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VEGF-A isoforms differentially regulate ATF-2–dependent VCAM-1 gene expression and endothelial–leukocyte interactions

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ABSTRACT Vascular endothelial growth factor A (VEGF-A) regulates many aspects of vascular physiology. VEGF-A stimulates signal transduction pathways that modulate endothelial outputs such as cell migration, proliferation, tubulogenesis, and cell–cell interactions. Multiple VEGF-A isoforms exist, but the biological significance of this is unclear. Here we analyzed VEGF-A isoform–specific stimulation of VCAM-1 gene expression, which controls endothelial–leukocyte interactions, and show that this is dependent on both ERK1/2 and activating transcription factor-2 (ATF-2). VEGF-A isoforms showed differential ERK1/2 and p38 MAPK phosphorylation kinetics. A key feature of VEGF-A isoform–specific ERK1/2 activation and nuclear translocation was increased phosphorylation of ATF-2 on threonine residue 71 (T71). Using reverse genetics, we showed ATF-2 to be functionally required for VEGF-A–stimulated endothelial VCAM-1 gene expression. ATF-2 knockdown blocked VEGF-A–stimulated VCAM-1 expression and endothelial–leukocyte interactions. ATF-2 was also required for other endothelial cell outputs, such as cell migration and tubulogenesis. In contrast, VCAM-1 was essential only for promoting endothelial–leukocyte interactions. This work presents a new paradigm for understanding how soluble growth factor isoforms program complex cellular outputs and responses by modulating signal transduction pathways.
(NRPs) NRP1 and NRP2 (Koch et al., 2011). The VEGF-A gene alone encodes seven or more different isoforms that bind VEGFR1 (Flt-1), VEGFR2 (KDR), and neuropilins (Harper and Bates, 2008). VEGF-A gene dose is critical, as heterozygous VEGF-A+/− knockout mouse embryos die during embryogenesis (Carmeliet et al., 1996; Keyt et al., 1996). VEGFR2−/− knockout mice also exhibit embryonic lethality (Shalaby et al., 1995). The most-studied VEGF-A ligand is a mature 165-residue processed polypeptide (VEGF-A165), which promotes endothelial cell survival, proliferation, migration, and angiogenesis. VEGF-A–regulated endothelial responses are especially associated with pathological conditions such as tumor progression (Chung and Ferrara, 2011; Meadows and Hurwitz, 2012).

The binding of VEGF-A to VEGFR2 triggers sustained signal transduction, increased trafficking, and proteolysis (Bruns et al., 2009; Horowitz and Seerapu, 2012; Koch and Claesson-Welsh, 2012; Nakayama and Berger, 2013). A key aspect of VEGF-A–stimulated reprogramming of endothelial cell function is elevated expression of 100–200 genes (Schweighofer et al., 2009; Rivera et al., 2011). VEGF–A–regulated target genes are implicated in a multitude of cellular functions, including cell adhesion, signal transduction, and transcriptional control. A major question concerns the nature of the mechanism(s) that control VEGF–A–stimulated gene expression. Although VEGF–A–stimulated signal transduction via MEK1–extracellular signal–regulated kinase 1 and 2 (ERK1/2), 38-kDa stress- and mitogen-activated protein kinase (p38 MAPK), and JNK pathways could potentially provide multiple means of elevating gene expression, the exact mechanism by which such signal transduction is integrated with nuclear transcriptional control is unclear. One well-known target is the membrane receptor vascular cell adhesion molecule 1 (VCAM-1), whose expression on endothelial cells promotes binding to leukocyte integrin α4β1 (VLA-4), thus promoting endothelial–leukocyte interactions (Jain et al., 1996; Melder et al., 1996). The mechanism underlying this VEGF–A–stimulated gene expression is unclear, with studies suggesting roles for NF-κB (Kim et al., 2001a) and forkhead (Abid et al., 2008) transcription factors in regulating VCAM-1 gene transcription.

A major question is the role of the increasing number of VEGF splice isoforms in regulating vascular and animal function. The human VEGF-A gene alone expresses eight isoforms ranging from 121 to 206 residues in length. One idea is that the VEGF-A gene encodes both proangiogenic and antiangiogenic isoforms that are expressed in different tissues to modulate the vascular response during health and disease (Harper and Bates, 2008). To evaluate the link between VEGF–A–stimulated gene expression and isoform functionality, we investigated VCAM-1 expression. Studies on VEGF-A165 and the VEGF-A isoform 121 residues in length (VEGF-A121) showed that these growth factor isoforms differentially activated signal transduction pathways linked to a novel event in the nucleus that regulates VCAM-1 expression.

RESULTS
VEGF-A isoforms differentially regulate VCAM-1 and VEGFR2 turnover and synthesis
The VEGF–A165 isoform promotes increased endothelial VCAM-1 expression (Melder et al., 1996; Kim et al., 2001a; Schweighofer et al., 2009). Although the pathway of VEGF–A–VEGFR2 signal transduction is well studied, it is unclear how such events are communicated to the nucleus to control nuclear gene transcription, such as increased VCAM-1 expression (Figure 1A). To investigate this phenomenon, we first asked whether two different VEGF–A–isoforms that differ in their carboxy-proximal regions (Figure 1B) caused similar or different effects on VCAM-1 expression levels in primary human endothelial cells (Figure 1C). We first compared VCAM-1 and VEGFR2 levels in endothelial cells stimulated with a maximal stimulatory dose (0.25 nM) of either VEGF–A165 or VEGF–A121 for 2, 4, 6, 8, and 24 h (Figure 1C). We used endothelial tubulin levels as a control, and such comparisons were used to evaluate varying protein expression in response to VEGF–A stimulation (Figure 1C). Quantification of endothelial VCAM-1 levels revealed a peak of VCAM-1 expression after VEGF–A165 stimulation for 8 h corresponding to ~6.5-fold increase compared with the 0 h time point (Figure 1D). This peak in VCAM-1 levels was transient and dropped to ~2.5-fold rise after VEGF–A165 stimulation for 24 h (Figure 1D). In comparison, VEGF–A121 stimulation failed to significantly elevate VCAM-1 levels (Figure 1C).

VEGFR2 activation leads to transautophosphorylation of multiple tyrosine residues: Y1175 is a key site that undergoes such phosphorylation (Takahashi et al., 2001; Holmqvist et al., 2004; Koch et al., 2011). Monitoring VEGFR2–pY1175 appearance showed that VEGF–A165 stimulates rapid and transient phosphorylation of this site, whereas VEGF–A121 treatment did not produce significant Y1175 phosphorylation (Figure 1C). VEGF–A–stimulation promotes VEGFR2 ubiquitination, endocytosis, and proteolysis (Ewan et al., 2006). We then asked whether VEGFR2 turnover and synthesis were different upon treatment with either VEGF–A165 or VEGF–A121 isoform (Figure 1E). VEGF–A165 stimulation promoted VEGFR2 degradation over a short time period (2–4 h), with VEGFR2 levels reduced by ~60% after 2 h (Figure 1E). However, VEGFR2 levels returned to baseline after VEGF–A165 stimulation for 8 h (Figure 1E). VEGFR2 levels continued on an upward trajectory, with ~50% increase after VEGF–A165 stimulation for 24 h (Figure 1E). In contrast, VEGF–A121 stimulation appeared to have little effect on VEGFR2 protein levels (Figure 1E). These findings show that two different VEGF–A isoforms have different capabilities in stimulating the turnover and synthesis of not only VEGF–R2, but also those of another membrane receptor, VCAM-1.

VEGF-A isoforms differentially regulate multiple signal transduction pathways
VEGF–A stimulates multiple MAPK signal transduction pathways in endothelial cells (Horowitz and Seerapu, 2012; Koch and Claesson-Welsh, 2012), which regulate multiple cellular outcomes (Nakatsu et al., 2003; Karihaloo et al., 2005; Zhang et al., 2008; Xu et al., 2011). In this context, we asked whether the increase in endothelial VCAM-1 levels (Figure 1D) was linked to altered signal transduction pathways activated by the two VEGF–A isoforms, using ligand titration followed by signal transduction pathway analysis (Figure 2). Activation of VEGFR2 and downstream signaling events was first assessed by monitoring transautophosphorylation at cytoplasmic residue Y1175 (Figure 2, A and B). Phosphorylation of Y1175 could be detected within 5 min of stimulation with either VEGF–A165 or VEGF–A121, but there were concentration-dependent effects (Figure 2A). Quantification showed that VEGF–A121–stimulated VEGFR2–Y1175 phosphorylation at 0.025 and 0.25 nM was significantly reduced (Figure 3B) in comparison to VEGF–A165 (Figure 3A). However, under saturating conditions of VEGF–A (1.25 nM), the peak level of VEGFR2 activation in response to VEGF–A165 (Figure 3A) was similar to that induced by VEGF–A121 (Figure 3B).

VEGF–A activates ERK1/2, p38 MAPK, and serine/threonine protein kinase c-Akt (Akt; also known as protein kinase B) pathways in endothelial cells (Koch et al., 2011; Koch and Claesson-Welsh, 2012). Both VEGF–A165 and VEGF–A121 stimulation promoted a rapid and transient peak in ERK1/2 activation within 15 min, with differing magnitudes (Figure 2). Quantification showed that VEGF–A121 stimulation resulted in a generally lower level of peak activation
with either VEGF-A165 or VEGF-A121 (Supplemental Figure S1). These data suggest that these two different VEGF-A isoforms have differential capabilities not only in stimulating VEGFR2 activation, but also in other downstream signal transduction pathways.

VEGF-A isoform–specific stimulation of activating transcription factor 2

Exactly how short-term RTK signal transduction integrates with long-term cellular responses is not well understood (Lemmon and Schlessinger, 2010). The VEGFR–VEGF-A axis stimulates intracellular signaling over a short time frame (0–1 h) and regulates long-term endothelial responses such as leukocyte recruitment, cell migration (>24 h), and tubulogenesis (5–7 d; Chung and Ferrara, 2011; Koch et al., 2011). To identify a nuclear switch that was responsive to VEGF-A isoform–specific MAPK signal transduction and could influence VCAM-1 expression, we focused on activating transcription factor 2 (ATF-2), which is known to undergo VEGF-A–stimulated phosphorylation in cardiac myocytes and endothelial cells (Seko et al., 1998; Salameh et al., 2010). ATF-2 belongs to the basic region

(Figure 3D) than VEGF-A165 (Figure 3C). Of interest, saturating conditions of VEGF-A, which resulted in similar levels of VEGFR2 peak activation (Figure 3, A and B), exhibited approximately twofold difference in ERK1/2 peak activation between the two isoforms (Figure 3, C and D). VEGF-A165 and VEGF-A121 also triggered sustained and pronounced p38 MAPK activation (Figure 2). Quantification showed that VEGF-A121–stimulated p38 MAPK activation was more pronounced (Figure 3F) than for VEGF-A165 (Figure 3E) under saturating ligand conditions. VEGF-A165 and VEGF-A121 also caused differential Akt activation (Figure 2, A and B). Quantification showed that both VEGF-A165 (Figure 3G) and VEGF-A121 (Figure 3H) promoted a rapid peak in Akt activation within 15 min. However, VEGF-A165 (Figure 3G) had greater efficacy than VEGF-A121 (Figure 3H), as a much lower concentration of ligand was required to achieve a significant response. Of interest, at saturating ligand conditions (1.25 nM), the peak in Akt activation was comparable between the two VEGF-A isoforms (Figure 3, G and H). Further analysis of these data sets presented as histograms shows the statistical significance of the changes in signal transduction events detected upon stimulation with either VEGF-A165 or VEGF-A121 (Supplemental Figure S1). These data suggest that these two different VEGF-A isoforms have differential capabilities not only in stimulating VEGFR2 activation, but also in other downstream signal transduction pathways.

VEGF-A isoform–specific regulation of VCAM-1 gene expression

(A) Schematic depicting VEGF-A isoform–specific regulation of VCAM-1 gene expression through modulation of gene transcription in endothelial cells. (B) Schematic depicting human VEGF-A–coding mRNA with exons 1–8 and splice variants VEGF-A165 and VEGF-A121. (C) Endothelial cells subjected to 0.25 nM VEGF-A165 or VEGF-A121 for the specified times indicated (hours), lysed, and probed by immunoblotting to assess phospho-VEGFR2 (VEGFR2-pY1175), VEGFR2, VCAM-1, or tubulin protein levels. (D, E) Quantification of (D) VCAM-1 and (E) VEGFR2 protein levels from immunoblotting studies of VEGF-A165– and VEGF-A121–stimulated endothelial cells. Error bars indicate ±SEM (n = 3). *p < 0.05, **p < 0.01, ****p < 0.001.

FIGURE 1: VEGF-A isoform–specific regulation of VCAM-1 gene expression. (A) Schematic depicting VEGF-A isoform–specific regulation of VCAM-1 gene expression through modulation of gene transcription in endothelial cells. (B) Schematic depicting human VEGF-A–coding mRNA with exons 1–8 and splice variants VEGF-A165 and VEGF-A121. (C) Endothelial cells subjected to 0.25 nM VEGF-A165 or VEGF-A121 for the specified times indicated (hours), lysed, and probed by immunoblotting to assess phospho-VEGFR2 (VEGFR2-pY1175), VEGFR2, VCAM-1, or tubulin protein levels. (D, E) Quantification of (D) VCAM-1 and (E) VEGFR2 protein levels from immunoblotting studies of VEGF-A165– and VEGF-A121–stimulated endothelial cells. Error bars indicate ±SEM (n = 3). *p < 0.05, **p < 0.01, ****p < 0.001.
MAPK is significantly reduced by addition of SB203580, which inhibits both the α and β forms of p38 MAPK (Figure 4D). Quantification of VEGF-A-stimulated phospho–ATF-2 levels showed that that U0126 (MEK1 inhibitor) but not SB203580 (p38 MAPK inhibitor) completely blocked ligand-stimulated phosphorylation of ATF-2 (Figure 4E).

A key aspect of growth factor–stimulated MAPK activation is nuclear translocation of activated protein kinases and phosphorylation of key substrates, which in turn regulate gene transcription (Plotnikov et al., 2011). We previously showed that VEGF-A stimulation causes translocation of activated ERK1/2 into the nucleus of endothelial cells (Jopling et al., 2009). To correlate ERK1/2 translocation with ATF-2 activation, we monitored the intracellular distribution of phospho-ERK1/2 and ATF-2–pT71 using microscopy (Figure 4F). Activated phospho-ERK1/2 was detected in both the cytoplasm and nucleus within 15 min; this also correlated with a peak of phospho-ATF-2 in the nucleus (Figure 4F). Microscopy analysis of phospho-ERK1/2 and phospho-ATF-2 in the nucleus revealed substantial codistribution of both proteins at ∼15 min post–VEGF-A165 stimulation (Figure 4G). Quantification of nuclear phospho-ERK1/2 and phospho–ATF-2 showed a >10-fold rise in codistribution after VEGF-A165 stimulation (Figure 4H). Such findings show a close link of VEGF-A165–stimulated MAPK signal transduction leading to ERK1/2 activation, nuclear translocation, and downstream activation of ATF-2.

The VEGF-A coreceptor NRP1 has been shown to attenuate VEGF-A–stimulated signal transduction (Pan et al., 2007; Herzog et al., 2011). Therefore we evaluated whether NRP1 was essential for optimal VEGF-A–stimulated ATF-2 activation. Using immunoblotting, we monitored ATF-2–pT71 levels after 15 min of stimulation with either VEGF-A165 or VEGF-A 121 in NRP1-depleted and control endothelial cells (Supplemental Figure S2A). Quantification revealed that both VEGF-A165– and VEGF-A121–stimulated ATF-2 activation was reduced in NRP1-depleted endothelial cells (Supplemental Figure S2B). One consequence of a reduction in NRP1 levels was a concomitant reduction in VEGF-A–stimulated ERK1/2 activation (Supplemental Figure S2C). These data suggest that NRP1 influences the ability of the VEGFR2–VEGF-A165 complex to effectively activate downstream ERK1/2 and thus ATF-2.

VEGF-A and ATF-2 are required for VCAM-1 expression and endothelial–leukocyte interactions

VEGF-A–stimulated VCAM-1 gene expression has implicated both the NF-κB pathway and forkhead transcription factors (Kim et al., 2001a,b; Abid et al., 2006; Dejana et al., 2007). On the basis of our data, we hypothesized that ATF-2 acts as a nuclear “switch” for converting VEGF-A isofrom–specific short-term cytosol-to-nucleus signaling (via the MEK1-ERK1/2 pathway) into VCAM-1 gene

![Figure 2: VEGF-A isoform-specific activation of signal transduction. (A, B) Endothelial cells subjected to different VEGF-A165 or VEGF-A121 concentrations (0, 0.025, 0.25, or 1.25 nM) for (A) 5 and 15 min or (B) 30 and 60 min were lysed and probed for phospho-VEGFR2, phospho-ERK1/2, phospho-p38 MAPK, and phospho-Akt (see Materials and Methods).](image)
transcription, thus modulating VEGF-A isoform–specific long-term endothelial responses (including leukocyte recruitment). To evaluate ATF-2 requirement in VEGF-A–stimulated gene transcription, we first used specific small interfering RNA (siRNA) duplexes to deplete endothelial ATF-2. As expected, ATF-2 mRNA levels were depleted only in endothelial cells treated with ATF-2–specific siRNA duplexes (ATF-2 knockdown) in comparison to scrambled siRNA duplex treatment (control), under both nonstimulated and VEGF-A–stimulated conditions (Figure 5A). We then analyzed whether ATF-2 depletion affected VCAM-1 mRNA levels (Figure 5B). On VEGF-A165 stimulation, we detected ~1.4-fold increase in VCAM-1 mRNA levels compared with controls (Figure 5B). VEGF-A121–stimulated endothelial cells produced ~1.2-fold increase in VCAM-1 mRNA levels, but this was substantially less than that observed for VEGF-A165 (Figure 5B). ATF-2 knockdown substantially reduced the VEGF-A–stimulated increase in VCAM-1 mRNA levels by ~25% (Figure 5B). There is thus a functional requirement for the presence of ATF-2 in VEGF-A–stimulated VCAM-1 expression in endothelial cells.

One question is the link between the requirement for ATF-2 in endothelial signal transduction and protein expression. To address this, we used immunoblotting to monitor protein levels and phosphorylation events 8 h after VEGF-A stimulation in control or ATF-2–depleted endothelial cells (Figure 5C). This time point of post–VEGF-A stimulation was used as the point of maximal ligand-stimulated VCAM-1 expression (Figure 1D). ATF-2 knockdown caused ~75% reduction in ATF-2 protein levels (Figure 5D). Activated VEGFR2-pY1175 titration. Error bars indicate ±SEM (n ≥ 4).
FIGURE 4: VEGF-A isoform–specific intracellular signaling regulates ATF-2 phosphorylation. (A) Immunoblotting of VEGF-A–stimulated endothelial cells for ATF-2-pT71, total ATF-2, and tubulin upon ligand titration. (B, C) Quantification of phosphorylated ATF-2-pT71 levels upon (B) VEGF-A165 and (C) VEGF-A121 titration. Error bars indicate ±SEM (n = 4). (D) Immunoblotting VEGFR2, ATF-2, ERK1/2, and p38 MAPK total and phosphorylated levels after preincubation with MEK1 inhibitor (U0126) or p38 MAPK inhibitor (SB203580), followed by VEGF-A isoform (1.25 nM) stimulation for 15 min. (E) Quantification of ATF-2-pT71 levels upon activation by VEGF-A165 or VEGF-A121 in the presence of MEK1 inhibitor (U0126) or p38 MAPK inhibitor (SB203580). Error bars indicate ±SEM (n = 3). (F) Endothelial cells stimulated with VEGF-A165 for 0, 15, or 30 min were processed for immunofluorescence microscopy using mouse
time point but were mirrored by a large decrease in VEGFR2 levels (Figure 5C). Differential phosphorylation in ERK1/2 and phospholipase Cγ1 was also evident (Figure 5C). These findings showed that ATF-2 knockdown did not significantly affect VEGFR2 turnover and downstream signal transduction in response to VEGF-A stimulation.

We probed for VCAM-1 expression in control or ATF-2–depleted cells 8 h after VEGF-A isoform stimulation (Figure 5C). VCAM-1 expression was clearly ATF-2 dependent (Figure 5C), and quantification highlighted a relatively large (greater than threefold) increase in VCAM-1 protein levels, which was also ATF-2 dependent (Figure 5, C and E). These data showed that increased VCAM-1 expression caused by VEGF-A not only was ATF-2 dependent but also influenced VCAM-1 mRNA levels.

Endothelial VCAM-1 binds leukocyte α4β1 integrin (VLA-4) and promotes leukocyte recruitment onto the endothelium before transendothelial migration (Sixt et al., 2006; Nourshargh et al., 2010; Reglero-Real et al., 2012). A major question is whether VEGF-A–stimulated and ATF-2–dependent VCAM-1 expression can influence leukocyte binding to endothelial cells. To test this idea, we used a binding assay that monitored the binding of fluorescent-labeled human leukocyte HL-60 cells to an endothelial cell monolayer (Figure 5F). VEGF-A 165 stimulated ∼75% increase in leukocyte binding to the endothelial monolayer (Figure 5F). However, VEGF-A121 caused only a small, ∼15% increase in leukocyte binding to endothelial cells (Figure 5F). ATF-2 knockdown completely ablated VEGF-A–stimulated binding of leukocytes to endothelial cells (Figure 5F). This phenomenon was VCAM-1 dependent, as VCAM-1 knockdown also completely inhibited endothelial–leukocyte interactions (Figure 5F). These data confirm that the VEGF-A–stimulated expression of endothelial VCAM-1 not only is ATF-2 dependent but also is sufficient to enable recruitment of leukocytes and enhance cell–cell interactions.

**FIGURE 5:** ATF-2 requirement for VEGF-A isoform–specific control of VCAM-1 expression in endothelial cells. (A, B) Endothelial cells stimulated with 0.25 nM VEGF-A165 or VEGF-A121 in different growth conditions for 4 h were analyzed by qRT-PCR for (A) ATF-2 or (B) VCAM-1 mRNA levels. GAPDH mRNA was used as an internal control. Error bars denote ±SEM (n = 3).

(C) Endothelial cells subjected to RNA interference and knockdown with either scrambled (Scr) or ATF-2–specific (ATF-2) siRNA duplexes were then stimulated with 0.25 nM VEGF-A165 or VEGF-A121 for 8 h, lysed, and subjected to immunoblot analysis for a variety of proteins, including ATF-2, VEGFR2, and VCAM-1. (D) Quantification of ATF-2 knockdown in endothelial cells. Error bars indicate ±SEM (n ≥ 3). (F) Endothelial cells treated with scrambled (Scr), ATF-2, or VCAM-1 siRNA duplexes were stimulated with 0.25 nM VEGF-A165 or VEGF-A121 (7 h) before binding of calcein-labeled, activated HL-60 leukocytes and lysis and measurement (see Materials and Methods). Error bars denote ±SEM (n ≥ 3). *p < 0.05, **p < 0.005.
question as to the importance of ATF-2 in endothelial cell function and responses such as cell migration and tubule formation (tubulogenesis). To address this, we first compared the roles of these two VEGF-A isoforms in promoting endothelial cell migration, tubulogenesis, and ex vivo angiogenesis. VEGF-A165 produced a marked dose-dependent stimulation in endothelial cell migration (Supplemental Figure S3, A and B) and tubulogenesis (Supplemental Figure S3, C and D). However, VEGF-A121 showed a much reduced or modest stimulation in such endothelial cell responses, and such effects were especially evident at intermediate or substoichiometric concentrations of VEGF-A (Supplemental Figure S3, B and D). Ex vivo angiogenesis assays using mouse aortic slices (Supplemental Figure S3E) showed VEGF-A165 had approximately threefold higher capacity to stimulate vascular sprouting (Supplemental Figure S3F). Thus each VEGF-A isoform had a distinct capacity to promote differential endothelial cell outputs; VEGF-A165 was generally more biologically active at low or substoichiometric concentrations.

This raised the question as to whether ATF-2 was equally important for such differential programming of these endothelial cell responses. ATF-2 knockdown completely abolished either VEGF-A165- or VEGF-A121-stimulated cell migration (Figure 6, A and B). ATF-2 knockdown also inhibited (∼50%) both VEGF-A165- and VEGF-A121-stimulated tubulogenesis (Figure 6, C and D). ATF-2 was also required for endothelial cell proliferation (Supplemental Figure S4). Depletion of ATF-2 resulted in a approximately twofold decrease in VEGF-A165-stimulated cell proliferation (Supplemental Figure S4). Of interest, depletion of ATF-2 also significantly reduced endothelial cell proliferation in complete media (Supplemental Figure S4).

Although VCAM-1 was required for endothelial–leukocyte adhesion (Figure 5F), this raised the possibility that it may also be required for other endothelial responses. To test this idea, we treated endothelial cells with scrambled or VCAM-1-specific siRNA duplexes before assessing VEGF-A isoform-specific endothelial tubulogenesis (Supplemental Figure S5, A and B). There was no significant difference in tubulogenesis between control and VCAM-1–depleted endothelial cells (Supplemental Figure S5B).

**DISCUSSION**

In this study, we show that different VEGF-A isoforms have differential capacities to regulate VCAM-1 gene expression and modulate endothelial–leukocyte binding via a novel mechanism (Figure 7). In this model, two VEGF-A isoforms with similar binding affinities differentially program VEGFR2 activation and downstream signal transduction to act on a common nuclear “switch” that regulates VCAM-1 expression. This “switch” comprised nuclear ATF-2, a transcription factor that is regulated by increased signal transduction from the MEK1-ERK1/2 pathway. Our findings show that ATF-2 is an important factor that regulates both VEGF-A–regulated responses and other essential pathways.

A key feature in VEGF-A–stimulated VCAM-1 expression is the requirement for ERK1/2 activation and ATF-2 expression. Maximal VCAM-1 expression is dependent on endothelial cell stimulation by a specific VEGF-A165 isoform. This isoform greatly increased VEGFR2 phosphorylation at residue Y1175 in comparison to the VEGF-A121 isoform. This correlated with an increased ability to promote ERK1/2 activation and nuclear translocation (Figure 7). Translocation of activated ERK1/2 into the nucleus revealed close proximity to activated phospho–ATF-2. It is feasible that the T71 residue on ATF-2 is directly phosphorylated by ERK1/2. Alternatively, another target of ERK1/2, such as the p90 ribosomal S6 kinase (p90rsk or MAPKAP-K1), can also translocate into the nucleus and phosphorylate key transcription factors (Arthur, 2008; Gerits et al., 2008).
VEGF-A–stimulated intracellular signaling over a short time frame (0–2 h) caused early VCAM-1 gene transcription and increased mRNA levels (2–8 h) with concomitant peak in VCAM-1 expression at the cell surface after 8 h. In this way, short-range signal transduction is translated into intermediate and long-range effects such as membrane protein expression and subsequent interactions that modulate endothelial interactions with the environment. A key feature is that two different VEGF-A isoforms of either 165 or 121 residues in length show significantly altered ability to promote VCAM-1 expression. This is largely due to decreased ERK1/2 activation by the shorter VEGF-A121 isoform. The different VEGF-A isoforms have a conserved N-proximal region (residues 1–111) and variable C-terminus (112–206). Of note, all VEGF-A isoforms display similar binding affinity to VEGFR2 (Keyt et al., 1996; Delcombel et al., 2013), but unique receptor–ligand complexes can produce different functional outputs. Of interest, it has been noted that the murine orthologues of VEGF-A121 and VEGF-A165 show capacity to differentially elevate expression of another cell adhesion molecule, ICAM-1, in the mouse ocular endothelium (Usui et al., 2004). The underlying mechanism regulating such differential VEGF-A–regulated ICAM-1 expression is unknown but raises the speculation that ATF-2 may be involved in this phenomenon as well. In this context, it is well known that different VEGF-A isoforms have the capacity to trigger differential VEGFR2 activation and downstream signal transduction (Zhang et al., 2000, 2008; Bates et al., 2002; Nakatsu et al., 2003; Herve et al., 2005; Chen et al., 2010). An important question concerns the mechanism underlying VEGF-A–stimulated gene transcription (Goddard and Iruela-Arispe, 2013). STAT3 (Bartoli et al., 2003), Egr3 (Liu et al., 2003), forkhead-like transcription factors (Abid et al., 2006), FoxO- and Ets-related factors (Dejana et al., 2007), and HLX (Testori et al., 2011) have all been implicated in regulating VEGF-A–dependent gene transcription.

How ATF-2 regulates VCAM-1 gene transcription is intriguing. ATF-2 was originally identified as a nuclear transcriptional switch that was activated upon DNA damage or stress, thus enabling gene expression linked to an antiapoptotic response or cell proliferation (Lau and Ronai, 2012). The ATF-2 polypeptide can undergo phosphorylation at different Ser/Thr residues at the N-terminus (T52, S62, T69, T71, S73, S121) or C-terminus (S490, S498; Lau and Ronai, 2012). The increased recruitment of activated leukocytes to a developing blood vessel during angiogenesis. This would be useful in controlling vascular development and endothelial–leukocyte interactions. Schematic describing VEGF-A isoform–specific stimulation of intracellular signaling and ATF-2–regulated VCAM-1 expression. Numbered steps denote the following: 1) VEGFR2 activation by either VEGF-A165 or VEGF-A121 programs differential phosphorylation of residue Y1175; 2) VEGF-A165 stimulates elevated ERK1/2 phosphorylation and activation compared with VEGF-A121; 3) phosphorylated ERK1/2 translocates to the nucleus and regulates ATF-2 phosphorylation; 4) VEGF-A165 is more potent than VEGF-A121 in promoting ATF-2 phosphorylation as a result of increased ERK1/2 activity; 5) VEGF-A165–stimulated ATF-2 activity regulates VCAM-1 gene transcription; 6) VCAM-1 gene expression then promotes increased endothelial–leukocyte interactions; and 7) VEGF-A–stimulated ATF-2 activity also modulates other VEGF-A isoform–specific endothelial responses.

**FIGURE 7:** A mechanism for VEGF-A isoform–specific regulation of endothelial–leukocyte interactions. Schematic describing VEGF-A isoform–specific stimulation of intracellular signaling and ATF-2–regulated VCAM-1 gene expression. Numbered steps denote the following: 1) VEGFR2 activation by either VEGF-A165 or VEGF-A121 programs differential phosphorylation of residue Y1175; 2) VEGF-A165 stimulates elevated ERK1/2 phosphorylation and activation compared with VEGF-A121; 3) phosphorylated ERK1/2 translocates to the nucleus and regulates ATF-2 phosphorylation; 4) VEGF-A165 is more potent than VEGF-A121 in promoting ATF-2 phosphorylation as a result of increased ERK1/2 activity; 5) VEGF-A165–stimulated ATF-2 activity regulates VCAM-1 gene transcription; 6) VCAM-1 gene expression then promotes increased endothelial–leukocyte interactions; and 7) VEGF-A–stimulated ATF-2 activity also modulates other VEGF-A isoform–specific endothelial responses.
balance within a vascular niche. Alternatively, such a phenomenon could be extremely useful during pathogenic infection or injury: the release of specific VEGF-A isoforms into the damaged vasculature not only could promote leukocyte recruitment but also could attenuate leukocyte recruitment to the extent of infection or injury. VEGF-A165 has been shown to stimulate VCAM-1 expression (Kim et al., 2001a; Abid et al., 2006), but this has also been contradicted (Stannard et al., 2007). In this context, it has been shown that proinflammatory cytokines such as interleukin 1β or tumor necrosis factor α (TNFα) promote NF-κB, SP1, AP-1, and IRF recruitment to the VCAM-1 locus to stimulate VCAM-1 expression (Collins et al., 1995; Weber, 1996; Hordijk, 2006; Sixt et al., 2006). A link between ATF-2 and NF-κB has also been proposed in regulating VCAM-1 expression during shear stress (Cuhilmann et al., 2011). Expression of a mutant ATF-2 in a mouse model has been shown to inhibit VCAM-1 expression (Reimold et al., 2001).

The interactions between endothelial cells and leukocytes can be subverted in major disease states ranging from atherosclerosis, rheumatoid arthritis, and pathogenic infection to cancer. This study now provides a mechanism to explain how different VEGF-A isoforms regulate not only angiogenesis but also inflammation in such disease states. Immune cells are well known to secrete proangiogenic cytokines such as TNFα and vascular endothelial growth factor A (VEGF-A; Griffioen and Molema, 2000; Naldini and Carraro, 2005). The angiocrine model postulated by Rafii and colleagues suggests that the endothelium secretes soluble and membrane-bound factors that act in a paracrine manner on neighboring cells to influence vascular development in tissues such as liver (Butler et al., 2010; Ding et al., 2010). Our work shows that VEGF-A isoforms have unique abilities to instruct the endothelium and influence leukocyte recruitment at local sites through cell–cell interactions. It will be a challenge to decipher the myriad of biological properties of the VEGF family with functional roles in both angiogenesis and inflammation in healthy and diseased states.

MATERIALS AND METHODS

Antibodies and growth factors

Antibodies were goat anti-VEGFR2 (R&D Systems, Minneapolis, MN), rabbit anti-ERK1/2, mouse anti-phospho-ERK1/2 (Thr202/Tyr204), rabbit anti-p38, rabbit anti-phospho-p38 (Thr180/Tyr182), rabbit anti-phospho-VEGFR2 (Tyr1175), rabbit anti–ATF-2, rabbit anti-phospho-AKT-2 (Thr473), rabbit anti-NRP1 (Cell Signaling Technology, Danvers, MA), mouse anti–α-tubulin, mouse anti–PECAM-1 (CD31; Santa Cruz Biotechnology, Santa Cruz, CA), and mouse anti–VCAM-1 (DAKO, Glostrup, Denmark).

Reagents were as follows. Endothelial cell growth medium (ECGM) was from PromoCell (Heidelberg, Germany). Scrambled, ATF-2, NRP1, and VCAM1 siRNA duplexes were purchased as siGENOME SMARTpools from Dharmacon (Thermo Scientific, Lafayette, CO) unless otherwise stated in the figure legends. Recombinant human VEGF-A165 was from Genentech (San Francisco, CA), and VEGF-A121 was from Promocell.

Cell culture, immunoblotting, and immunofluorescence studies

Human umbilical vein endothelial cells (HUVECs) were prepared as previously described (Howell et al., 2004). Cells were seeded into six-well plates and cultured (for at least 24 h) in ECGM until ~80% confluent, washed three times with phosphate-buffered saline (PBS), and then starved in MCDB131 plus 0.2% (wt/vol) bovine serum albumin (BSA) for 2–3 h. HUVECs were then stimulated with 0, 0.025, 0.25, or 1.25 nM VEGF-A isoform for the desired time period. Cells were then washed three times with ice-cold PBS and lysed in buffer with 2% (wt/vol) SDS, Tris-buffered saline, 1 mM phenylmethylsulfonyl fluoride, and protease inhibitor cocktail (Sigma-Aldrich, Poole, United Kingdom). Protein concentration was determined using the bicinchoninic acid assay (ThermoFisher, Loughborough, United Kingdom). A 25 μg amount of protein lysate was subjected to SDS–PAGE before analysis by immunoblotting. For immunofluorescence analysis, cells were serum starved for 3 h before being stimulated with VEGF-A165. Cells were fixed and processed as previously described (Bruns et al., 2010). Images were acquired using a DeltaVision wide-field deconvolution microscope (Applied Precision, Issaquah, WA). Relative colocalization was quantified using ImageJ (National Institutes of Health, Bethesda, MD) as previously described (Bruns et al., 2010; Jopling et al., 2011).

Pharmacological inhibition of signal transduction

Cells were seeded and starved as stated previously, then pretreated with 10 μM SB203580 or U0126 (LC Labs, Boston, MA) for 30 min before stimulation with 1.25 nM VEGF-A isoform in MCDB131 plus 0.2% (wt/vol) BSA for 15 min. Cells were then processed via SDS–PAGE before immunoblot analysis.

Lipid-based transfection of siRNA duplexes

Cells were reversed transfected with siRNA duplexes using Lipofectamine RNAiMAX (Invitrogen, Paisley, United Kingdom). Per well of a six-well plate, 15 μl of 2 μM siRNA duplexes was added to 481 μl of serum/antibiotic-free OptiMEM (Invitrogen) and allowed to settle at room temperature for 5 min. Then 4 μl of Lipofectamine was added, and the mixture was inverted briefly and incubated at room temperature for 20 min. HUVECs were seeded at 2.5 × 10^5 cells/ml in a 1 ml volume of OptiMEM, followed by immediate dropwise addition of the siRNA/Lipofectamine mixture. Cells were left at room temperature for 30 min before being returned to the incubator. After 6 h total of incubation, medium was replaced for ECGM. Cells were allowed to recover for 72 h before treatment or processing for analysis.

Quantitative reverse transcription PCR

HUVECs were treated with siRNA duplexes specific for either ATF-2 or a scrambled (Scr) sequence for 72 h before growth arrest induced by overnight serum starvation (serum free) and 2 mM thymidine supplementation. Control cells were released for 4 h in full growth medium together with either 0.25 nM VEGF-A165 or VEGF-A121 before extraction of total RNA with the RNasea Plus Mini Kit (Qiagen, Manchester, United Kingdom). A 1 μg total amount of RNA was reverse transcribed using the GoScript Reverse Transcription System (Promega, Southampton, United Kingdom). Real-time quantitative reverse transcription PCR (qRT-PCR) was performed using Power SYBR Green master mix (Applied Biosystems, Warrington, United Kingdom) with the following primer sets: glyceraldehyde-3-phosphate dehydrogenase (GAPDH; endogenous control), forward primer 5′-GTC TCC TCT GAC TTC AAC AGC G-3′, reverse primer 5′-ACC ACC CTG TTG CTG TAG CCA A-3′; ATF-2, forward primer 5′-GCT TCC TCT GAC TTC AAC AGC G-3′, reverse primer 5′-ACC ACC CTG TTG CTG TAG CCA A-3′; VEGF-A165, reverse primer 5′-TGG TCA CAG AGC CAC CTT GGT AGG ACT T-3′, forward primer 5′-GTG TGC CCT TCG ACC AGC AAG C-3′, reverse primer 5′-GCC AGC GGA TTT GGT AGG ACT T-3′; and VCAM-1, forward primer 5′-GAT CAG TCC CCG ACC ACC ACT T-3′, reverse primer 5′-GAT CAG TCC CCG ACC ACC ACT T-3′. qRT-PCR was carried out in multwell plates run on an ABI 7900HT Fast Real-Time PCR System (Applied Biosystems) and gene expression analyzed using the ΔΔCT method standardized against an endogenous control, GAPDH.
Leukocyte-binding assay
We labeled 2 × 10^5 HL-60 leukocytes/well with 0.5 μg/ml calcein (Invitrogen) for 30 min at 37°C. Cells were then pelleted and washed twice in 5 ml RPMI plus 10% (vol/vol) fetal calf serum (Invitrogen). Cells were left for 30 min at 37°C to allow deesterification of calcein agent. Then 100 nM phorbol 12-myristate 13-acetate (PMA; Sigma-Aldrich, Poole, United Kingdom) was added to the cells and left to incubate for 30 min at 37°C. Cells were again pelleted and washed twice in 5 ml RPMI. Then 2 × 10^5 HL-60 leukocytes/well were added onto a confluent layer of HUVECs that had been previously stimulated with full growth medium (±VEGF-A165 or VEGF-A121 for 7 h) and left to adhere for 1 h at 37°C. Nonadhered leukocytes were removed by gentle rinsing with PBS. Cells were then lysed in 200 μl of RIPA buffer. Then 50 μl was analyzed by fluorescence excitation at 488 nm and emission at 520 nm in a multiwall plate format using a 96-well FLUOstar OPTIMA fluorescence plate reader (BMG LABTECH, Aylesbury, United Kingdom). Values were compared with controls where VEGF-A was absent.

Cell migration assay
HUVECs were seeded at 3 × 10^4 cells/well into a 8 μm pore size Transwell filter inserted into a 24-well companion plate (BD Biosciences, Oxford, United Kingdom) in MCDB131 plus 0.2% (wt/vol) BSA. ECGM or MCDB131 plus 0.2% (wt/vol) BSA containing the desired concentration of VEGF-A was added to the lower chambers to stimulate cell migration. Cells were allowed to migrate for 24 h before being fixed and stained with 0.2% (wt/vol) crystal violet in 20% (vol/vol) methanol. Nonmigrated cells were then removed from the upper chamber using a moist cotton bud. Three to five random fields were imaged per Transwell filter and the average number of migratory cells calculated.

Tubulogenesis assay
Primary human foreskin fibroblasts (Promocell) were cultured to confluency in 48-well plates in Q333 fibroblast growth medium (PAA Laboratories, Pasching, Austria). Then 6500 HUVECs were seeded onto the fibroblast monolayer in a 1:1 mixture of Q333 and ECGM and left for 24 h. Medium was then removed and replaced with fresh ECGM ± VEGF-A as desired; medium was replaced every 2–3 d for 7 d. Cocultures were then fixed in 200 μl for 20 min and blocked in 1% (wt/vol) BSA for 30 min at room temperature. Cocultures were then incubated with 1 μg/ml mouse anti-human PECAM-1 (CD31; Santa Cruz Biotechnology, Santa Cruz, CA) overnight at room temperature. Cells were washed three times with PBS before incubation with donkey secondary antibody anti-mouse Alexa Fluor 594 conjugate (Invitrogen) for 2–3 h at room temperature. Wells were then washed three times with PBS. Endothelial tubules were then visualized by immunofluorescence microscopy using an EVOS-fl inverted digital microscope (Life Technologies). Five random fields were imaged per well. Both the number of branch points and the total tubule length were then quantified from each photographic field using the open source software AngioQuant (www.cs.tut.fi/sgn/csb/angioquant) and values averaged. For a more detailed method see Fearnley et al. (2014).

Ex vivo aortic sprouting assay
This protocol was adapted from previous studies (Baker et al., 2012). All animal and tissue procedures were carried out in accordance with United Kingdom Home Office regulations and guidance at room temperature unless otherwise stated. Briefly, male wild-type C57Bl/6 mice were killed in accordance with United Kingdom Home Office regulations. Thoracic aorta was harvested from aortic arch to diaphragm and flushed with 500 μl of Hank’s balanced salt solution to remove blood products. Fat and fascia were cleaned from the aorta by sharp dissection and the vessel sliced into 0.5-mm rings with a scalpel. Rings were serum starved overnight at 37°C in 5 ml OptiMEM supplemented with penicillin-streptomycin. On ice, purified type 1 rat-tail collagen (Millipore, Watford, United Kingdom) was diluted to 1 mg/ml with DMEM before adding 2 μl/ml of 5 M NaOH. A 55 μl amount of this embedding matrix was pipetted per well into a 96-well plate and aortic ring submerged within. Plates were left for 15 min at room temperature before incubation at 37°C for 30 min. A 150 μl amount of OptiMEM containing 2.5% (vol/vol) FCS and penicillin-streptomycin was added per well with appropriate VEGF-A. Aortic rings were incubated at 37°C for 5 d with a medium change on day 3. Wells were washed with 150 μl of PBS containing 2 mM CaCl2 and 2 mM MgCl2 and fixed in 4% (vol/vol) Formalin for 30 min. The collagen was permeabilized with three 15 min washes with PBS buffer containing 2 mM MgCl2, 2 mM CaCl2, and 0.25% (vol/vol) Triton X-100. Rings were blocked in 30 μl of 1% (wt/vol) BSA in PBLEC (PBS containing 100 μM MnCl2, 1% [vol/vol] Tween-20, 2 mM CaCl2, 2 mM MgCl2) for 30 min at 37°C. A 2.5 μg amount of BS1 lectin–fluorescein isothiocyanate (Sigma-Aldrich) in PBLEC was added per well, followed by overnight incubation at 4°C. Wells were washed three times with 100 μl of PBS containing 2 mM MgCl2, 2 mM CaCl2, and 0.25% (vol/vol) Triton X-100 and incubated for 2 h with 1 μg/ml 4′,6-diamidino-2-phenylindole (in PBLEC). Wells were washed three times with 100 μl PBS containing 0.1% (vol/vol) Triton X-100 and then with 100 μl of sterile water. Aortic sprouts were imaged using an EVOS-fl inverted digital microscope (Life Technologies). The number of initial sprouts (vascular sprouts emanating directly from the aortic ring) was counted, and sprout intensity (total image intensity— aortic ring intensity) was determined using ImageJ software.

Endothelial cell proliferation assay
Two thousand endothelial cells were seeded per well of a 96-well plate and left to acclimatize in complete growth medium overnight. On the next day, medium was changed and cells starved in MCD8131 medium plus 0.2% BSA (wt/vol) for 3 h. Cells were then stimulated with the desired concentration of VEGF-A isoforms in a final 100 μl volume for 24 h. Bromodeoxyuridine, 10 μM, was added per well after 20 h. A cell proliferation enzyme-linked immunosorbent assay was then used according to manufacturer’s instructions (Roche Diagnostics, Mannheim, Germany). The color change was developed using 3,3′,5,5′-tetramethylbenzidine solution and the reaction quenched with 1 M H2SO4. Absorbance was measured at 450 nm using a variable-wavelength 96-well plate reader (Tecan, Manndorf, Switzerland).

Statistical analysis
This was performed using a one-way analysis of variance (ANOVA), followed by Tukey’s post hoc test or two-way ANOVA followed by Bonferroni multiple comparison test, using Prism software (GraphPad, La Jolla, CA). Significant differences between control and test groups were evaluated with *p < 0.05, **p < 0.01, ***p < 0.005, and ****p < 0.001 indicated on the graphs. Error bars in graphs and histograms denote ±SEM.

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