\[ \beta \text{-Catenin Inversely Regulates Vascular Endothelial Growth Factor-D mRNA Stability}^{*} \]

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The angiogenic and lymphangiogenic vascular endothelial growth factor (VEGF)-D is the only member of the VEGF family that is not induced by hypoxia or by serum factors, but its induction is mediated by direct cell-cell contact. Here we show that VEGF-D mRNA is down-modulated either by \( \beta \text{-catenin} \) mobilization from the cell membrane, by activation of the Wnt signaling pathway, or by transfection with the \( \beta \text{-catenin} \) stable mutant. Down-modulation of \( \beta \text{-catenin} \) by means of RNA interference showed an increase of VEGF-D mRNA steady state in fibroblasts. The \( \beta \text{-catenin} \)-dependent decrease of VEGF-D mRNA is indirect and mainly due to reduced VEGF-D mRNA stability, as demonstrated by experiments of mRNA decay in the presence of transcription or translation inhibitors. By transient transfection of chimeric constructs carrying fusion of VEGF-D sequences under the control of the cytomegalovirus early promoter, we demonstrated that \( \beta \text{-catenin} \) negative regulation is on the VEGF-D mRNA 3′-untranslated region. We mapped the VEGF-D mRNA destabilizing element to a sequence, conserved between mouse and human VEGF-D, which contains an AU-rich element of group I. These results unveiled a new regulatory pathway for VEGF-D, which explains, at least in part, VEGF-D regulation in tumor progression.

During development and in the vascularization of tumors, the newly forming tissues produce inductive signaling that leads to the formation of capillaries throughout. In particular, progression of tumor malignancy is characterized by the acquisition by tumor cells of angiogenic and lymphangiogenic ability (1, 2). This is obtained by the expression of secreted angiogenic factors, which induce endothelial cell differentiation (3–5). The VEGF\(^{1} \) family of angiogenic factors includes VEGF-A, the placental growth factor; VEGF-B, VEGF-C, VEGF-D, and VEGF-E (6–16). VEGF-A is a potent angiogenic factor able to induce vessel sprouting. It recognizes the receptors VEGFR-1 and VEGFR-2 on endothelial cells. It is strongly expressed in tumors as it is induced by hypoxia with induced transcription and increasing mRNA stability (17–19). VEGF-A is also up-regulated by epidermal growth factor, transforming growth factor-\( \beta \), and interleukin-6 in several cell types and by interleukin-1\( \beta \) in smooth muscle cells (20–22).

VEGF-D, like VEGF-C, shows some structural and functional differences from VEGF-A (14, 23–26). They bind and activate VEGFR-2 and VEGFR-3. This latter is a tyrosine kinase receptor specifically found in adult lymphatic endothelium. In cell culture, VEGF-C is induced by serum, phorbol 12-myristate 13-acetate, and several factors including interleukin-1\( \beta \) and tumor necrosis factor-\( \alpha \) (27, 28). In contrast, VEGF-D is highly expressed in fibroblasts grown under low serum conditions and is induced by direct cell-cell contact mediated by the surface molecule cadherin-11 (14, 29).

VEGF-D was brought to attention with respect to tumor development, as in mice models tumors expressing this factor showed development of intra-tumor lymphatic vessels and dissemination of tumor cells in lymph nodes (2, 30). Importantly, recent data show (31–35) that in several tumors the expression of VEGF-D is associated with lymph node metastasis and may be used as a novel prognostic factor in cancer development. However, some authors (Refs. 36 and 37 and our results on lung tumors)\(^{2} \) reported that VEGF-D was underexpressed in tumors when compared with normal tissues.

To understand VEGF-D regulation by cell-cell contact, we analyzed VEGF-D mRNA levels by altering cytoplasmic \( \beta \text{-catenin} \) expression in fibroblasts. \( \beta \text{-Catenin} \) is present in the cell in two fractions, a membrane-associated fraction linked to cadherins with a structural function, and an unstable cytoplasmic fraction that acts as a transcriptional regulator (38, 39). Our data indicate that cytoplasmic \( \beta \text{-catenin} \) down-modulates VEGF-D inducing the degradation of VEGF-D mRNA. This regulation requires new protein synthesis suggesting an indirect regulation. These results might explain VEGF-D regulation in tumors.

EXPERIMENTAL PROCEDURES

Cloning and Plasmid Constructs—To obtain the luciferase reporter gene under the control of the CMV early promoter (FG470), a 578-bp Bgl\(^{II} \) blunt-ended/Hind\(^{III} \) fragment that contains the CMV early promoter was cut from the pcDNA3 vector (Invitrogen) and subcloned into the Sac\(^{I} \) blunt-ended/Hind\(^{III} \) sites of the pGL3-Basic vector (Promega).

To generate the entire mouse VEGF-D 3′-UTR (nucleotides 1360–1875), the nucleotide sequence of mouse VEGF-D is numbered according to the sequence with GenBank\(^{TM} \) accession number NM010216 and the deletion mutants of this region (nt 1360–1612, nt 1616–1875, and nt 1757–1875) fused to the luciferase reporter gene, or to generate the entire human VEGF-D 3′-UTR (nt 1575–2110; GenBank\(^{TM} \) accession number NM004469) and the deletion mutant of this region (nt 1989–2110) fused to the luciferase reporter gene, DNA fragments were PCR-

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\(^{2} \) M. Rocchigiani and S. Oliviero, unpublished results.
amplified from a cDNA clone corresponding to the complete sequence of the mouse (14) or the human (26) VEGF-D gene. The following pairs of primers containing an XbaI restriction site in the sense primer and a BamHI restriction site in the antisense primer were used: H192, 5′-GAGATCTAGATTCACCTTCTTTCCATGTC-3′ (1860–1875); H192 and H403, 5′-GAGATGACTAGTGTATGACTAGCCATGCTATTCA-TTCC-3′ and H193, 5′-GAGATCTAGATTTAAGTTATAGAATATGGGTTTTTG-3′. The reporter plasmids pTOPCAT and pFOPCAT/H9252 region of mouse axin, which prevents transcription or cycloheximide (10 mM HEPES, pH 7.4, and 2 mM EDTA) containing Complete protease inhibitor cocktail. RNA samples were size-fractionated in a denaturing formaldehyde-agarose gel and stained with ethidium bromide to verify that each lane contained similar amounts of total RNA before hybridization. Protein samples were separated by SDS-PAGE and transferred to a nitrocellulose membrane. Equal loading was confirmed by staining in Ponceau S solution. The blots were washed and incubated with horseradish peroxidase-labeled sheep anti-mouse (Amersham Biosciences) or horseradish peroxidase-conjugated goat anti-rat (Chemicon International) at 1 h at room temperature, washed, and finally developed by using the enhanced chemiluminescence substrate (Amersham Biosciences).

Immunofluorescent Microscopy—Mouse fibroblasts were grown on glass coverslips and after treatment fixed with 3% paraformaldehyde in PBS for 15 min at room temperature. For permeabilization, cells were incubated with 0.5% Triton X-100 in PBS for 5 min at 4 °C. Cells were washed twice in PBS, blocked with 1% bovine serum albumin in PBS for 1 h at room temperature, and incubated for 1 h at 37 °C with primary antibodies, diluted in 1% bovine serum albumin/PBS (15 μg/ml for β-catenin and 15 μg/ml for anti-HA Abs). After washing, cells were incubated for 1 h at 37 °C in the presence of Alexa Fluor-568 goat anti-mouse or Alexa Fluor-488 goat anti-rat secondary antibodies (Molecular Probes). To localize actin filaments, fluorescein isothiocyanate-labeled phallolidin (Sigma) was added along with secondary antibodies at 2 μg/ml. Coverslips were counterstained with 0.1 μM 4′,6-diamidino-2-phenylindole dihydrochloride (DAPI; Sigma) and mounted in Mowiol 4-88 (Calbiochem). Fluorescent images were captured using a Nikon DXM1200 digital camera from a Nikon Eclipse E600 microscope.

RNA Interference—siRNA duplexes were synthesized by Dharmacon Research Inc. (Lafayette, CO). The sequence of the 5′-β-catenin oligonucleotides was 5′-GUAGCUCCAGUGGCGCTTGT-GC-3′ and 5′-GCCGUCAAUAGCAGCUA TT-3′. Cells were transfected twice, 48 h apart, with the siRNA duplex by using OligofectAMINE reagent (Invitrogen) according to the manufacturer’s directions. As a negative control the single-stranded siRNA was used. 96 h after the first transfection cells were analyzed for Northern blot, immunoblotting, and immunofluorescent microscopy.

Reporter Assays—In chloramphenicol acetyltransferase (CAT) assays, mouse 3T3-type and BALB/c 3T3 fibroblasts were seeded in 6-well dishes and transiently transfected. Typically a transfection experiment included 0.4 μg of reporter plasmid (TOPCAT or FOPCAT) and 0.1 μg of pBSV-β-galactosidase plasmid for the transfection efficiency control. The transfection mix was added to the reporter plasmids were used for the transfection. Efficiency control, the expression vector was used. As a control the polyadenylation signal of SV40 was used. 0.05 mM 5-bromo-4-chloro-3-indolyl-2-phenylindole dihydrochloride (DAPI; Sigma) and mounted in Mowiol 4-88 (Calbiochem). Fluorescent images were captured using a Nikon DXM1200 digital camera from a Nikon Eclipse E600 microscope.

In luciferase assay, mouse 3T3-type fibroblasts and HEK 293 cells were seeded in 6-well dishes and transiently transfected with 0.1 μg of the reporter plasmid containing the luciferase gene under the control of the CMV early promoter either fused to the full-length VEGF-D 3′-UTR or to its deletion mutants. As control the polyadenylation signal of SV40 was used. 0.05 μg of pBSV-β-galactosidase plasmid were used for the transfection efficiency control, and the expression vector was co-transfected as indicated in Figs. 6 and 7, maintaining constant at 2 μg by the addition of empty vectors. CAT activity was determined as described previously (46). Acetylated forms of chloramphenicol were quantified by using the ImageQuant radio analytic system from Amersham Biosciences.

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Statistical Analysis—All results are presented as means ± S.D. of at least three independent experiments. Statistical analysis was performed by using Student’s t test, and a value of p < 0.05 was considered to be significant.

RESULTS

The Presence of Cellular Free β-Catenin Correlates with VEGF-D mRNA Down-regulation—VEGF-D expression is not induced by growth factors which is different from the other members of the VEGF family. We demonstrated previously in mouse fibroblasts that VEGF-D mRNA is induced by cell-cell contact mediated by cadherin-11, a calcium-dependent adhesive protein (29). Depletion of calcium from the culture medium induced caherin-11 re-localization from the cell surface to the cytoplasm and VEGF-D mRNA degradation. In contacting cells the majority of β-catenin is localized at cell-cell contacts where it links the cytoplasmic tail of cadherins to the cytoskeleton. In epithelial cells a direct consequence of cadherin disassembly is

monoclonal Abs specific for Myc tag (0.2 μg/ml; Santa Cruz Biotechnol-
ogy), and mouse monoclonal anti-FLAG (5 μg/ml; Sigma). The blots were washed and incubated with horseradish peroxidase-labeled sheep anti-mouse (Amersham Biosciences) or horseradish peroxidase-conju-
gated goat anti-rat (Chemicon International) for 1 h at room temperature, washed, and finally developed by using the enhanced chemilumi-
nescence substrate (Amersham Biosciences).

Cell Culture and Transfections—Mouse 3T3-type fibroblasts, murine BALB/c 3T3, and human embryonic kidney (HEK) 293 cells were main-
tained in modified Eagle’s medium (Invitrogen), 100 units/ml penicillin, and 100 μg/ml streptomycin at 37 °C in a humidified 5% CO2 atmosphere.

Stable clones expressing murine Wnt-1 were obtained from BALB/c 3T3 fibroblasts transfected with the Wnt-1 expression vector PLNC- NHα by standard CaPO4 precipitation procedures (29). Selection was performed by culturing for 2 weeks in the presence of 1 mg/ml G418 (Invitrogen).

Transient transfection experiments were performed by using Poly-
Fect transfection reagent (Qiagen) according to instructions from the manufacturer.

The efficiency of the mRNAs was studied in mouse 3T3-type fibro-
blasts. The cells were grown in complete medium until they reached confluence, and then actinomycin D (5 μg/ml; Sigma) as an inhibitor of transcription or cycloheximide (10 μg/ml; Sigma) as an inhibitor of protein synthesis, with or without EGTA (2.2 mM), was added to the cell cultures for 2, 4, and 6 h.

In luciferase assay, mouse 3T3-type fibroblasts and HEK 293 cells were seeded in 6-well dishes and transiently transfected with 0.1 μg of the reporter plasmid containing the luciferase gene under the control of the CMV early promoter either fused to the full-length VEGF-D 3′-UTR or to its deletion mutants. As control the polyadenylation signal of SV40 was used. 0.05 μg of pBSV-β-galactosidase plasmid were used for the transfection efficiency control, and the expression vector was co-transfected as indicated in Figs. 6 and 7, maintaining constant at 2 μg by the addition of empty vectors. CAT activity was determined as described previously (46). Acetylated forms of chloramphenicol were quantified by using the ImageQuant radio analytic system from Amersham Biosciences.

The presence of cellular free β-catenin correlates with VEGF-D mRNA down-regulation—VEGF-D expression is not induced by growth factors which is different from the other members of the VEGF family. We demonstrated previously in mouse fibroblasts that VEGF-D mRNA is induced by cell-cell contact mediated by cadherin-11, a calcium-dependent adhesive protein (29). Depletion of calcium from the culture medium induced caherin-11 re-localization from the cell surface to the cytoplasm and VEGF-D mRNA degradation. In contacting cells the majority of β-catenin is localized at cell-cell contacts where it links the cytoplasmic tail of cadherins to the cytoskeleton. In epithelial cells a direct consequence of cadherin disassembly is

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Immunofluorescent Microscopy—Mouse fibroblasts were grown on glass coverslips and after treatment fixed with 3% paraformaldehyde in PBS for 15 min at room temperature. For permeabilization, cells were incubated with 0.5% Triton X-100 in PBS for 5 min at 4 °C. Cells were washed twice in PBS, blocked with 1% bovine serum albumin in PBS for 1 h at room temperature, and incubated for 1 h at 37 °C with primary antibodies, diluted in 1% bovine serum albumin/PBS (15 μg/ml for β-catenin and 15 μg/ml for anti-HA Abs). After washing, cells were incu-
The release of free β-catenin within the cytoplasm (47). We examined the fate of β-catenin in contacting mouse fibroblasts treated with EGTA by using anti-β-catenin antibodies (Fig. 1A). In untreated cells, a positive staining was revealed at intercellular contacts. In contrast, within 1 h after cell treatment with EGTA, the β-catenin signal disappeared from the cell surface and re-localized to the cytoplasm. The reintroduction of Ca²⁺ into the culture medium restored β-catenin staining at intercellular contacts. After 2 h from Ca²⁺ addition, the β-catenin signal was detectable both in the cytoplasm and at the cell-cell contact surfaces, while after 20 h it was mostly present at the intercellular junctions similarly to untreated cells.

The presence of transcriptional active nuclear β-catenin could be demonstrated by transient transfection of a reporter gene containing multimeric responsive TCF-binding sites (TOPCAT) with respect to its control plasmid containing mutated TCF-binding sites (FOPCAT). A significant response to β-catenin-TCF complex was measured by the TOPCAT construct in fibroblasts grown for 4 h in the presence of EGTA (Fig. 1C). The same EGTA treatment showed reduction of
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**Fig. 3.** β-Catenin is responsible for the decrease of VEGF-D mRNA levels. A, mouse fibroblasts were transiently transfected with wild-type or mutant β-catenin. Cells were seeded 5 × 10^5 per 10-cm Petri dish and transfected with 4 μg of wild-type β-catenin (β-myc), mutant β-catenin (β-4SA), or empty vector (mock). 2 days post-transfection total RNA was isolated, and cell lysates were prepared from different plates. Endogenous VEGF-D mRNA expression was followed by Northern blot (NB) analysis, and a quantitative analysis of VEGF-D mRNA levels, normalized to the gapdh mRNA, from three independent experiments is shown. Ectopic β-catenin expression was determined by immunoblotting using mAbs specific for Myc tag. WB, Western blot. B, transcriptional activity of TOPCAT in mouse fibroblasts transfected with β-catenin wild-type (β-myc) or β-4SA mutant. TOPCAT or FOPCAT reporter constructs were co-transfected with pRSV-β-galactosidase and 1.5 μg of wild-type or mutant β-catenin. 48 h post-transfection triplicate samples were counted, normalized for β-galactosidase activities, and averaged.

VEGF-D mRNA with lower levels at 4 and 6 h (Fig. 1B). VEGF-D mRNA levels were increased to values of the untreated cells at about 24 h after calcium reintroduction in the culture medium, thus suggesting that forced re-localization of free β-catenin to the cytoplasm induced an inhibitory signal on the VEGF-D mRNA expression.

**Wnt-1 Signaling Inhibits VEGF-D Expression**—In cells, cytoplasmic levels of free β-catenin are maintained low via the proteasome-dependent degradation, as phosphorylated β-catenin is recognized by the F box factor β-TrCP (48–50). Wnt pathway down-regulates β-catenin phosphorylation via the activation of the Frizzled receptor, which induces down-regulation of GSK-3β-adenomatous polyposis coli-axin complex causing the accumulation of cytoplasmic β-catenin (51, 52). To investigate whether the degradation of VEGF-D mRNA could be modulated via the Wnt signaling pathway, we generated stable clones constitutively expressing Wnt-1, which acts as an autocrine factor on the Frizzled receptor (42). As shown in Fig. 2, A and B, clones W1-1 and W1-34 expressed high levels of Wnt-1, whereas clone W1-18 expressed lower levels of the factor. As expected, wild-type cells showed low levels of TOPCAT activity, whereas clones expressing Wnt-1 showed significantly higher expression of TOPCAT promoter (Fig. 2C). According to our previous results, wild-type fibroblasts expressed low levels of VEGF-D mRNA at low cell density, while it increased after a few days of growth when cells reached confluence (29). In contrast, in clones W1-1 and W1-34, expressing high levels of Wnt-1, VEGF-D mRNA did not accumulate, whereas a small VEGF-D mRNA increase was observed in clone W1-18, which expressed lower levels of Wnt-1 (Fig. 2, D and E).

**β-Catenin Regulates VEGF-D Expression**—To observe directly whether free β-catenin was responsible for the decrease of VEGF-D mRNA expression, cells were transiently transfected with β-catenin wild-type or the mutant β-4SA, both carrying a C-terminal Myc tag. In the mutant β-4SA, amino acid residues Ser-33, Ser-37, Thr-41, and Ser-45 have been all substituted with alanine residues to stabilize the protein by blocking its turnover (40). Strong activity of the TOPCAT reporter construct was observed in cells transfected with β-4SA mutant, whereas the wild-type molecule was less effective (Fig. 3B). This result was in agreement with Western blot analysis, which revealed higher levels of β-4SA mutant with respect to the wild type as cytoplasmic β-catenin is actively eliminated via the ubiquitin-proteasome pathway. Northern blots analysis of RNA extracted from confluent cells transfected with wild-type or mutant β-catenin showed a significant decrease of the endogenous VEGF-D mRNA levels (Fig. 3A). The converse experiment, i.e. β-catenin depletion, was obtained by means of siRNA. Transfection into BALB/c 3T3 cells of double-stranded modified oligonucleotide obtained from the β-catenin sequence strongly reduced β-catenin both from the cell surface and the cytoplasm (Fig. 4, A and B). RNAi-dependent reduced β-catenin expression significantly induced VEGF-D mRNA (Fig. 4, C and D) confirming that β-catenin down-regulates VEGF-D mRNA expression in fibroblasts.

**β-Catenin Affects VEGF-D mRNA Stability**—It is generally accepted that β-catenin transduces Wnt signaling by interacting with TCF, and together they translocate into the nucleus where they activate Wnt target genes (39). To investigate whether VEGF-D mRNA down-modulation was due to negative regulation of VEGF-D transcription, we performed co-transfection experiments of a reporter gene under the control of the VEGF-D promoter together with constructs expressing β-catenin. These experiments did not show significant alteration of VEGF-D transcriptional rates (not shown). In contrast, meas-

**Fig. 4.** Down-regulation of β-catenin raises VEGF-D mRNA levels. A, immunofluorescence analysis using anti-β-catenin mAbs (red), fluorescein (FITC)-labeled phallolidin (green) for actin filaments staining, and DAPI (blue) for nuclei staining. BALB/c 3T3 cells were grown in 24-well Petri dishes and transfected with 60 pmol of single-stranded sense siRNA (control) or 60 pmol of siRNA duplex (β-cat-RNAi). Scale bar, 20 μm. B, Western blot analysis of cell extracts from BALB/c 3T3 cells grown in 6-cm Petri dishes and transfected with 600 pmol of single-stranded sense siRNA (control) or 600 pmol of siRNA duplex (β-cat-RNAi). The membranes were probed with anti-β-catenin mAbs. C, Northern blot analysis of total RNA extracted from BALB/c 3T3 transfected as in B, using VEGF-D and gapdh probes. D, quantitative analysis of VEGF-D mRNA levels normalized to the gapdh mRNA. The mean ± S.D. of triplicate experiments is shown.
VEGF-D mRNA stabilization is affected by calcium depletion. **A**, Northern blot analysis of total RNA extracted from mouse fibroblasts, using VEGF-D and gapdh probes. Cells were plated in 6-cm Petri dishes and grown to confluence in normal culture medium (lanes 1–4). Actinomycin D (actD) was added to the culture medium at time 0, and RNA levels were determined after 2, 4, and 6 h (lanes 5–7). Confluent cells were treated with EGTA (lanes 8–11), and after 1.30 h of EGTA treatment, actinomycin D was added to the culture medium (lanes 12–14). Alternatively, the inhibitors actinomycin D and cycloheximide (chx) were added to confluent cells 30 min before EGTA treatment (lanes 15–20). A representative experiment is shown. **B**, analysis of the mRNA hybridization signals quantified by densitometric scanning as in **A**. Values in the graph indicate the percentage of VEGF-D mRNA signals remaining either in untreated (un; lanes 5–7 of A) or in EGTA-treated cells (EGTA; lanes 12–14 of A) after normalization for the gapdh signals. mRNA half-lives were deduced from the regression line. **C**, quantitative analysis of VEGF-D mRNA levels normalized to the gapdh mRNA from a representative experiment as in **A** (mean ± S.D. of triplicate experiments). mRNA levels from confluent cells treated with actD (lanes 15–17 of A), or cycloheximide (chx; lanes 18–20 of A).

**Fig. 6. β-Catenin destabilizes VEGF-D messenger.** **A**, schematic representation of plasmids used for co-transfection experiments. The CMV early promoter was inserted into the pGL3-Basic vector containing the luciferase reporter gene and the SV40 polyadenylation signal (SV40). The SV40 polyadenylation signal was replaced by the entire VEGF-D 3′-UTR (VEGF-D). **B–D**, luciferase activities of the constructs shown in **A** co-transfected with increasing amounts of either mutant β-catenin (B), Dvl-2 (C), or axin(501–560) (D). Values of luciferase activities were normalized for β-galactosidase activities. The results represent the means ± S.D. of four independent experiments. Expression of mutant β-catenin, Dvl-2, and axin(501–560) was analyzed by immunoblotting using anti-Myc tag, anti-HA tag, and anti-FLAG mAbs, respectively. **E**, transcriptional activity of TOPCAT in mouse fibroblasts transfected with either mutant β-catenin (β.4SA), Dvl-2 (Dvl-2), or axin(501–560) (axin), TOPCAT or FOPCAT reporter constructs were co-transfected with pB5V-β-galactosidase, and 48 h post-transfection triplicate samples were counted, normalized for β-galactosidase activities, and averaged. **WB**, Western blot.

**Vegetin** showed a decrease in the luciferase activity in a concentration-dependent manner (Fig. 6B). When the stable mutant β-catenin co-expressed with luciferase, carrying in its 3′-UTR the SV40 polyadenylation signal, luciferase activity was not affected, suggesting that β-catenin exerts its action specifically on VEGF-D mRNA. Similar results were obtained co-transfecting vectors expressing Dvl-2 or axin(501–560), which stabilize cytoplasmic β-catenin (Fig. 6, C–E), thus suggesting that β-catenin plays a role in VEGF-D mRNA degradation through instability elements contained within its 3′-UTR.

**β-Catenin-dependent VEGF-D-destabilizing Sequence Contains a Conserved AU-rich Element**—To map the element responsible for β-catenin-dependent VEGF-D mRNA destabilization, we generated a series of deletion constructs of the VEGF-D 3′-UTR fused downstream to the luciferase reporter gene under the control of the CMV early promoter. These deletion constructs were co-transfected with the mutant β.4SA or the empty vector in mouse fibroblasts. Deletion constructs restricted the destabilizing element to the 3′ end of VEGF-D mRNA (Fig. 7A).

The human orthologue VEGF-D was co-transfected with the vector expressing the stable mutant β.4SA in HEK 293 cells. Human VEGF-D mRNA was degraded to comparable levels as the mouse mRNA (not shown). Deletion analysis of the human

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β-Catenin plays a key role in the destabilization of the VEGF-D mRNA—As the stability of the messenger RNA of many genes is regulated through their 3′-UTR, which contains gene-specific destabilization signals (53, 54), VEGF-D mRNA 3′-UTR was fused to the luciferase reporter gene. As a control, the luciferase reporter gene containing the SV40 polyadenylation signal was used (Fig. 6A). Because transcription of these chimeric constructs was driven by the vector containing the CMV early promoter, differences of the luciferase activity could be attributed to differences in RNA stability of the two constructs. The chimeric plasmid containing VEGF-D 3′-UTR was transfected alone or together with the mutant β.4SA in mouse fibroblasts. After transfection, cell extracts were analyzed by Western blotting and analyzed for luciferase activity. Under these conditions the construct carrying the VEGF-D 3′-UTR

**WB**, Western blot.
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**Fig. 7. β-Catenin-dependent VEGF-D mRNA destabilizing element is conserved between mouse and human.**

The different constructs used containing the luciferase reporter gene under the control of the CMV early promoter are shown. Chimeric constructs containing either the SV40 polyadenylation signal or deletion mutants of the VEGF-D 3'-UTR were cotransfected with 1.85 µg of either empty vector or mutant β-catenin. A, luciferase activities of the mouse chimeric constructs transfected in mouse fibroblasts. B, luciferase activities of the human chimeric constructs transfected in HEK 293 cells. Values of luciferase activities were normalized for β-galactosidase activities. The data shown represent the ratio of the values obtained cotransfecting the mutant β-catenin to the values obtained with control vector. The results represent the means ± S.D. of four independent experiments. C, alignment of the distal region of the mouse and human VEGF-D mRNA 3'-UTR. Vertical bars indicate identical nucleotides. Gray box depicts ARE of group I, and the polyadenylation sequence is indicated by a dashed box.

VEGF-D 3'-UTR mapped the β-catenin destabilizing element to a sequence conserved between mouse and human (Fig. 7, B and C). The minimal VEGF-D mRNA sequence able to respond to the β-catenin destabilizing signal contained a conserved ARE of group I found in cis-regulatory sequences of unstable RNAs like c-fos and c-myc (reviewed in Refs. 53 and 54).

**DISCUSSION**

This study demonstrates that β-catenin is a negative regulator of VEGF-D mRNA stability. We showed that endogenous levels of VEGF-D mRNA are reduced by β-catenin signaling in numerous ways including β-catenin re-localization to the cytosol from the membrane-associated fraction, transfection of ectopic stable mutant β-catenin, or with activation of the Wnt pathway. On the contrary, down-modulation of cellular β-catenin, obtained with siRNA, showed an increase of the endogenous VEGF-D mRNA. This regulation is conserved between mouse and human VEGF-D.

Cells have two pools of β-catenin: a membrane-associated stable protein with structural function that links cadherins to cytoskeleton and a soluble highly unstable cytoplasmic protein that transduces Wnt signaling. Wnt cell stimulation, inhibiting GSK-3β, blocks the degradation of the cytoplasmic β-catenin, which can bind to TCF and translocates into the nucleus where it co-activates Wnt target genes (39). Several identified β-catenin target genes are involved in the cell cycle progression including c-Myc and cyclin D1 (52). In addition, in colorectal cancer cells, disruption of the β-catenin-TCF-4 complex induces G1 arrest and the start of the differentiation program, suggesting that β-catenin constitutes a master switch that controls proliferation versus differentiation (55), and mutations that constitutively activate β-catenin are involved in colorectal cancer. In this view, our observation that VEGF-D is negatively regulated by β-catenin suggests that this growth factor, different from the other members of the family, is not expressed in cells actively proliferating, whereas it is induced in mesenchymal cells in which a differentiation program is activated. Indeed, the pattern of VEGF-D expression in mouse embryo as well as our previous observation that VEGF-D is down-modulated by serum induction and induced by cell-cell interaction are in line with this model (14, 29, 56).

Because constitutive β-catenin signaling has been correlated with colorectal cancer formation (57), its regulation of VEGF-D mRNA is particularly important considering that the expression of this factor has been correlated with tumor progression (33, 34, 36, 37, 58). In this respect, it is worth noting that β-catenin has been described as a master gene for cell proliferation (55), but its role in tumor progression is less clear. Although β-catenin plays a pivotal role in the development of colorectal tumors, mutations in the gene are not so common, and the majority of CRC shows mutations in the adenomatous polyposis coli gene (57). Even if a correlation between β-catenin signaling and up-regulation of VEGF-A was observed in primary adenomatous polyposis coli tumors, which may be important in early stages of colon cancers, no β-catenin mutations were observed in tumor metastases (59). On the other hand, it has been observed that down-regulation of β-catenin expression plays a significant role in progression of the disease in melanomas, and in these tumors, loss of β-catenin expression was observed at the invasive tumor front (60, 61). In oral squamous cell carcinomas, underexpression of β-catenin significantly correlated with positive lymph node status, whereas in most of the carcinomas with strong β-catenin expression there was no lymph node metastasis (62), thus suggesting that β-catenin mutations may be an early event in tumor formation,
and its loss could play a significant role in progression of the disease. Further experiments will be necessary to prove the hypothesis that VEGF-D expression could be responsible for the nodal metastatic behavior of tumors underexpressing β-catenin. In light of the present results, it will also be important for the future analysis of VEGF-D expression in tumors to take into account that VEGF-D might be expressed as a late marker of tumor progression and only in cells that have lost or reduced expression of β-catenin. These analyses will probably clarify the apparent discrepancy of VEGF-D expression in tumors reported by different authors (31–37).

Although the model of β-catenin-TCF complex as nuclear transcriptional regulator has been recently challenged, this mechanism of action remains the most likely (39, 63). Our experiments with inhibitors of transcription and translation demonstrated that β-catenin-dependent regulation of VEGF-D expression is indirect and occurs at the level of VEGF-D mRNA stability. This has been confirmed by transient transfection experiments that demonstrated that VEGF-D 3′-UTR was the target for β-catenin VEGF-D mRNA destabilization. Deletion analysis allowed us to map precisely within both mouse and human VEGF-D 3′-UTR the β-catenin-responsive element. This element, conserved in mouse and human, contained the sequence AUUUA, which corresponds to one ARE of group I (54), thus suggesting that VEGF-D instability element could be recognized by some members of the ELAV family of RNA-binding proteins (64).

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REFERENCES