Regulation of the vascular endothelial growth factor (VEGF) receptor Flk-1/KDR by estradiol through VEGF in uterus

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Abstract

The induction of vascular endothelial growth factor (VEGF) expression by 17β-estradiol (E2) in many target cells, including epithelial cells, fibroblasts and smooth muscle cells, suggests a role for this hormone in the modulation of angiogenesis and vascular permeability. We have already described a cyclic increase in Flk-1/KDR-expressing capillaries in the human endometrium during the proliferative and mid-secretory phases, strongly suggestive of an E2 effect on Flk-1/KDR expression in the endometrial capillaries. However, it is unclear whether these processes are due to a direct effect of E2 on endothelial cells. Using immunohistochemistry, we report an increase in Flk-1/KDR expression in endometrial capillaries of ovariectomized mice treated with E2, or both E2 and progesterone. This process is mediated through estrogen receptor (ER) activation. In vitro experiments using quantitative RT-PCR analysis demonstrate that Flk-1/KDR expression was not regulated by E2 in human endothelial cells from the microcirculation (HMEC-1) or macrocirculation (HUVEC), even in endothelial cells overexpressing ERα or ERβ after ER-mediated adenovirus infection. In contrast, Flk-1/KDR expression was up-regulated by VEGF itself, in a time- and dose-dependent manner, with the maximal response at 10 ng/ml. Thus, we suggest that E2 up-regulates Flk-1/KDR expression in vivo in endothelial cells mainly through the modulation of VEGF by a paracrine mechanism. It is currently unknown whether or not the endothelial origin might account for differences in the E2-modulation of VEGF receptor expression, particularly in relation to the vascular bed of sex steroid-responsive tissues.


Introduction

Hormonally controlled angiogenesis is fundamental for endometrial development and the differentiation necessary for implantation, as well as for the uterine changes associated with pregnancy (Giudice 1996, Perrot-Applanat 2000). Physiological angiogenesis is also required to support endometrial regeneration after shedding of the uterine surface in the absence of implantation and to support the proliferation of the human endometrium during the menstrual cycle under the control of estradiol (E2) and progesterone. Models of endometrial angiogenesis in the proliferative phase describe the growth of vasculature under the influence of estrogen, while the secretory phase involves growth of the coiled arteries mediated by progesterone. Previous studies have demonstrated that E2 increases the secretion of vascular endothelial growth factor (VEGF) in uterine cells (Cullivan-Bove & Koos 1993, Shifren et al. 1996, Bausero et al. 1998); this factor has emerged as one of the central regulators of the uterine vasculature (see review by Perrot-Applanat 2000).

In vivo, VEGF induces a potent angiogenic response in a variety of models and acts as a vascular permeability factor based on its ability to induce vascular leakage (see reviews by Ferrara & Davis-Smyth 1997, Ferrara et al. 2003). VEGF is also a survival factor for endothelial cells, preventing apoptosis induced by serum starvation. Molecular cloning of the human VEGF gene has revealed that differential exon splicing generates multiple tissue- and function-specific variants containing 121, 165, 189, and 206 amino acids (see review by Ferrara & Davis-Smyth 1997). In most systems, VEGF121 and VEGF165 are the major species expressed, while VEGF189 is only minimally present and VEGF206 is limited to embryonic tissue. In the human endometrium, E2 up-regulates all VEGF isoforms (Shifren et al. 1996, Bausero et al. 1998), while progesterone selectively increases the expression of the VEGF189 isoform (Ancelin et al. 2002). The role of these isoforms is still debated. Also, little is known about...
the effect of E₂ on the endothelial cells and on VEGF signaling.

The angiogenic effects of VEGF are believed to be mediated by two tyrosine kinase receptors, Flt-1 (Fms-like tyrosine kinase-1 or VEGFR-1) and Flk-1/KDR (fetal liver kinase/kinase-insert domain receptor or VEGFR-2). These receptors initiate different signaling cascades in endothelial cells (Gille et al. 2001). Flk-1/KDR is now considered to be the main receptor involved in endothelial cell proliferation, migration and survival (Millauer et al. 1993, Ferrara et al. 2003). In contrast, Flt-1 has a decoupling effect on VEGF signaling, possibly with variations related to the vascular bed type (Ferrara et al. 2003).

Factors regulating Flk-1/KDR expression in vivo in endothelial cells are not clearly defined. In tumors, Flk-1/KDR appears to be regulated by hypoxia, an effect probably mediated by VEGF (Kremer et al. 1997). VEGF and its receptor, Flk-1/KDR, which are expressed in most tissues during embryonic development, are down-regulated in the adult in physiological conditions, except in the reproductive tract (Perrot-Applanat 2000, Ferrara et al. 2003). In the human endometrium, Flk-1/KDR expression in endometrial blood vessels seems to exhibit menstrual cycle-dependent changes, with higher expression in the proliferative and the early or early-mid secretory phases, suggesting that ovarian hormones influence the expression of this receptor in the uterus (Meduri et al. 2000). In vitro studies have shown that Flk-1/KDR expression is regulated by several growth factors (Shen et al. 1998, Ferrara et al. 2003) and by shear stress (Abumiya et al. 2002). Treatment of endothelial cells with E₂ directly increases the proliferation and survival of these cells (Morales et al. 1995) through inhibition of apoptosis (Spyridopoulos et al. 1997). However, although E₂ increases VEGF expression in the endometrium, the relationship between E₂ and Flk-1/KDR expression involved in endothelial cell proliferation is poorly understood.

To better ascertain the role of E₂ in Flk-1/KDR expression, we have examined the role of E₂ and the mechanisms controlling Flk-1/KDR expression in a mouse model of angiogenesis. We have also analyzed the expression of the receptor in endothelial cells treated with E₂ and VEGF.

Materials and Methods

Materials

Reagents for cell culture and PCR were from Gibco (Life Technologies, Cergy-Pontoise, France). Estradiol was purchased from Sigma (Sigma-Aldrich GmbH, Steinheim, Germany). Trizololation kit, Moloney murine leukemia virus (MMLV) reverse transcriptase, and Taq polymerase were from Life Technologies (Cergy-Pontoise, France). Recombinant VEGF was provided by R&D Systems (Minneapolis, MN, USA).

Mice uteri

Mice were housed in the animal care facility at the National Institute of Environmental Health Sciences (NIEHS), Research Triangle Park, NC, USA. They were treated in accordance with NIH guidelines for the humane use of animals in research. The generation and characterization of the estrogen receptor α knockout (αERKO) mice have previously been reported (Couse et al. 1995). Adult wild-type (WT) or αERKO mice were ovarioctomized and rested for two weeks to clear endogenous hormones before any treatment. Mice (4 animals/group) were implanted with a pellet of E₂ (200 ng), progesterone (35 mg), E₂ and progesterone or placebo over 21 days. Animals were killed by cervical dislocation and the uterus was removed, fixed in 4% paraformaldehyde and embedded in paraffin.

Utteri were also dissected out of C57BL6/129 Svj mice (8- to 12-weeks-old, random cyclic females), fixed in Bouins and embedded in paraffin as previously described (Kurita et al. 2001).

Immunocytochemistry

Immunological detection of VEGF receptor Flk-1/KDR was performed using the polyclonal rabbit antibody CT128 directed against Flk-1/KDR (1:400 dilution; Millauer et al. 1993), as previously described (Meduri et al. 2000). This antibody has previously been characterized and does not cross-react with other protein kinase receptors. Immunocytochemical staining included overnight incubation at 4°C with the primary antibody, followed by incubation with biotinylated anti-rabbit IgG and streptavidin–biotin peroxidase (LSAB2 immunostaining kit Dakopatts, Glostrup, Denmark). Controls included omission of the first antibody and incubation of tissue sections with irrelevant rabbit IgG immunoglobulins. Adjacent sections were incubated with a marker of vascular endothelial cells, the polyclonal anti-Von Willebrand factor (vWF) antibody (Dako, Glostrup, Denmark) (Meduri et al. 2000).

The number of Flk-1/KDR-stained capillaries in each section was determined after identification of the areas containing the highest number of stained capillaries at low power magnification, as previously described (Meduri et al. 2000). Counts of individual immunostained capillaries were performed at higher magnification (×16 objective, 0.322 mm² per field), using a stereomicroscope (Leitz, Orthoplan) equipped with a CDD video camera. Five different fields in each section were digitized by image analysis and computerized using the Histolab program (Microvision, Evry, France). Capillary quantification was assessed blindly. The total number of capillaries in each biopsy was previously assessed by vessel counts in serial sections stained by anti-Von Willebrand factor using the same program. Values were expressed as means ± S.E.M.
Immunohistochemical detection of estrogen receptor (ER) β was performed on mouse uteri using an anti-ERβ sheep polyclonal antibody, as previously described (Kurita et al. 2001, Saunders et al. 2001).

Endothelial cell isolation and stimulation

Endothelial cells (human umbilical vein endothelial cells; HUVEC) were isolated from fresh human umbilical cords using digestion with Collagenase I according to the method of Jaffe et al. (1973). Cells were plated in 0.2% gelatin-coated flasks. They were grown in Medium 199 supplemented with 20% fetal calf serum (FCS) and 2 mM glutamine, 100 µg/ml penicillin/streptomycin, 15 mM HEPES and sodium bicarbonate. Cells were cultured in 5% CO2 at 37°C. The media was replaced with the same phenol red-free medium containing 5% serum in the presence of hormone. Cells were rinsed in PBS and 10% stripped SVF-containing medium was added. Cells were treated with various concentrations of E2 for 7 or 24 h at 37°C and visualized in ethidium bromide-stained agarose gels.

Cell culture and infection

Infectious viral particles adr5 (backbone virus), ad-hERα and ad-hERβ were generated by in vitro recombination of pACsk12 CMV5-hER plasmid with pJM17 in HEK-293 cells, as previously described (Lazenec et al. 2001; Viraquest Inc., North Liberty, IA, USA). Titered virus stock was used to infect HUVEC and HMEC-1 (human microvascular endothelial cells from dermis) using a previously described protocol (Lazenec et al. 2001). Briefly, 10⁶ HUVEC or HMEC-1 were seeded in a 60-mm diameter petri dish until confluence in M199 containing 1% FCS in the absence of steroid (charcoal-stripped serum) and phenol red. For stimulation, the medium was replaced with the same phenol red-free medium containing 5% serum in the presence of E2 (10⁻¹⁰ to 10⁻⁷ M) for 3–72 h. Control cells were incubated in phenol red-free medium without hormone.

RNA extraction and RT-PCR analysis

Total RNA was isolated from treated or stimulated confluent cultures of human endothelial cells with TriZOL according to the manufacturer’s instructions. For the reverse transcription stage, single-stranded cDNA was synthesized from 1 µg total RNA in the MMLV reverse transcriptase and hexamers primers. The presence of mRNA encoding the VEGF receptors and estrogen receptors (ER) in endothelial cells was determined using reverse transcriptase-polymerase chain reaction (RT-PCR) and specific oligonucleotide primers.

Detection of estradiol receptors

PCR amplification was performed using 5% RT product and primers chosen at positions 598–623 and 1392–1416 in human ERα cDNA and positions 124–146 and 498–519 in human ERβ cDNA (Bausero et al. 2000). The PCR products are 395 and 818 bp for ERβ and ERα respectively. Glyceraldehyde–3-phosphate dehydrogenase (GAPDH) was used as an internal control (450 bp). Amplification was performed using standard Gibco-BRL PCR buffer with 100 nM dNTP, 50 pmole primers, 1.5 mM MgCl₂ and 1.2 U Taq polymerase, in a 20 µl final volume. The parameters for amplification were: 4 min at 94°C, 40 cycles of 30 s at 94°C, 1 min at 57°C, 1 min at 72°C and a 10 min final extension at 72°C. Products were separated and visualized in ethidium bromide-stained agarose gels.

Quantitative RT-PCR (qPCR) of ERα and ERβ was also performed using Taqman apparatus, according to a method previously described (Bieche et al. 2001).

Quantification of Flk-1/KDR expression by real time RT-PCR

All PCRs for the detection of Flk-1/KDR were performed using the real-time fluorescence detection method with the LightCycler System and a FirstStart DNA Master SYBR Green I kit (Roche Diagnostic, Meylan, France). The primer sequences for Flk-1/KDR were performed using the real-time fluorescence detection method with the LightCycler System and a FirstStart DNA Master SYBR Green I kit (Roche Diagnostic, Meylan, France). The primer sequences for Flk-1/KDR were as follows: forward, 5’ TCTCAATGT GGTCACCTTCTAG; reverse, 5’ TTTAACGCTCT TAAGGGTGTTAGTG. To avoid amplification of contaminating genomic DNA, two primers were chosen in two different exons. The cycling conditions were as follows: initial denaturation at 95°C for 10 min, followed by 40 amplification cycles at 95°C for 15 s, 55°C for 5 s, and 72°C for 20 s. A negative control without the cDNA template was performed to assess the overall specificity. Expression levels were normalized to β2-microglobulin, which was unaffected in the different treatment groups. Results are expressed as the mean of 5 independent experiments assayed in duplicate.

Statistical analysis

Student’s t-test was used to determine the significance between treated and untreated cells, and P<0.05 was considered significant.

Results

Estradiol induces Flk-1/KDR expression in vivo

We have previously described the presence and modulation of VEGF and its Flk-1/KDR receptor in the human
cyclic endometrium (Meduri et al. 2000). The expression of this receptor, deduced from the semi-quantitative analysis of capillaries immunostained for Flk-1/KDR, was maximal in the proliferative and in the mid-secretory periods. This observation suggests a possible effect of E$_2$ on the expression of Flk-1/KDR in the endometrium.

In order to assess the possible effect of E$_2$ on Flk-1/KDR expression in vivo, we have chosen the mouse uterus model. Ovariectomized mice were treated with E$_2$ or vehicle, as described in Materials and Methods, and uterine sections were immunostained for Flk-1/KDR (Fig. 1A-D). Quantification of VEGF receptor was examined using a protocol previously described by Meduri et al. (2000). Morphometric analysis showed a significant increase in the number of Flk-1/KDR-stained vascular structures expressed per unit area in the uteri of E$_2$-treated (4.1-fold induction, $P<0.05$) or E$_2$+progesterone-treated (4.3-fold induction, $P<0.05$) mice as compared with
controls. In contrast, there was no change in the expression of Flk-1/KDR in wild-type progesterone-treated mice (Fig. 1E).

In order to analyze the mechanism of E2 up-regulation of Flk-1/KDR in mice uteri, similar experiments were performed in E2-treated mice with a disruption of the ERα gene (ERα knockout mice) (Fig. 1C,D). As shown in Fig. 1E, the number of uterine Flk-1/KDR expressing vascular structures was significantly lower in E2- or E2+progesterone-treated ERα−/− mice as compared with E2-treated wild-type mice (P < 0·05), suggesting that ERα could be involved in this regulation process. However, the number of Flk-1/KDR stained vascular structures was also lower in untreated ERα−/− mice versus untreated wild-type mice (P < 0·05) (Fig. 1E). Also, E2 or E2+ progesterone significantly increased Flk-1/KDR expression in ERα−/− mice (P < 0·06), suggesting that ERβ could also be involved in this regulation. As shown in Fig. 2, endothelial cells from mouse uteri do express ERβ, similar to the situation described in human uteri (Lecce et al. 2001). Altogether, our in vivo data show that E2 increases Flk-1/KDR expression via estrogen receptor (α or β) activation. Comparative experiments using immunostaining with anti-vWF (a marker of endothelial cells) indicate that E2-treated mice results in an increase in the total number of blood vessels, but not in an increase in the number of blood vessels expressed per unit area (not shown). Therefore, the increase in Flk-1/KDR-positive blood vessels of E2-treated mice does not result from an overall increase in blood vessels.

The E2-induced Flk-1/KDR expression observed in vivo could result either from a direct effect of E2 on endothelial cells, or from an indirect effect through the secretion of VEGF by surrounding cells.

**Figure 2** Expression of ERβ in mouse uterus. Uterine sections were immunostained with anti-ERβ antibodies (Saunders et al. 2001). ERβ-positive cells are seen in epithelial (arrowheads) and endothelial (open arrow) cells, as well as in some stromal cells (arrows). G, gland; L, lumen. Original magnification, ×20. Insert, high magnification of an immunostained vessel (open arrow).

**Figure 3** VEGF, but not E2, up-regulates Flk-1/KDR expression. (A, B) HUVEC (passage 2) express Flk-1/KDR receptors, as shown by RT-PCR analysis (A) and immunocytochemistry with monoclonal anti-Flk-1/KDR antibodies (CT128 clone) and biotinylated fluorescein-streptavidin (B). Note in (B) that Flk-1/KDR is mainly detected at the plasma membrane level and in the cytoplasm. Original magnification, ×40. (C) VEGF up-regulates Flk-1/KDR expression. HUVEC were treated with VEGF (10 ng/ml) or E2 (10−10 to 10−7 M) for 7 h. Relative RNA units for Flk-1/KDR were normalized with the β2-microglobulin level, as calculated from standard curves, and compared with untreated cells. The results are expressed as the mean ± S.E.M. of three experiments. *P < 0·05 compared with untreated control cells.

VEGF, but not estradiol, increases Flk-1/KDR expression in endothelial cells (HUVEC)

VEGF levels have previously been shown to increase in human uterine cells in response to E2 stimulation (Shifren et al. 1996, Bausero et al. 1998). In order further to analyze the possible effects of E2 and VEGF on Flk-1/KDR expression in vitro, we used endothelial cells prepared from umbilical cord (HUVEC). As shown by immunofluorescence and RT-PCR analysis, these cells expressed Flk-1/KDR receptor (Fig. 3A, B).

The modulation of Flk-1/KDR expression by E2 and VEGF was further analyzed using quantitative real-time PCR analysis and a LightCycler protocol developed as described in Materials and Methods. This allows the sensitive, specific and quantitative detection of VEGF receptor.
Stimulation of HUVEC by VEGF (10 ng/ml) significantly increased the level of Flk-1/KDR mRNA over control values (Fig. 3C). The increase in Flk-1/KDR expression by VEGF was dose- and time-dependent (not shown), with a maximal effect at 10 ng/ml and 7 h (1.5-fold induction, \( P < 0.05 \)) (Fig. 3C). VEGF increased Flk-1/KDR expression in all HUVEC samples tested (\( n = 7 \)).

Treatment of HUVEC endothelial cells with E\(_2\) (10\(^{-10}\) to 10\(^{-7}\) M) for 7 h (Fig. 3C) or with 10\(^{-8}\) M for 0–72 h (not shown) did not induce significant Flk-1/KDR expression. Using quantitative RT-PCR analysis (Bieche et al. 2001), ER\(\alpha\) was absent in all HUVEC samples (\( n = 7 \)), while ER\(\beta\) was present in very low amounts (not shown) with values always set below the lowest range (below the first tertile) found using the same method in a series of 131 primary breast cancer tumors (Bieche et al. 2001). The absence of an effect of E\(_2\) on Flk-1/KDR expression in HUVEC could be explained by a loss of ER expression in the primary endothelial cells when isolated from the umbilical cord. Therefore, we have overexpressed ER\(\alpha\) or ER\(\beta\) in macro- (HUVEC) and micro- (HMEC-1) vascular cells, using adenovirus infection as described in Materials and Methods (see Fig. 4D) and have analyzed the modulation of Flk-1/KDR in
these cells (Fig. 4A–C). Results indicate that E2 does not affect the Flk-1/KDR expression in endothelial cells, whether E2 was used at 10^{-8} M (Fig. 4A,B) or at various concentrations (Fig. 4C).

Altogether, these results suggest that the regulation of Flk-1/KDR expression by E2 in endothelial cells does not involve an autocrine mechanism and mainly occurs through the VEGF pathway.

Discussion

VEGF is a key mediator of angiogenesis. Its expression, abundant in the embryo, is down-regulated in the adult, except during cyclical endometrial growth and corpus luteum formation (Ferrara & Davis-Smyth 1997, Perrot-Applanat 2000). Alterations in the expression of VEGF and its receptors are associated with disruption of ovarian and uterine functions (Ferrara et al. 2003). Despite the biological relevance of Flk-1/KDR in angiogenesis, little is known about the molecular mechanisms controlling its expression. In the present work, we describe the up-regulation of Flk-1/KDR by E2 in vivo in the mouse endometrium, while experiments on endothelial cells in vitro show the up-regulation of Flk-1/KDR by VEGF in the absence of a direct E2 effect, suggesting a paracrine mechanism of regulation of Flk-1/KDR in vivo.

In vivo regulation of Flk-1/KDR expression by E2 in the uterus

Endometrial cyclical growth depends on capillary proliferation and increased blood flow caused by vasodilatation and changes in vascular permeability (Giudice 1996). These changes are regulated by E2 and progesterone through activation of their respective nuclear receptors (Perrot-Applanat et al. 1994, Lecce et al. 2001). E2 directly modulates VEGF expression in the human endometrium in vivo (Shifren et al. 1996, Bausero et al. 1998). Preliminary observations suggest that E2 also modulates endometrial Flk-1/KDR (Meduri et al. 2000), essential for the development of the uterine vasculature during physiological angiogenesis (Heryanto et al. 2003). However, the mechanisms controlling E2-induced Flk-1/KDR expression are unclear. As functional ERs are essential for the E2-induced increase in angiogenesis, wild-type and αERKO mice (Couse et al. 1995) provide a valuable model to examine the ER-mediated estrogenic effect on uterine Flk-1/KDR expression. We quantified Flk-1/KDR expression in ovarioctomized wild-type or αERKO E2-treated mice using an established protocol (Meduri et al. 2000). Our data show that E2 induces Flk-1/KDR expression through functional ERα activation in the mouse uterus, as previously suggested for the human endometrium (Meduri et al. 2000). From our data, ERα does not seem to be the only mediator for Flk-1/KDR expression. Since ERβ is also expressed in uterine endothelial cells, we can anticipate a possible role for ERβ in E2-induced Flk-1/KDR expression in the absence of ERα. This hypothesis could be strengthened by the study of Kurita et al. (2001), who has previously described a role for ERβ in E2 induction of progesterone receptor in αERKO mice. Further experiments using mice with ERβ invalidation are required to elucidate the respective roles of ERα and ERβ in Flk-1/KDR induction.

We have shown that progesterone modulates VEGF secretion in decidual cells (Ancelin et al. 2002). While adjunction of progesterone does not modify the E2 effect on Flk-1/KDR expression in wild-type and αERKO mice, progesterone alone increases Flk-1/KDR expression only in αERKO but not in wild-type mice (see Fig. 1). We do not know why progesterone has an effect only in the absence of ERα. Previous studies have demonstrated the presence of progesterone receptors in αERKO mice; progesterone is able to induce a decidual reaction and to regulate gene expression in these animals (Curtis et al. 1999). Our data on the role of progesterone in Flk-1/KDR expression in the mouse uterus need to be confirmed on a larger series of animals.

E2 and in vitro regulation of Flk-1/KDR expression in endothelial cells

Experimental studies show that E2 exerts direct effects on endothelial cells, including up-regulation of endothelial nitric oxide synthase activity, modulation of adhesion molecule expression, angiogenic activity and proliferation in vitro after 6 days of culture (Morales et al. 1995). However, it is unclear whether these effects are mediated through modulation of VEGF receptors. In our study, E2 did not increase significantly Flk-1/KDR expression in HUVEC samples from early passages (P1 to P2). A small increase in Flk-1/KDR expression with E2 was observed in one of the 7 samples analyzed (not shown), which could be mediated by ERβ, as suggested by the presence of low levels of ERβ. The presence of ERβ, but not of ERα mRNA, was previously described in HUVEC (Enmark et al. 1997, Stefano et al. 2000). Our results could be interpreted by the fact that the response could vary among different subjects, or by a loss of ER expression in most samples. Gargett et al. (2002) report a moderate increase in Flk-1/KDR expression in E2-treated myometrial endothelial cells, mediated primarily by ERα. These discrepancies may reflect differences in endothelial cell origin and/or conditions of culture such as the number of passages. We and others have detected only ERβ and not ERα in human and mouse endothelial cells in vivo (Critchley et al. 2001, Kurita et al. 2001, Lecce et al. 2001, as shown in this study). To counteract the loss of ER expression in our primary endothelial cells, HUVEC, we have overexpressed ERα or ERβ in macro- (HUVEC) and micro- (HMEC-1) vascular cells. Our results show
that E₂ does not modulate Flk-1/KDR expression in endothelial cells. In our studies, we have also used transient transfection of ERα and ERβ cDNA along with a Flk-1/KDR promoter-luciferase gene reporter in an umbilical cord cell line (HUV-E-C), which expresses low levels of Flk-1/KDR, as compared with primary HUVEC. E₂ did not activate Flk-1/KDR in these cells but activated an estrogen response element luciferase construct (data not shown). Thus, E₂ does not directly modulate Flk-1/KDR in endothelial cells; a direct effect of E₂ could be limited to the vasculature of sex steroid-responsive tissues, such as the myometrium.

VEGF induces up-regulation of Flk-1/KDR in vitro and in vivo

Previous studies have demonstrated that E₂ increases VEGF secretion in human and animal uterine cells (Cullinan-Bove & Koos 1993, Shifren et al. 1996, Bausero et al. 2000). The present study demonstrates a VEGF-induced up-regulation of Flk-1/KDR mRNA in endothelial cells (HUVEC), in agreement with a previous study on the capillary endothelium of bovine adrenal cortex (Shen et al. 1998). By qPCR we can barely detect VEGF mRNA in HUVEC (unpublished results). Altogether, these results suggest that VEGF cannot stimulate Flk-1/KDR via an autocrine mechanism. Up-regulation of Flk-1/KDR protein levels was also reported in other studies using either endothelial cells from human saphenous veins infected with an adenoviral vector encoding VEGF165 (Weisz et al. 2001), or mouse cerebral slices incubated with recombinant VEGF165 (Kremer et al. 1997). These data suggest that Flk-1/KDR is regulated by VEGF synergistically with other factors, such as transforming growth factor-β, tumor necrosis factor-α and shear stress (Ferrara & Davis-Smyth 1997, Shen et al. 1998).

The up-regulation of VEGF expression by E₂ has been established in vivo in the injured-carotid model of angiogenesis in which E₂ increases re-endothelialization (Concina et al. 2000) while a direct modulation of Flk-1/KDR appears to be very inconsistently observed, suggesting that, in this model also, E₂ regulates angiogenesis mainly through a paracrine VEGF action.

In conclusion, we describe the effects of E₂ on the increase in Flk-1/KDR expression in a sex steroid-responsive tissue - the human and mouse uterus. The increase in Flk-1/KDR expression by E₂ leading to an increase in angiogenesis is secondary to an E₂ up-regulation of VEGF expression, previously observed in vivo, associated with VEGF-induced Flk-1/KDR expression in endothelial cells as shown in this study.

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