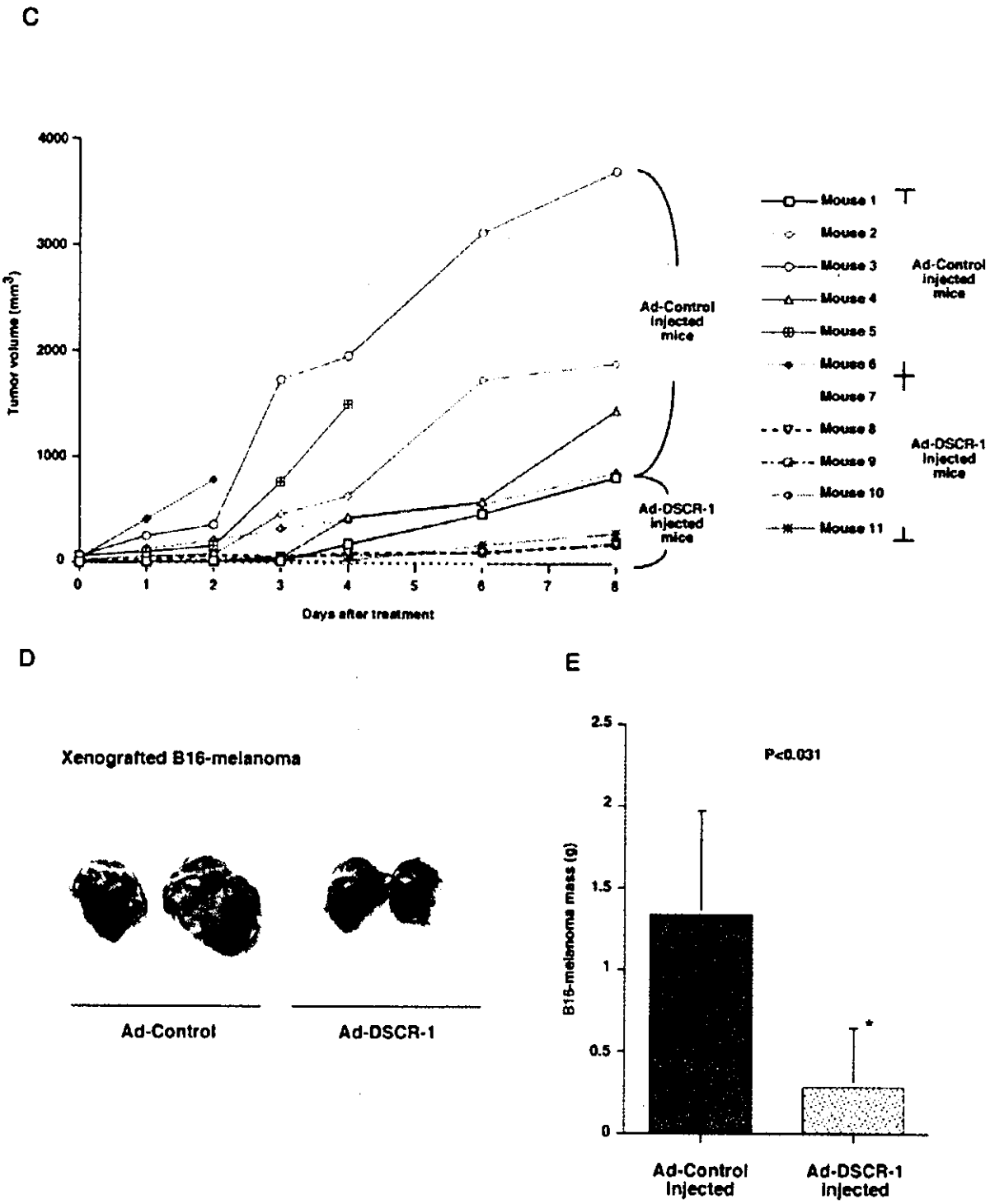

FIG. 7—*continued*

incubated with nuclear extracts derived from VEGF-treated HUVEC. These experiments resulted in specific DNA-protein complexes (Fig. 5*E*, *lane 2*, *arrow*), which were inhibited by the addition of 100-fold molar excess of unlabeled NF-AT mutant self-competitor but not inhibited by unlabeled GATA mutant competitor (Fig. 5*E*, *lanes 3* and *4*). Furthermore, the complexes were inhibited by preincubation with anti-GATA-2 or -3 antibodies but not by anti-GATA-6 antibody (Fig. 5*E*, *lanes 5–7*). To further study NF-AT binding, a radiolabeled probe containing the GATA mutant (Fig. 5*A*) was incubated with nuclear extracts derived from VEGF-treated HUVEC. The mixture resulted in a specific DNA-protein complex, which was

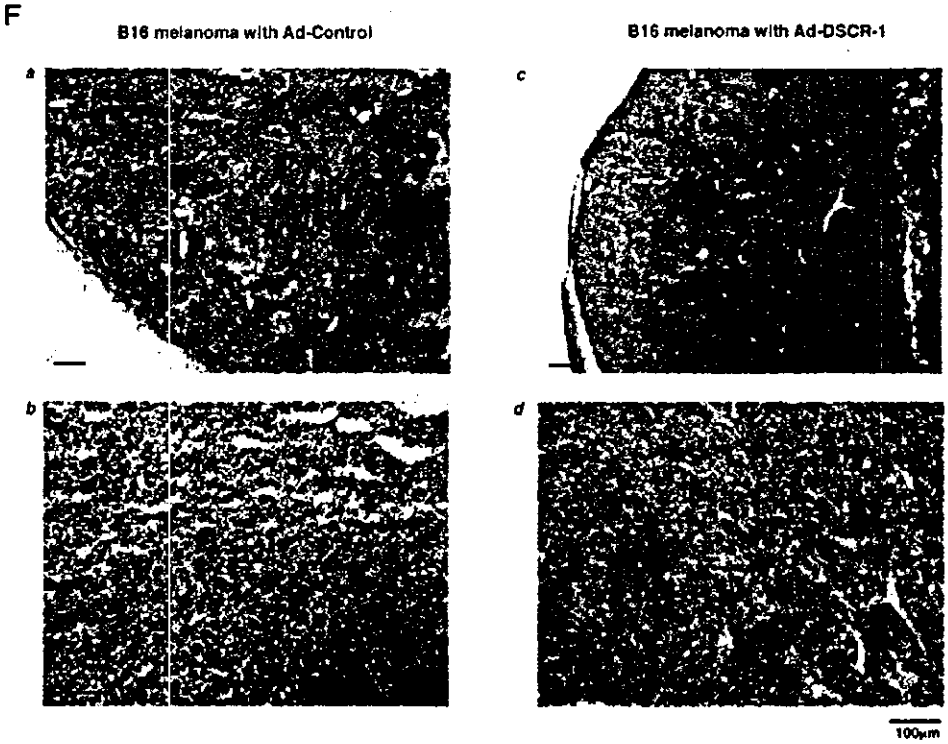

FIG. 7—*continued*

inhibited by the addition of 100-fold molar excess of unlabeled GATA mutant self-competitor but not a NF-AT mutant competitor. The DNA-protein complex was strongly supershifted by anti-NF-ATc antibody and only weakly supershifted by NF-ATp antibody (Fig. 5*F*, *lanes 3–6*). Similar results were obtained with nuclear extracts derived from thrombin-treated HUVEC (data not shown). The faster migrating DNA-protein complex includes NF-ATc, as it was specifically supershifted by anti-NF-ATc antibody (Fig. 5, *C*, *D*, and *F*, open arrows). Together with the transfection assays, the mobility shift results suggest that VEGF and thrombin induce DSCR-1 expression through the coordinate binding of NF-ATc and GATA-2/3 to closely positioned NF-AT and GATA motifs in the intragenic promoter.

DSCR-1 Inhibits Nuclear Localization of NF-ATc and Tube Formation in Primary Human Endothelial Cells—We next wished to determine the functional relevance of VEGF- and thrombin-mediated DSCR-1 induction. To that end, we infected HUVEC with IRES-containing adenoviruses expressing both DSCR-1 and EGFP (Ad-DSCR-1) or EGFP alone (Ad-Control). Adenovirus-mediated overexpression of DSCR-1, but not control EGFP, inhibited VEGF- and thrombin-mediated nuclear localization of NF-ATc at 1 h, 94.2 and 92.8%, respectively. (Fig. 6, *A* and *B*). In collagen gel assays of HUVEC, VEGF induced the formation of capillary or tube-like structures (compare Fig. 6*C*, *a* and *b*). Compared with Ad-Control, Ad-DSCR-1 infection resulted in marked reduction of tube formation (29.2% of basal level) under the same infection rate and EGFP expression levels (Fig. 6*C*, *panels b–h*, and *D*). Together with the transient transfection and EMSA results, the above findings suggest that VEGF and thrombin each induce the nuclear localization of NF-ATc, cooperative binding of NF-ATc and GATA-2/3 to the DSCR-1 promoter, secondary induction of DSCR-1 mRNA expression, and subsequent attenuation of NF-AT signaling and blood vessel growth.

DSCR-1 Attenuates Cell Proliferation of Primary Human Endothelial Cells—Angiogenesis involves a complex interplay of myriad cellular functions, including endothelial cell migration and proliferation. To evaluate the effect of DSCR-1 on cell proliferation, we performed FACS analysis with subconfluent HUVEC infected with either Ad-Control, Ad-DSCR-1, or Ad-DSCR-1 plus Ad-CA-NFAT. FACS analysis of Ad-Control-infected HUVEC (at 90% confluence) revealed 67.2, 17.7, and 15.1% in G_0/G_1, S, and G_2/M phases, respectively. Ad-mediated overexpression of DSCR-1 increased the percentage of cells in G_0/G_1 phase and decreased the fraction in S phase, an effect that was reversed by co-infection with Ad-CA-NFAT (Fig. 6*E*). Similar findings were obtained with HUVEC at 50% confluence (data not shown). Compared with Ad-Control, Ad-DSCR-1 did not result in increased apoptosis (Fig. 6*F*), arguing against a toxic effect of DSCR-1 overexpression. Taken together, these findings suggest that the constitutive DSCR-1 expression in endothelial cells induces G_0/G_1 arrest.

DSCR-1 Blocks Matrix Neo-vascularization and Tumor Progression in Mice—Having established an inhibitory role for DSCR-1 on cell cycle arrest and angiogenesis *in vitro*, we wished to evaluate the functional relevance of these findings *in vivo*. To that end, we investigated the effects of DSCR-1 overexpression on new blood vessel formation in a matrigel plug assay. In these experiments, matrigel containing either Ad-Control, Ad-DSCR-1, or Ad-DSCR-1 plus Ad-CA-NFAT was implanted as subcutaneous plugs into C57BL/6 mice. Fourteen days after implantation, cross-sections from control matrigel plugs demonstrated significant blood vessel formation (Fig. 7*A*, *left*). In contrast, overexpression of DSCR-1 in the matrigel markedly reduced plug vascularity (Fig. 7*A*, *middle*). Importantly, the inhibitory effect of DSCR-1 was rescued by co-infection with adenovirus expressing constitutive active NF-AT (Fig. 7*A*, *right*). To quantify the extent of neo-angiogenesis, we

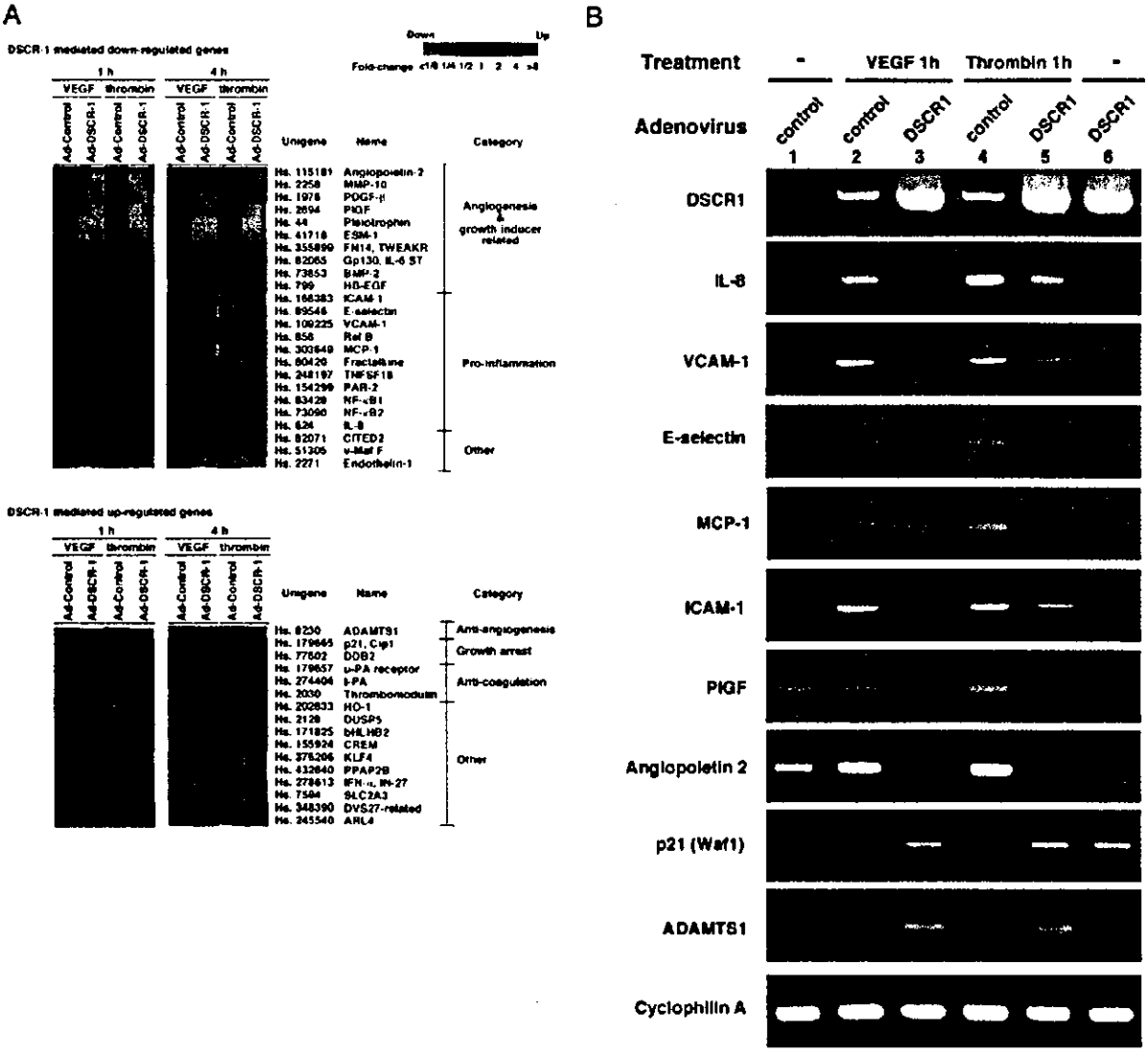

FIG. 8. **DSCR-1 attenuates VEGF- and thrombin-mediated induction of pro-angiogenesis and pro-inflammatory genes in primary endothelial cells.** *A*, DNA microarray studies demonstrating the effect of DSCR-1 overexpression on VEGF and thrombin-responsive genes in HUVEC. *B*, RT-PCR was performed with either Ad-Control (*lanes 1, 2,* and *4*)- or Ad-DSCR-1 (*lanes 3, 5,* and *6*)-infected HUVEC treated in the absence (−) (*lanes 1* and *6*) or presence of VEGF (*lanes 2* and *3*) or thrombin (*lanes 4* and *5*). Cyclophilin A indicates the internal control. The results are representative of at least two separate experiments.

measured hemoglobin content in the matrigel plugs. Matrigel that contained no virus or Ad-Control demonstrated comparable levels of angiogenesis. However, Ad-DSCR-1 resulted in a significant (67%) reduction of the hemoglobin content. This effect was reversed by co-expression of constitutively active NF-AT (Fig. 7*B*).

To evaluate whether DSCR-1 has anti-tumor activity, mice were injected subcutaneously with B16-melanoma cells. When tumor size reached 50 mm^3 in volune, the xenografts were injected with Ad-DSCR-1 or Ad-Control. Tumor mass was measured on each subsequent day (Fig. 7*C*). Compared with control, Ad-DSCR-1 treatment resulted in statistically significant reduction in blood vessel density and tumor size (Fig. 7, *D–F*). There was no difference in body weight between the groups (data not shown). Collectively, these findings suggest that DSCR-1, a negative feedback regulator of NF-AT signaling, acts as an inhibitor of angiogenesis.

DSCR-1 Overexpression in Primary Endothelial Cells Results in Down-regulation of Multiple Pro-angiogenic and Pro-inflammatory Genes—Finally, to gain insight into the broader role for DSCR-1 in auto-inhibition of VEGF and thrombin signaling, HUVEC were infected with Ad-Control or Ad-DSCR-1, treated in the absence or presence of VEGF or thrombin, and then processed for DNA microarray analyses. From the duplicate arrays, a total of 24 genes (from a total of 8974 genes) were induced by VEGF or thrombin and strongly reduced in the presence of DSCR-1 (Fig. 8*A*). Notably, 10 genes in this group are associated with cell proliferation and angiogenesis and 11 with inflammation. Interestingly, when the filter was changed to the DSCR-1-mediated up-regulated genes, a total of 16 genes emerged, including the cell cycle inhibitor, p21, anti-angiogenesis factor, ADAMTS1 (28), and anti-coagulation factors t-PA, u-PAR, and thrombomodulin (Fig. 8*A* and supplemental Table II). These results, many of which have been validated in RT-

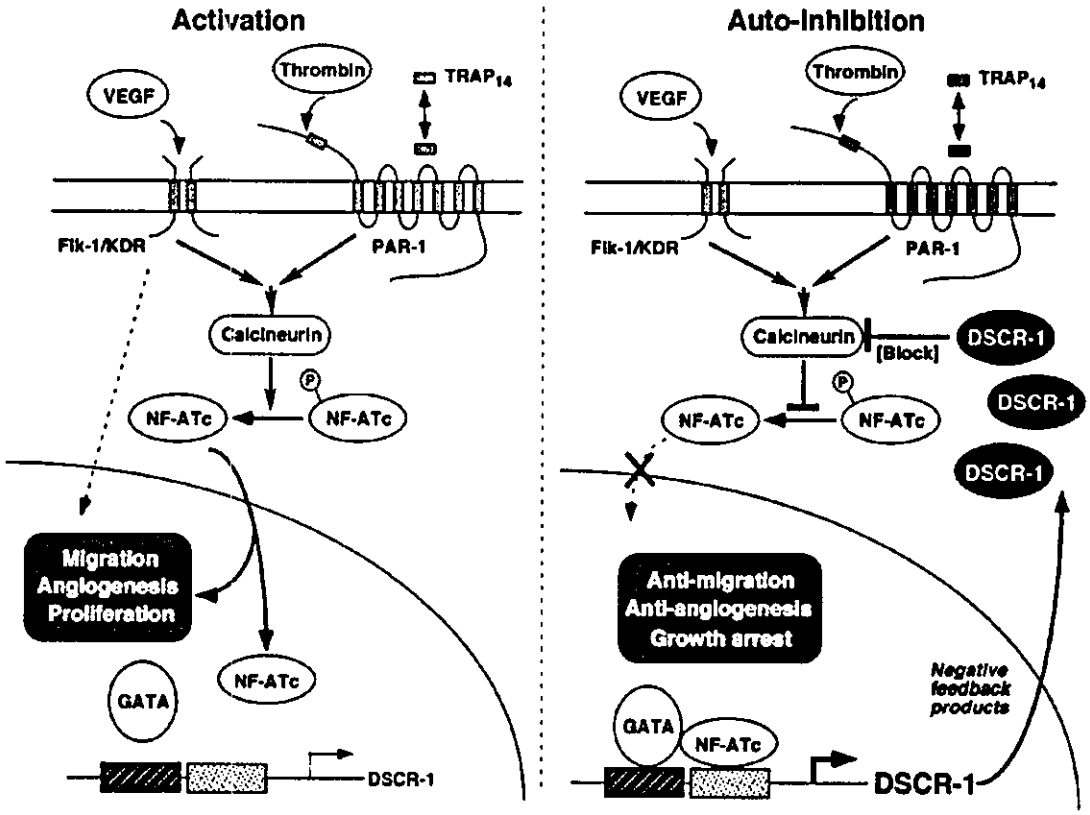

FIG. 9. **Model.** Schematic shows the VEGF or thrombin-calcineurin-NF-ATc signaling and the DSCR-1-mediated auto-inhibition system in endothelium.

PCR (Fig. 8*B*), suggest that DSCR-1 works as a key negative feedback regulator responding not only with VEGF- and thrombin-mediated angiogenesis and cell proliferation but also with inflammation and hemostatic balance.

DISCUSSION

The activation of endothelial cells by extracellular stimuli is a key mechanism underlying the development of many vascular diseases. In the present study, we have employed DNA microarrays to analyze the global gene expression profile of activated primary human endothelial cells and show that VEGF and thrombin, but not TNF-α, resulted in the rapid and pronounced induction of DSCR-1. Activated DSCR-1, in turn, profoundly attenuated calcineurin-dependent NF-AT signaling (see below). Thus, we hypothesize that DSCR-1 functions as a circuit breaker, ensuring balanced regulation of endothelial cell proliferation, migration, and angiogenesis (Fig. 9).

The VEGF and thrombin signals are transduced through calcineurin-dependent nuclear translocation of NF-AT. The NF-AT family of transcription factors includes four structurally related members, NF-ATp, NF-ATc, NF-AT3, and NF-AT4. NF-ATp and NF-ATc have been detected in endothelial cells (29–31). Previous studies in non-endothelial cells have shown that NF-AT cooperates with other transcription factors, including AP1 (32), GATA (33, 34), cMAF (35), or MEF2 (36), to enhance target gene expression. Among the functional sequelae of calcineurin-NF-AT signaling is immune response, cardiac and skeletal and vascular smooth muscle proliferation and/or hypertrophy (37), cardiac valve development (30, 38), differentiation of adipocytes and skeletal muscle (39, 40), synaptic plasticity, and cellular apoptosis. Here, we show that VEGF and thrombin induce the nuclear translocation of NF-ATc in HUVEC and that NF-ATc cooperates synergistically with GATA-2/3 to transactivate the DSCR-1 promoter. These data are consistent with our previous studies demonstrating an important role for the GATA family of transcription factors as signal transducers in the endothelium (20).

While previous investigations have established the importance of PI3K and MAPK signaling pathways in mediating endothelial cell survival, proliferation, and angiogenesis, comparatively little is known about the functional role for calcium-calcineurin signaling in these biological processes. Activated GSK-3β has been shown to promote the cytosol translocation of NF-AT (41, 42) and to negatively regulate endothelial cell proliferation and angiogenesis (43). Together with our results, these data support the notion that both calcineurin and PI3K-AKT-dependent inactivation of GSK-3β contribute to nuclear retention of NF-AT and secondary endothelial cell migration, growth, and angiogenesis.

Our data suggest that DSCR functions as an endogenous anti-angiogenic factor. In addition to its effect on nuclear localization of NF-ATc and tube formation in primary endothelial cells, DSCR-1 inhibited endothelial cell migration and promoted G_0/G_1 cell cycle arrest. Most importantly, DSCR-1 blocked matrix neo-vascularization and tumor progression in mice. Moreover, in repeated microarray studies, overexpression of DSCR-1 resulted in down-regulation of pro-angiogenic factors such as PlGF, angiopoietin-2, BMP-2, and PDGF-B and up-regulation of the growth-arrest factors p21 and anti-angiogenic factor ADAMTS1 (28). It will be interesting to determine whether DSCR-1 expression is modulated in tumor endothe-