Filt1 acts as a negative regulator of tip cell formation and branching morphogenesis in the zebrafish embryo

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SUMMARY
Endothelial tip cells guide angiogenic sprouts by exploring the local environment for guidance cues such as vascular endothelial growth factor (VegfA). Here we present Filt1 (Vegf receptor 1) loss- and gain-of-function data in zebrafish showing that Filt1 regulates tip cell formation and arterial branching morphogenesis. Zebrafish embryos expressed soluble Filt1 (sFilt1) and membrane-bound Filt1 (mFilt1). In Tg(flt1<sup>BAC</sup>:yfp) × Tg(kdrl:ras-cherry)<sup>916</sup> embryos, ftt1:yfp was expressed in tip, stalk and base cells of segmental artery sprouts and overlapped with kdrl:cherry expression in these domains. ftt1 morphants showed increased tip cell numbers, enhanced angiogenic behavior and hyperbranching of segmental artery sprouts. The additional arterial branches developed into functional vessels carrying blood flow. In support of a functional role for the extracellular VEGF-binding domain of Filt1, overexpression of sflt1 or mflt1 rescued aberrant branching in ftt1 morphants, and overexpression of sflt1 or mflt1 in controls resulted in short arterial sprouts with reduced numbers of filopodia. ftt1 morphants showed reduced expression of Notch receptors and of the Notch downstream target efnb2a, and ectopic expression of ftt4 in arteries, consistent with loss of Notch signaling. Conditional overexpression of the notch1a intracellular cleaved domain in ftt1 morphants restored segmental artery patterning. The developing nervous system of the trunk contributed to the distribution of Filt1, and the loss of ftt1 affected neurons. Thus, Filt1 acts in a Notch-dependent manner as a negative regulator of tip cell differentiation and branching. Filt1 distribution may be fine-tuned, involving interactions with the developing nervous system.

KEY WORDS: Filt1, VEGF, Angiogenesis, Notch, Tip cells, Nerves, Zebrafish

INTRODUCTION
Sprouting angiogenesis plays a crucial role in vascular network expansion during normal development and pathophysiological conditions (Carmeliet et al., 2009). Angiogenic sprouting involves the specification of endothelial cells into tip and stalk cells in the growing sprout (Phng and Gerhardt, 2009), with the tip cell being localized at the leading edge of the sprout. Tip cells extend numerous filopodia and respond to guidance cues including vascular endothelial growth factor (VegfA), directing the movement of the sprout. The endothelial cells that follow the tip cells are called stalk cells. Stalk cells have fewer filopodia, they proliferate in response to VegfA, and they contribute to vessel lumen formation. Within the sprout, endothelial cells dynamically compete with each other for the tip cell position (Jakobsson et al., 2010). The full repertoire of genes controlling endothelial tip cell differentiation is unknown, but VEGF receptors including Flk1 (Kdr, Vegfr2) and Flt4 (Vegfr3) and Notch–delta-like 4 (Dll4) signaling pathways play key roles (Benedito et al., 2009; Gerhardt et al., 2003; Hellstrom et al., 2007; Lobov et al., 2007; Siekmann and Lawson, 2007; Suchting et al., 2007; Tammela et al., 2008). Here, we present genetic evidence that ftt1 (vegfr1) acts, in a Notch-dependent manner, as a negative regulator of tip cell formation and sprout guidance in the trunk vasculature of zebrafish embryos.

In mammals, thus far three VEGF receptors have been identified, namely Filt1, Flk1 and Flt4. In all other vertebrate classes, four receptors exist (Bussmann et al., 2008). These receptors bind VEGF ligands and regulate angiogenesis and lymphangiogenesis (Alitalo et al., 2005; Ferrara et al., 2003). Zebrafish VEGF receptor proteins are encoded by the ftt1, kdr (previously kdrb), kdr-like (kdrl, previously kdra) and the ftt4 (Bussmann et al., 2008) orthologs. Whereas the roles of ftt1, kdr and kdrl, and of ftt4 in mediating vascular development in zebrafish are well described (Covassin et al., 2009; Covassin et al., 2006; Habeck et al., 2002; Hogan et al., 2009b; Lawson et al., 2002; Liao et al., 1997; Siekmann and Lawson, 2007), surprisingly little is known about ftt1. Thus far, ftt1 has been implicated in the regulation of embryonic heart function and cardiac morphogenesis (Bussmann et al., 2007; Rottbauer et al., 2005), but its specific role in endothelial tip cell formation in zebrafish is unknown.

In mammals, Filt1 encodes one membrane-bound form, which has an intracellular tyrosine kinase signaling domain, and soluble forms, which only contain the extracellular VEGF-binding domain (Sela et al., 2008). Genetic studies in mice have shown that Filt1 plays a pivotal role in both developmental and pathological forms of angiogenesis (Ferrara et al., 2003; Fong et al., 1995). Filt1-null mice die at ~E8.5 and show disorganized blood vessels and overgrowth of endothelial cells (Fong et al., 1995). However, Filt1 tyrosine kinase-deficient homozygous mice (Filt1<sup>TK/−</sup>) survive and appear to develop normal vessels, suggesting that the tyrosine
kinase activity is dispensable for vascular morphogenesis (Hiratsuka et al., 1998). Other studies show that the soluble form of Flt1 regulates vessel development by acting as a sink for VegfA, thus limiting both extracellular VegfA availability and signaling through Flk1 (Ambati et al., 2006; Gerhardt et al., 2003; Roberts et al., 2004).

Here, we focused on the role of flt1 in tip cell formation and branching morphogenesis of segmental vessels in the trunk of zebrafish embryos. We show that flt1 regulates tip cell formation and segmental artery branching. We furthermore reveal a contribution of the developing nervous system to the distribution of Flt1.

MATERIALS AND METHODS

Zebrafish experiments

Zebrafish were kept at 26.5°C and bred under standard conditions. Tg (fltl:egfp)\(^{s3}\), Tg(kdrl:hras-mcherry)\(^{s896}\), Tg(kdrl:ras-cherry)\(^{s3}\), Tg(fltl flipping;sfll)\(^{s3}\), Tg(tha:egfp), Tg(hsp70:Gal4) and Tg(uas: notch1a-ICD) transgenic zebrafish lines were used as described (Chi et al., 2008; Hogan et al., 2002; Siekmann and Lawson, 2007; Lawson and Weinstein, 2002; Park et al., 2009; Siekmann et al., 2003). Egg water containing DMSO alone was utilized as control.

Isolation and cloning of sfll

We identified the 3′ and 5′ ends of the sfll isoform by RACE PCR using Clontech RACE Kits on first-strand cDNA prepared from RNA of zebrafish embryos (30 hpf). The primers for the 3′ ends of the sfll isoform were designed specific to the mflt1 (GenBank accession 72535147) and sflt1 (GenBank accession 12025). Amplification was carried out using an ABI Prism 7000 sequence detector (Applied Biosystems). Gene expression data were normalized against elongation factor 1-alpha.

Whole-mount in situ hybridization, western blot and immunohistochemistry

Whole-mount in situ hybridization with antisense RNA probes was performed as described (Joewett and Lettice, 1994); see Table S1 in the supplementary material for details. The polyclonal antibody against zebrafish Flt1 extracellular domain (CQVTSGPSKRETNTT; Eurogentec, Belgium) was purified by affinity matrix and used at 1:1000. To verify the specificity of the Flt1 antibody in a western blot, we overexpressed zebrafish Flt1 coupled to GFP. Immunoprecipitation was performed on extracts from HeLa cells transfected with the expression vector pEGFP-C3-zebrafish flt1. At 24 hours after transfection, the fusion protein was purified from cell lysates using an anti-GFP antibody (Sigma-Aldrich) and protein G sepharose (Invitrogen).

For immunofluorescence staining, embryos were fixed in 4% paraformaldehyde and permeabilized with methanol and acetone. To detect Flt1 staining in vessels, the immune signal was amplified by tyramide signal amplification (TSA; Perkin Elmer). Anti-phospho-histone H3 (Ser10, Millipore), ImmunoPure goat anti-rabbit IgG (Thermo scientific) and zn-12 (ZFIN) antibodies were used. As secondary antibodies, polyclonal goat anti-rabbit HRP (Dako, Denmark) and Alexa Fluor 633 goat anti-rabbit IgG (Invitrogen) were used.

Drugs

DAPT was purchased from Sigma-Aldrich and dissolved in DMSO. DAPT was used at a final concentration of 100 μM diluted as described (Leslie et al., 2007). Egg water containing DMSO alone was utilized as control.

Imaging

In vivo blood flow was imaged using a Zeiss intravital microscope setup (Zeiss AxioScope A1, Carl Zeiss MicroImaging, Jena, Germany) with a 20× (N.A. = 0.50) water-emersion objective. Images were stored on digital tape (Sony DVCAM64) using a digital video recorder (Sony DVCAM-DSR-25). For confocal time-lapse imaging of segmental vessel sprouting in Tg(flty:egfp)\(^{s3}\) and Tg(kdrl:hras-mcherry)\(^{s896}\) zebrafish, embryos were injected with flt1 or control MO, anesthetized with egg water/0.16 mg/ml tricaine/1% 1-phenyl-2-thiourea (Sigma) and embedded in 1% agarose. Using a 25× objective, confocal stack images of the trunk region were obtained in time intervals of 20 minutes. Confocal imaging was performed with a Zeiss LSM 510 microscope (Carl Zeiss MicroImaging). The analysis was performed using Zeiss ZEN software.

Statistics

Data are expressed as mean ± s.e.m. Statistical analysis was performed using Student’s two-tailed t-test (P < 0.05).

RESULTS

Zebrafish embryos express membrane-bound and soluble Flt1

We examined the expression pattern of flt1 isoforms in zebrafish embryos by Taqman analysis, western blot and whole-mount in situ hybridization (Fig. 1; see Fig. S1 in the supplementary material). We detected one long form of flt1 compatible with membrane-bound Flt1 (mFlt1) (Fig. 1A; see Fig. S1A-C in the supplementary material), and by 3′ and 5′ RACE-PCR we identified a shorter flt1 isoform, compatible with membrane-bound (flt1)1 isoforms in zebrafish material (Fig. 1A; see Fig. S1A-C in the supplementary material). The sfll isoform resulted from alternative splicing, causing an extension of exon 10. This extension encodes the 5′ region of intron 10. Based on this mRNA sequence in sfll (Fig. 1A; see Fig. S1C in the supplementary material) that is not shared by mflt1, we were able to design isoform-specific Taqman primers and antisense riboprobes for isitu hybridization (see Table S1 in the supplementary material).
Flt1 controls tip cell formation

Fig. 1. Expression of flt1 isoforms in zebrafish embryos. (A) Structural organization of membrane-bound flt1 (mflt1) and soluble flt1 (sflt1). sflt1 contains a unique mRNA sequence, not present in mflt1, that encodes the 5’ region of intron 10. (B) Taqman analysis shows higher expression of sflt1 than mflt1 in control embryos at 24 hpf, 30 hpf and 48 hpf. f.c., fold change relative to mflt1 expression at indicated time-points. Error bars indicate s.e.m. (200 embryos/group from four separate experiments). (C) Whole-mount in situ hybridization with antisense riboprobes directed against mflt1 or sflt1; embryos at 30 hpf. Note that mflt1 is expressed in segmental sprouts, aorta and cardinal vein; sflt1 is expressed in segmental sprouts and aorta. Aa, dorsal aorta; PCV, posterior cardinal vein; Se, segmental artery.

Taqman analysis revealed ~3- to 5-fold higher expression levels of sflt1 compared with mflt1 during the period 24–48 hours post-fertilization (hpf) (Fig. 1B). In toto in situ hybridization showed that mflt1 was expressed in the aorta, the cardinal vein and developing segmental vessels (Fig. 1C). Expression of sflt1 was detectable in the aorta and segmental vessels, but not in the posterior cardinal vein (Fig. 1C). Expression of mflt1 and sflt1 protein in control embryos was confirmed by western blot (Fig. 2A) using whole-embryo membrane fractions and lysate, respectively.

**Flt1 regulates segmental vessel branching morphogenesis**

flt1 was knocked down by injecting an ATG-targeting MO into Tg(fli1:eGFP)y1 zebrafish embryos (Fig. 2). For technical reasons, during imaging embryos were incubated at 26.5°C. Knockdown of flt1 using an ATG-targeting MO reduced mflt1 and sflt1 protein levels (Fig. 2A) and resulted in excessive branching of segmental vessels (Fig. 2B). Similar branching defects were observed using the flt1 5’UTR-targeting MO (see Fig. S2E in the supplementary material). For the ATG-blocking MO, effects were observed at a dose of 3 ng; at higher dosages, we observed dysmorphogenesis of the embryo, and these were therefore not examined in detail. We observed striking changes in segmental vessel branching of flt1 morphants (Fig. 2B). Although the position of the initial sprout formation was not affected (Fig. 2B, 30 hpf), at later stages segmental vessels formed aberrant connections laterally, both in the posterior and anterior direction, connecting with the segmental vessels of the adjacent somites (Fig. 2B, 48 and 72 hpf). Once the intersegmental vessel (ISV) sprouts reached the horizontal myoseptum, they subsequently deviated by an angle of ~20–30 degrees in the anterior or posterior direction. The progression of the sprouts appeared slower in flt1 morphants than in the control. The aberrant vessel connections formed a lumen, carried blood flow and were not pruned (Fig. 2B, 72 hpf; see Movies 1 and 2 in the supplementary material). This aberrant branching phenotype was observed in 75% of all flt1 ATG-blocking MO-injected animals (Fig. 2D; n=420, six separate sets of experiments), but never in controls (n=420, six separate sets of experiments).

To verify that the vascular phenotype was due to a reduction in flt1 expression, we performed rescue experiments by co-injection of the flt1 ATG-targeting MO with either mflt1 or sflt1 mRNA (Fig. 2C). Co-injection of flt1 MO with mflt1 or sflt1 mRNA resulted in a significant rescue of the vascular phenotype (Fig. 2C,D).

Consistent with a role for flt1 in ISV branching, injection of mflt1 or sflt1 mRNA increased Flt1 protein levels (see Fig. S2A in the supplementary material) and reduced sprouting of the segmental arteries (Fig. 2E,F). Although the initial segmental sprout positioning was correct, sprout expansion stopped halfway towards the dorsal roof. The tip cells of such sprouts displayed shorter or no filopodial extensions (Fig. 2E).

flt1 has been implicated in the regulation of heart rate (Rottbauer et al., 2005). We assessed heart rate (see Fig. S2C,D in the supplementary material) and perfusion of the trunk vasculature using an intravital imaging approach (see Movies 3 and 4 in the supplementary material). Heart rate was lower in flt1 morphants than in control MO-injected embryos, but dorsal aorta, posterior cardinal vein and segmental vessels were perfused with blood (see Movies 3 and 4 in the supplementary material), indicating that a circulatory loop was established in flt1 morphants.

**Flt1 regulates tip cell differentiation**

We imaged segmental artery sprouting in flt1 morphants and observed an increase in tip cell number and angiogenic sprouting behavior (Fig. 3; see Fig. S3A and Movies 5 and 6 in the supplementary material). In control embryos, segmental sprouts consisted of three endothelial cells arranged as follows: tip cell, followed by the connective/stalk cell, followed by the base cell, the latter connecting to the aorta (Fig. 3A; see Movie 5 in the supplementary material). In segmental vessels of flt1 morphants, we observed increased endothelial cell numbers and more cells with endothelial tip cell characteristics (Fig. 3A-D; see Movie 6...
in the supplementary material). Specifically, *flt1* morphants showed: (1) segmental vessels spearheaded by two endothelial cells displaying filopodia extensions; (2) increased filopodia extensions throughout the segmental sprout; (3) endothelial cells at a position normally taken by the connector/stalk or base cells that displayed filopodia extensions and formed connections to adjacent vessels; (4) increased endothelial cell numbers in segmental vessels (Fig. 3A-D; see Movies 5 and 6 in the supplementary material). Dorsal extension of ISVs in *flt1* morphants, at the anatomical location normally occupied by stalk/connector cells, it could be argued that these cells have a mixed tip cell/stalk cell phenotype.

Collectively, these results suggest that loss of *flt1* results in increased tip cell formation. The observed increase in angiogenic cell behavior and migration within the segmental sprout is reminiscent of the effects of loss of Notch signaling (Siekmann and Lawson, 2007).

**Tip and stalk cell marker expression and Notch signaling in *flt1* morphants**

The Notch-Dll4 signaling pathway has been implicated in the regulation of tip and stalk cell differentiation (Phng and Gerhardt, 2009; Roca and Adams, 2007) and in angiogenic cell behavior in segmental vessels (Hogan et al., 2009b; Siekmann and Lawson, 2007). Expression of the tip cell markers *kdrl, flt4* and *dll4* and of the stalk cell markers *nrarp* and *nrarb* (Phng et al., 2009) was evaluated in *flt1* morphants (Fig. 4A,B). In *kdrl* reporter fish, the leading edge of the segmental vessel is clearly wider than normal, compatible with the presence of more than one tip cell guiding the sprout. Similar results were obtained by *kdrl* whole-mount in situ hybridization. Reduced expression of *nrarp* and *nrarb* in *flt1* morphants (Fig. 4B) suggests conversion of stalk/connector cells into tip cells. In support of this, and as described above, in *flt1* morphants, at the anatomical location normally occupied by stalk/connector or base cells, endothelial cells displaying filopodia extensions were observed (see Movie 6 in the supplementary material). Since some of these cells were in the process of creating a vessel lumen, a feature that is normally assigned to a stalk/connector cell, it could be argued that these cells have a mixed tip cell/stalk cell phenotype.

In *flt1* morphants, we observed ectopic *flt4* expression in the dorsal aorta (Fig. 4A), a feature previously associated with loss of Notch signaling (Siekmann and Lawson, 2007). Since *dll4*
expression was maintained in flt1 morphants (Fig. 4A,B), we examined changes in Notch expression. Expression of the receptors notch1a, notch1b, notch2 and notch3, the Notch ligands jag1a, jag1b and jag2, and the Notch downstream target efna2a was reduced in flt1 morphants (Fig. 4C,D). These data suggest that loss of Notch signaling in flt1 morphants most likely occurs through downregulation of Notch receptors.

In flt1 morphants, conditional overexpression of the notch1a intracellular cleaved domain (NICD), using Tg(hsp70:Gal4) × Tg(UAS: notch1a-ICD) transgenic embryos as described (Siekmann and Lawson, 2007), inhibited excessive sprouting and restored segmental patterning (Fig. 4E; see Fig. S3B-F in the supplementary material). Overexpression of notch1a-ICD in control embryos resulted in severely reduced segmental vessel sprouting (see Fig. S3B,E in the supplementary material). Expression of flt1 mRNA increased after conditional overexpression of notch1a-ICD (see Fig. S3G in the supplementary material). When compared with untreated controls, in flt1 morphants with overexpression of NICD, endothelial nuclei were more frequently found at a level below the horizontal myoseptum or at the base of the segmental vessel (Fig. 4E; see Fig. S3F in the supplementary material). This suggests that restoring Notch activity affected endothelial cell movements in the sprout. However, segmental sprouts reached the dorsal roof and formed a dorsal longitudinal anastomotic vessel (DLAV), indicating that tip cell differentiation per se is not completely suppressed.

To test whether loss of Notch-Dll4 signaling is sufficient to explain the vascular branching pattern observed in flt1 morphants, we knocked down dll4 (Fig. 4F) or treated normal embryos with the Notch γ-secretase inhibitor DAPT (Fig. 4E). In line with previous reports (Leslie et al., 2007), both approaches resulted in endothelial sprouting phenotypes at the level of the DLAV (Fig. 4F, red arrows and arrowheads), but the segmental vessel branching pattern was not comparable to that of flt1 morphants (Fig. 4F, yellow arrowhead). Thus, loss of dll4 is associated with loss of Notch, but loss of Notch signaling did not phenocopy that of flt1 morphants.

**Distribution of Flt1 in vessels and the nervous system**

We examined the expression and distribution of Flt1 in more detail using Tg(fl1BAC:yfp) × Tg(kdrl:ras-cherry) embryos and Flt1 immunostaining. In Tg(fl1BAC:yfp) embryos (Hogan et al., 2009a), YFP expression was mainly observed in the arterial domain including the aorta and the segmental arteries (Fig. 5A,B), with YFP expression in the venous domain being less pronounced. Detailed examination of segmental arterial vessel sprouts revealed YFP expression in tip cells and filopodia, stalk cells and base cells (Fig. 5A, arrowhead). In segmental sprouts, the expression domain of flt1:yfp was comparable to that of kdrl:cherry (Fig. 5A). At 30 hpf, flt1:yfp expression was restricted to the vasculature; YFP expression in neural tissue was not observed at this time. By contrast, in Tg(fl1BAC:yfp) embryos at 48 hpf, we also noted non-vascular YFP expression domains, most notably in the spinal cord neurons and their axonal projections (Fig. 5B, arrowhead).

We next knocked down flt1 using the ATG-blocking MO in Tg(fl1BAC:yfp) × Tg(huc:egfp) double-transgenic embryos and observed hyperbranching of segmental arteries, similar to that observed in flt1 transgenics (Fig. 5B, left panels). The neuronal YFP expression domain was lost in flt1 morphants (Fig. 5B, lower left panel). In Tg(huc:egfp) neuronal reporter fish, knockdown of flt1 also affected neurons (Fig. 5B, right panels; see Fig. S4D in the supplementary material). This loss of neurons might also explain the reduced Notch receptor and ligand expression in the neural tube (Fig. 4C and Fig. 5B, right panels).
To determine whether the nervous system contains or binds Flt1 protein, we performed immunostaining for Flt1 using a custom-made affinity-purified antibody directed against the extracellular domain of zebrafish Flt1 (Fig. 5C-G; see Fig. S1A and Fig. S4B,C in the supplementary material). The antibody specificity was verified in a series of experiments (see Fig. S2A,B and Fig. S4B,C in the supplementary material). Whole-mount immunostaining for Flt1 in control Tg(flt1BAC:yfp) or Tg(fli:egfp)y1 embryos showed staining in vessels, neuronal tissue and somites (Fig. 5C-G; see Fig. S4A,B in the supplementary material).
Tg(huC:egfp) embryos at 30 hpf showed neuronal Flt1 immunolabeling (Fig. 5C-E), and immunopositive domains included motoneurons, interneurons and sensory nerves. In Tg(flt1BAC:yfp) embryos, neuronal YPF expression started at ~38-40 hpf. Immunostaining in Tg(flt1BAC:yfp) embryos showed co-localization of Flt1 antibody staining with YFP expression in neurons in the spinal cord (Fig. 5F), and it cannot therefore be ruled out that this neuronal population is capable of producing Flt1 protein. However, Flt1 immunostaining was already detectable on neurons at 24-30 hpf, prior to the emergence of flt1 promoter activity in the nervous system, and not all Flt1 immunopositive neurons expressed YPF. This observation is perhaps best explained by some neurons scavenging soluble Flt1 protein.
In the period 24-30 hpf, immunostaining showed clear Flt1 localization on cells situated in the dorsal aspect of the trunk (see Fig. S4B in the supplementary material). Based on their position, size and appearance, we speculated that these cells might represent Rohon-Beard primary sensory nerves (Reyes et al., 2004). We performed co-immunostaining for Flt1 and the Rohon-Beard marker zn-12 (Fig. 5G) and confirmed Flt1 immunostaining in Rohon-Beard neurons. Flt1 morphants showed reduced Flt1 immunostaining in this domain (see Fig. S4B in the supplementary material). Between 24 and 30 hpf, Rohon-Beard neurons lacked flt1 promoter activity (Fig. 5A; first and second upper panels).

We next overexpressed sflt1-cherry under the control of the flt1ep promoter in Tg(huc:egfp) embryos and noted co-localization of sflt1-cherry with neuronal cell bodies throughout the neural tube (Fig. 5H). In addition, a more diffuse sFlt1-cherry signal was observed in between the neurons (Fig. 5H). Although the fliep promoter may be active in neural crest-derived neural tissue, we clearly observed sFlt1-cherry co-localizing with spinal cord neurons located in the ventral part of the neural tube, and these neurons are not neural crest derived. These observations support the hypothesis that neurons located in the neural tube can bind soluble Flt1 protein produced by other cells. To substantiate that soluble Flt1 produced by the vasculature can reach the neural tube, we overexpressed sflt1-GFP under the control of the kdr promoter (Fig. S1) and detected the sFlt1-GFP signal at the level of the neural tube (Fig. 5I, arrowheads).

**Flt1 and macrophages**

In mice, Flt1 influences VEGF-induced macrophage migration, and macrophages are implicated in coordinating the fusion of two endothelial tip cells leading to the formation of a vessel anastomosis that can carry blood flow (Fanti et al., 2010). In whole-mount in situ hybridizations for the macrophage marker l-plastin (lymphocyte cytosolic plastin 1 – Zebrafish Information Network), we observed reduced l-plastin expression in flt1 morphants at 30 hpf (see Fig. S3H in the supplementary material). Whereas the brain regions were colonized by macrophages in flt1 morphants and control embryos, macrophages were less abundant in the trunk region of flt1 morphants. At 48 hpf, l-plastin expression was still slightly reduced in the trunk region of flt1 morphants (see Fig. S3H, I in the supplementary material). We next inhibited the formation of macrophages by MO knockdown of pu1 (spi1 – Zebrafish Information Network) (see Fig. S3J in the supplementary material). Knockdown of pu1 did not affect sprouting of segmental vessels, neither in the control nor in flt1 morphants (see Fig. S3J in the supplementary material). It is therefore unlikely that macrophages contribute to the sprouting phenotype of flt1 morphants.

**DISCUSSION**

Here we present Flt1 loss- and gain-of-function data in zebrafish embryos showing that Flt1 regulates tip cell formation and segmental artery branching morphogenesis in a Notch-dependent manner. We furthermore uncovered a role for the nervous system in the distribution of Flt1.

**Tip cell formation, Notch signaling and vessel branching in flt1 morphants**

Zebrafish embryos express membrane-bound Flt1 (mFlt1) and soluble Flt1 (sFlt1). In the vasculature, mflt1 mRNA is expressed in the aorta, the cardinal vein and the segmental arteries, whereas sflt1 mRNA expression is restricted to the arterial domain. Using Tg(flt1BAC:yfp) embryos as a readout, flt1 expression is much stronger in the arterial domain than in the venous domain. In segmental artery sprouts of Tg(flt1BAC:yfp) embryos, flt1 is expressed in the tip cell, the stalk cell and the base cell, and flt1 expression overlaps with that of kdr in these domains.

flt1 morphants show an increase in tip cell number in segmental artery vessel sprouts. In these sprouts, tip cells project filopodia extensions both dorsally and laterally, in anterior and posterior directions, and form connections with sprouts from adjacent segmental vessels. These connections are lumenized, carry blood flow and are not pruned, suggesting that the aberrant branches develop into functional vessels. The extracellular VEGF-binding domain of Flt1 appears sufficient to explain this vascular phenotype, as overexpression of sflt1 or mflt1 rescued aberrant branching in flt1 morphants. In line with this, overexpression of sflt1 or mflt1 resulted in short segmental sprouts and smaller filopodia extensions, most likely by reducing VEGF levels.

In flt1 morphants, we noticed segmental vessel sprouts spearheaded by two endothelial cells that displayed tip cell characteristics, instead of the one tip cell observed in control embryos. Cell tracking revealed that the leading endothelial tip cell gave rise to two progeny cells displaying tip cell behavior. Such tip cell differentiation events have been described in Notch-Dll4 loss-of-function models in mouse and zebrafish (Hellstrom et al., 2007; Lobov et al., 2007; Siekmann and Lawson, 2007; Suchting et al., 2007). In addition, endothelial cells displaying tip cell characteristics migrated from the base of the segmental vessel and integrated at the leading, sprouting edge. These movements are highly reminiscent of the endothelial cell movements observed in rbpsuh (rbpja)-deficient zebrafish embryos (Siekmann and Lawson, 2007). Excessive filopodia activity, increased tip cell numbers and enhanced endothelial cell migration events in sprouts are consistent with loss of Notch signaling (Siekmann and Lawson, 2007). Indeed, flt1 morphants show reduced expression of Notch receptors and of the Notch downstream target efus2a, as well as ectopic expression of flt4 in the dorsal aorta, all of which are consistent with loss of Notch signaling in our setting (Siekmann and Lawson, 2007). The expression of dll4 was slightly augmented in flt1 morphants, suggesting intact VEGF receptor signaling, and the loss of Notch signaling in flt1 morphants is thus most likely due to a reduction in Notch expression. Taken together, flt1 morphants have more tip cells and these tip cells display a high degree of migratory behavior along the developing sprout. We postulate that these two features, combined with a presumed increase in VegfA in the local extravascular compartment caused by loss of soluble Flt1, account for the hyperbranching of segmental arteries.

Notch signaling can regulate angiogenic cell behavior and tip cell differentiation in segmental sprouts (Jakobsson et al., 2010; Siekmann and Lawson, 2007). In a developing sprout, endothelial cells frequently shuffle from the tip to the stalk cell position and vice versa (Jakobsson et al., 2010). Activated Notch signaling restricts such endothelial movements, whereas loss of Notch facilitates shuffling and allows integration of tip cells at the leading edge. Conditional overexpression of NICD rescued segmental vessel patterning defects in flt1 morphants. In this setting, segmental sprouts reach the dorsal roof and make a DLAV, but endothelial cell movements in the sprout appear to be restricted. Endothelial cells are more frequently localized at the base of the segmental vessel, instead of being distributed evenly along its length. This is compatible with a model in which (conditional) activation of Notch signaling in flt1 morphants limits endothelial cell migration events in the sprout. A reduction in the shuffling of
endothelial cells (with tip cell characteristics) from the stalk cell/base position towards the leading edge of the segmental sprout might prevent the formation of the additional lateral branches.

Consistent with activated Notch signaling, flt1 mRNA expression increased after overexpression of NICD, and an increase in Flt1 levels may contribute to the rescue by reducing tip cell formation. Since our data points towards a functional role for the extracellular domain of Flt1 in regulating vascular branching, it remains to be determined how loss of flt1 causes loss of Notch signaling. In human endothelial cells in vitro, VEGFA stimulates shedding of KDR (VEGFR2), which involves the activation of metalloproteases (Swendeman et al., 2008), but it remains to be clarified to what extent such ectodomain shedding affects Kdr and Notch signaling at the tip-stalk cell interface in zebrafish.

flt1 morphants show functional and molecular characteristics compatible with a loss of Notch signaling, but knockdown of dll4 or pharmacological inhibition of Notch signaling with DAPT did not phenocopy the vascular branching pattern observed in flt1 morphants. flt1 and dll4 morphants both show ISV branching defects but several differences exist with respect to the onset of hypersprouting (which occurs later in dll4 than in flt1 morphants) and the functionality of the additional sprouts (Leslie et al., 2007). Whereas blood flow through the aorta, cardinal vein and ISVs is severely reduced in dll4 morphants (Leslie et al., 2007), we show that blood flow through these compartments is uncompromised in flt1 morphants. The lumen diameter of the additional branches in flt1 morphants is sufficiently large to allow red blood cell perfusion. By contrast, in dll4 morphants, ISVs are largely unperfused, and this difference from flt1 morphants might involve differential effects on stalk cell differentiation, as these cells are thought to contribute to lumen formation in developing sprouts. Additional differences exist at the level of arterial-venous marker expression. dll4 morphants show unaltered expression of the arterial markers notch3 and efhb2a and of the venous marker ephb4a (Leslie et al., 2007), whereas flt1 morphants show reduced expression of Notch receptors and efhb2a and ectopic expression of dll4 in the aorta (at this stage, dll4 is normally expressed in veins and tip cells).

TheDll4-Notch signaling pathway regulates Flt1 expression in stalk cells, but differences might exist in the extent of Flt1 reduction or Flt1 distribution induced by DAPT or dll4 knockdown as compared with flt1 knockdown. In addition, flt1 might exert a functional role beyond the level of the tip-stalk cell interface, independently of Notch. For example, the production of soluble Flt1 by endothelial cells at the base of a developing vessel sprout is relevant for preventing lateral branching or turning of the tip cell back towards the base of the sprout (Chappell et al., 2009). To what extent expression of soluble Flt1 at the base of the sprout is regulated by Notch signaling is not known. We show that the nervous system is a potential source of Flt1. Loss of flt1 affects neurons, and in flt1 morphants the additional lateral segmental artery branches develop at a level at which the sprout is in close contact with the neural tube. Thus, although both loss of Notch and flt1 knockdown are associated with reduced Flt1 expression, it is conceivable that differences exist at the level of Flt1 distribution or function that might contribute to the differences in the vascular phenotypes.

Expression and distribution of Flt1 in the developing nervous system

Flt1 immunostaining shows the presence of Flt1 protein in the developing nervous system of the trunk. We show Flt1 immunostaining in neuronal cells throughout the neural tube, including Rohon-Beard sensory neurons, motoneurons and interneurons. Since, in the trunk, not all of these neurons show flt1 promoter activity, we postulate that some neuronal populations might actually bind or sequester soluble Flt1 protein produced by other cells.

Examination of the spinal cord in the trunk of Tg(flt1BAC:yfp) embryos revealed strong YFP expression in interneurons and their axonal projections, and we detected Flt1 protein on interneurons by immunostaining. In rats, retrograde and anterograde transport of VEGF in axons has been demonstrated (Storkebaum et al., 2005), and VEGF appears to be co-transported with its receptor Flk1. Whether mFlt1 or sFlt1 can also be transported along axons remains to be determined. Loss of neuronal YFP expression after knockdown of flt1 in Tg(flt1BAC:yfp) embryos might suggest that Flt1 is required for the maintenance or growth of neurons. In mice and rats, the Flt1 ligands VegfA and VegfB promote neuronal survival and exert neuroprotective effects, and reduced expression of these ligands is associated with neurodegenerative diseases (Azzouz et al., 2004; Poesen et al., 2008; Ruiz de Almodovar et al., 2009; Storkebaum et al., 2005). Knockdown of flt1 in Tg(flt1BAC:yfp) embryos predicts increased VegfA and VegfB availability and it is likely that the loss of neurons in our setting is not caused by loss of Flt1 ligands but by reduced mFlt1 expression and signaling. In line with this, VegfB-Flt1 signaling is relevant for the survival of neurons in mice, and in Flt1TK−/− mice, which lack Flt1 signaling, VegfB fails to exert neuroprotective activity (Poesen et al., 2008).

Rohon-Beard cells are mechanosensory neurons which in zebrafish innervate the dorsal caudal fin fold and the skin and play a role in sensing touch (Reyes et al., 2004). Rohon-Beard cells arise around day 1 of development, and during the phase of active segmental vessel remodeling these cells are immunopositive for Flt1, without displaying flt1 promoter activity. This leaves open the possibility that Rohon-Beard neurons attract or sequester soluble Flt1 protein produced by other cells. It is unclear how these neurons would bind or scavenge soluble Flt1, as soluble Flt1 lacks a membrane-spanning domain. Soluble Flt1 might get to the neurons by diffusion, potentially from sources including the developing trunk vasculature. Since some nerve projections develop in close proximity to segmental vessels, it is also tempting to speculate that developing axons or nerve fibers bind or take up soluble Flt1, which, via retrograde transport, then ends up in the neuronal cell bodies. The existence of such an uptake mechanism remains to be proven. Blood vessels and nerve fibers can often be found alongside one another and, in the mouse embryo skin, the patterning of nerves and blood vessels is interdependent (Mukouyama et al., 2002). Skin sensory nerves determine the pattern of arterial differentiation, which involves the local secretion of VegfA from sensory nerve fibers and Schwann cells (Mukouyama et al., 2002). The open question for future research is whether Flt1 plays a functional role at the neurovascular interface by fine-tuning VEGF levels to determine arterial differentiation and patterning events.

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