Loss of Function of Parathyroid Hormone Receptor 1 Induces Notch-Dependent Aortic Defects During Zebrafish Vascular Development


Objective—Coarctation of the aorta is rarely associated with known gene defects. Blomstrand chondrodysplasia, caused by mutations in the parathyroid hormone receptor 1 (PTHR1) is associated with coarctation of the aorta in some cases, although it is unclear whether PTHR1 deficiency causes coarctation of the aorta directly. The zebrafish allows the study of vascular development using approaches not possible in other models. We therefore examined the effect of loss of function of PTHR1 or its ligand parathyroid hormone-related peptide (PTHrP) on aortic formation in zebrafish.

Approach and Results—Morpholino antisense oligonucleotide knockdown of either PTHR1 or PTHrP led to a localized occlusion of the mid-aorta in developing zebrafish. Confocal imaging of transgenic embryos showed that these defects were caused by loss of endothelium, rather than failure to lumenzene. Using a Notch reporter transgenic (CSL:Venus[qmc61]), we found both PTHR1 and PTHrP knockdown-induced defective Notch signaling in the hypochord at the site of the aortic defect before onset of circulation, and the aortic occlusion was rescued by inducible Notch upregulation.

Conclusions—Loss of function of either PTHR1 or PTHrP leads to a localized aortic defect that is Notch dependent. These findings may underlie the aortic defect seen in Blomstrand chondrodysplasia, and reveal a link between parathyroid hormone and Notch signaling during aortic development. (Arterioscler Thromb Vasc Biol. 2013;33:1257-1263.)

Key Words: aortic coarctation ■ angiogenesis ■ parathyroid hormone ■ zebrafish

Coarctation of the aorta (CoA) arises in 3:10,000 live births, accounting for 5% to 8% of congenital heart defects.1 Its pathogenesis is unclear and most are sporadic. However, genetic diseases that cause CoA may provide insight into mechanisms of aortic formation.

Isolated CoA is associated with significant heritability,2 and can be inherited in a Mendelian fashion,3,4 suggesting an oligogenic or monogenic cause. However, few conditions associated with CoA (eg, Alagille syndrome, Pallister–Hall syndrome, Transaldolase deficiency, Mowat–Wilson syndrome, and Blomstrand chondrodysplasia) are caused by well-validated gene defects (JAG1/NOTCH2, GLI3, TALDO1, ZEB2, and PTH1R, respectively), and penetrance is <100% in these diseases.5 All these conditions are associated with multiple abnormalities that might indirectly affect aortic construction, making the direct contribution of these genes to aortic formation difficult to test. In addition, many such mutations are lethal perinatally or prenatally in either humans or knockout mice, making assessment of aortic formation challenging.

Blomstrand chondrodysplasia, attributable to mutations in the parathyroid hormone receptor 1 (PTHR1*), is a rare lethal skeletal disorder, in which <50% of infants display CoA.6–12 The Pthrl knockout mouse displays an identical skeletal phenotype and suffers multiple cardiovascular abnormalities, but does not display CoA,13,14 casting uncertainty over whether PTHR1 is directly involved in aortic construction. PTH1R has 2 ligands: parathyroid hormone (PTH) and parathyroid hormone-related peptide (PTHrP). PTHrP has been reported to both induce15 and inhibit angiogenesis16; parathyroid hormone (PTH) has not been implicated in vascular development. Impaired PTHrP/PTH1R signaling is therefore a candidate mechanism for the aortic defect seen in Blomstrand chondrodysplasia.

Zebrafish embryos allow detailed visualization of embryonic vascular development. Specific gene knockdown can be achieved using morpholino antisense oligonucleotides,17 and the embryo’s size and milieu provide oxygenation via diffusion in the absence of blood flow.18 Developing embryos survive for days without cardiac output, blood, or in the presence of severe vascular...
abnormalities.18,19 This allows differentiation of the direct effects of gene knockdown from indirect effects attributable to other defects. Zebrafish possesses homologs of PTHRI and its ligands,20 although no functional assessment has been performed.

The zebrafish previously allowed delineation of pathways leading to aortic formation. The morphogen Sonic hedgehog (Shh) is released from the notochord, which induces signaling via Notch to specify arterial gene expression and aortic development.21 This pathway is therefore a candidate for spontaneous or inherited abnormalities that give rise to aberrant aortic development. The Hey2 mutant zebrafish (gridlock) has been suggested as a model of CoA22,23 although Hey2 knockout mice do not develop CoA.24 Hey2 interacts with Notch, although it is less clear whether Hey2 is downstream25 or upstream26 of Notch. However, among human Mendelian diseases associated with CoA, only Alagille syndrome (caused by mutations in the Notch ligand Jagged1 or the Notch2 receptor) is linked to defective Notch pathway.27 We therefore examined the role of pthrl (the zebrafish homolog of PTHRI) in aortic development and its relationship to Notch signaling.

We find that pthrl knockdown in zebrafish induces a localized aortic occlusion attributable to aberrant endothelial patterning (more distal than that in gridlock mutants), implicating PTHRI directly in aortic construction. This defect is associated with a defect in hypochordal Notch signaling and is rescued by Notch upregulation but not VEGF induction. Knockdown of the PTHRI ligand pthrp induces an identical aortic defect to that seen in pthrl morphants.

Our data therefore show for the first time that PTHRI/PTHrP signaling controls Notch signaling to orchestrate correct patterning of the aorta. This is strongly suggestive that the CoA seen in Blomstrand chondrodysplasia is attributable to defective Notch signaling. Our findings illustrate the usability of the zebrafish for the study of congenital vascular defects.

Materials and Methods
Materials and Methods are available in the online-only Supplement.

Results
We first examined pthrl expression during zebrafish embryonic development. By reverse transcriptase polymerase chain reaction (rt-PCR) of whole embryo RNA, we found pthrl was expressed from as early as 1 day postfertilization (dpf) to at least 5 dpf (Figure 1A), despite the absence of mineralized bone at these stages. Using whole mount in situ hybridization, we observed ubiquitous pthrl expression (Figure 1B). By using combined fluorescent in situ hybridization with anti-green fluorescent protein (GFP) immunostaining in Fli1:GFP transgenics (Figure 1C), we found that most pthrl expression was detected in somitic muscle without obvious vascular expression, although in situ hybridization is relatively insensitive. To determine whether pthrl is expressed in endothelial cells in zebrafish, we dissociated Fli1:GFP-NLS embryos that express GFP in endothelial cells. We then used fluorescent automated cell sorting to sort fluorescent endothelial cells from nonfluorescent cells and examined expression of pthrl. Figure 1D shows that the GFP+ve cells expressed the endothelial marker VE-Cadherin by rt-PCR, whereas GFP–ve cells did not, confirming our ability to isolate relatively pure populations of endothelial cells. Figure 1E shows that these fluorescent automated cell sorting-sorted endothelial cells do indeed express pthrl, although at lower overall levels than in whole embryo RNA. We conclude from these studies that pthrl is expressed in endothelium during zebrafish development, in keeping with previous studies showing pthrl expression in cultured endothelial cells.28,29 but that most pthrl expression is nonvascular.

Having confirmed pthrl is expressed during development, we examined the effect of reducing pthrl expression using antisense morpholinos (MO). Injection of a splice-blocking MOs targeting the boundary between intron 1 and exon 2 induced a truncated transcript at 2 dpf (Figure 2A), although this effect was incomplete. Sequencing the aberrant transcript revealed the splice-blocking MO-induced partial deletion of exon 2 of pthrl, leading to variable alterations, including major abnormalities in the predicted protein sequence or a premature stop codon (Figure 2B). These would be highly likely to induce significant or complete loss of function of pthrl.

When we examined the effect of pthrl knockdown on general embryonic development, neither the splice-blocking MOs nor the translation-blocking MOs targeting the pthrl start site altered general embryo morphology. This is in keeping with the fact that skeletal ossification does not commence until ~7 dpf, and chondrodysplastic effects of pthrl would not be likely to appear until these stages.

When we examined vascular development in pthrl morphants immediately after circulation is established, we found ~50% of pthrl morphants had a localized occlusion in the mid-aorta, at the 17th somite (situated 10±2 intersegmental vessels from the end of aorta) apparent immediately after onset of circulation. The aortic occlusion seen in pthrl morphants is more distal than that in gridlock mutants, which manifests at the junction between the paired dorsal aortae.23

Both start-blocking, or splice-blocking, pthrl MO induced the same aortic defect, which was never observed in control morphants or uninjected embryos. This phenotype was particularly obvious when the circulation was well established at 2 dpf. Figure 2C shows digital motion angiograms from 2 dpf pthrl and control morphants, demonstrating the site of aortic occlusion. Movies I–IV in the online-only Data Supplement show light and digital subtraction movies of representative 2 dpf pthrl and control morphants, demonstrating the site of aortic occlusion. Movies I–IV in the online-only Data Supplement show light and digital subtraction movies of representative 2 dpf control and pthrl morphants (see the online-only Data Supplement).

The aortic defect seen in pthrl morphants was seen in both splice-blocking and translation-blocking MO with similar penetrance (49±8%; n=4 groups of 30–40 embryos/group). Although <100% penetrance is normal with MO because these are rarely 100% efficient and only partially reduce target gene expression, we examined the reason for this incomplete penetrance. When we injected embryos with the splice-blocking pthrl morpholino, morphants with no aortic abnormality did not have aberrant pthrl transcripts on rt-PCR (Figure 1 in the online-only Data Supplement), suggesting the incomplete penetrance was attributable to inefficient pthrl knockdown.

We next attempted to determine the nature of the aortic occlusion induced by pthrl knockdown. We used double Fli1:GFP/GATA1:dsRED transgenics expressing GFP in the endothelium and dsRED in erythrocytes. Examination of
**Figure 1.** *pthr1* is ubiquitously expressed during embryonic development but is expressed in isolated endothelium. **A**, rt-PCR for *pthr1* of whole embryo RNA in 1-5 df postfertilization embryos, demonstrating *pthr1* expression at all time points. **B**, Whole mount *pthr1* in situ hybridization in 2 dpf embryo, showing trunk. Head is to the left. **A** indicates site of aorta; and **V**, site of cardinal vein. **C**, Combined fluorescent in situ hybridization for *pthr1* and anti-green fluorescent protein (GFP) immunostaining in 2 dpf Flk1:GFP transgenic embryo sectioned at mid-trunk. **D**, rt-PCR for VE-Cadherin expression in fluorescent automated cell sorting (FACS)-sorted GFP+ve and GFP−ve cells from 5 dpf Flk1:GFP-NLS transgenics. **E**, rt-PCR for *VE-Cadherin* expression in fluorescent automated cell sorting (FACS)-sorted GFP+ve and GFP−ve cells from 5 dpf Flk1:GFP-NLS transgenics, confirming endothelial *pthr1* expression.

*pthr1* morphant embryos revealed that compared with control morphants (Figure 2D), *pthr1* knockdown induced a blind-ended aorta with localized loss of endothelium at the site of occlusion (Figure 2E) extending 1 to 2 somites. These data indicate that the aortic defect induced by *pthr1* knockdown is not caused by a failure to lumenize, but rather a primary failure of formation of aortic endothelium at this site. We next performed immunostaining for active Caspase 3, in control and *pthr1* morphant Flk1:GFP-NLS embryos at 24 hpf. We colocalized active Caspase 3 with endothelial nuclei but detected no difference in endothelial apoptosis to account for the aortic defects seen in *pthr1* morphants (Figure 2F).

These data confirmed *pthr1* directly plays a role in aortic development. We next attempted to determine the mechanism of this contribution. Specifically, we set out to test whether *pthr1* sits in the same pathway as Sonic hedgehog, VEGF, and Notch.

We first examined whether *pthr1* knockdown impairs aortic formation via a reduction in hedgehog signaling. During vascular development, Sonic hedgehog is secreted from the notochord, which induces VEGF expression. To examine hedgehog signaling, we examined expression of the hedgehog receptor *ptch1* in control or *pthr1* morphants. Because *ptch1* expression is upregulated by hedgehog, its expression is a useful readout of hedgehog signaling. As previously described, we detected *ptch1* expression by in situ hybridization in the neural tube of control morphants, responding to Shh. However, we did not detect any reduction in *ptch1* expression in *pthr1* morphants, either by in situ hybridization (Figure 3A) or by qPCR (Figure 3B), suggesting that the effect of *pthr1* knockdown on aortic formation is not mediated by a reduction in hedgehog signaling.

We next attempted to determine the relationship of PTHR1 with VEGF signaling, which lies downstream of Shh signaling. Incubation of gridlock mutants in the VEGF inducer GS4012 completely prevents development of the aortic blockage seen in these mutants. We therefore incubated *pthr1* morphant embryos with the same VEGF inducer in identical conditions ([25 umol/L] immediately postfertilization), but this did not suppress the morphant phenotype (Figure 3C).

Next, we examined whether Notch signaling was impaired in *pthr1* morphants. We used a Tg(CSL:Venus)qmc61 transgenic expressing the yellow fluorescent protein derivative Venus at sites of Notch signaling during development. Figure 4A shows representative images from 24 hpf control and *pthr1* morphant Tg(CSL:Venus)qmc61 embryos (just before the onset of circulation, before aortic occlusions could be observed). Control morphants demonstrate Notch signaling in the hypochord (thick arrow) along the length of the embryo. The hypochord is a transient structure sitting immediately between the notochord and the developing aorta, and is believed to contribute to aortic development.

Compared with control morphants, *pthr1* morphant embryos (Figure 4B) frequently demonstrated defects in Notch signaling in the hypochord (thin arrow). When we quantified the percentage of embryos with such a defect in a blinded manner, we found that defective Notch signaling could be identified in 58% of PTHR1 morphants (n=40), whereas only 5% (1 embryo from 20) of control morphants had any interruption in hypochordal Notch signaling (Figure 4C). We observed *pthr1* morphants during the following 24 h, and whereas 79% of 2 dpf embryos that had a defect in Notch signaling at 24 hpf (before onset of circulation) had an aortic occlusion at the same site of earlier defective Notch signaling, no *pthr1* morphant with normal Notch signaling (and no control morphant) displayed abnormal aortic development (Figure 4D).

These data suggested that *pthr1* knockdown induces defects in hypochord Notch signaling that could explain the localized aortic defect. We therefore attempted to rescue the defective aortic phenotype in *pthr1* morphants by upregulating Notch signaling. We used a heatshock:Gal4 / UAS:NICD transgenic in which heatshock drives expression of the Notch intracellular domain
responsible for Notch signaling. When we used this system to upregulate Notch signaling in 12 hpf pthr1 morphants, we did not observe alterations in general embryonic morphology at 24 hpf, but we were able to significantly reduce the proportion of embryos with defective aortae at 2 dpf (Figure 5). Heat shocking wild-type pthr1 morphants (that do not carry the temperature inducible transgene) had no effect on the percentage of embryos with aortic occlusions (data not shown), indicating that the morphant phenotype is not simply heat sensitive. These results indicate that the aortic defect induced by pthr1 knockdown is indeed attributable to abnormal Notch signaling.

Finally, we attempted to determine which ligand is responsible for pthr1 signaling. Zebrafish have 3 pthr1 ligands; pth1, pth2, and PTH-related peptide (pthrp).20 Previous work has demonstrated that pth1 and pth2 are not expressed in the vasculature of the developing zebrafish.20 During bone development, hedgehog signaling has been shown to induce pthrp expression in developing chondrocytes.13 We therefore asked whether a similar mechanism regulates vascular development.

When we performed in situ hybridization to examine pthrp expression, we observed a similar ubiquitous staining pattern to that of pthr1 expression, with no vascular (or hypochordal) staining to account for the pthr1 morphant phenotype (Figure 6A). We then knocked down pthrp by morpholino antisense and found that this induced an identical aortic occlusion at the same location as PTH1R knockdown (Figure 6B), with a similar penetrance (Figure 6C). When we examined the effect of pthrp knockdown on Notch signaling in the Tg(CSL::Venus)qmc61 transgenic, this induced defective
hypochordal Notch signaling similar to that seen in pthr1 morphants (Figure 6D). These data suggest that pthrp is the ligand responsible for induction of Notch signaling by pthr1.

**Discussion**

We have shown that despite apparently ubiquitous expression during the early stages of embryonic development, morpholino antisense knockdown of either pthr1 or pthrp induces a localized occlusion in the aorta in developing zebrafish embryos. Coupled with the fact that humans with homozygous mutations in PTHR1 have been described to suffer aortic coarctation in association with the other severe skeletal manifestations of Blomstrand chondrodysplasia, these data strongly suggest that PTHR1 is required for correct aortic formation in both humans and zebrafish. The fact that defective aortic formation can be observed in pthr1 morphant zebrafish before skeletal development and without other abnormalities suggests pthr1 contributes directly to aortic formation, rather than inducing aortic defects as an effect of other malformations.

The reason for the localized nature of the defect remains unclear. Mutations in hey2 (gridlock) cause a similarly localized (although more proximal) aortic occlusion, although hey2 is expressed throughout the aorta.33 It is clear therefore that during aortic development, some locations are more sensitive to genetic perturbation. We found no evidence to suggest the affected region expresses different levels of pthr1 or pthrp, which might have accounted for our findings. Although it is possible that persistence of maternal mRNA might protect aortic development in its early stages, we saw the same effect with a splice-blocking morpholino, making this less likely. We frequently saw restoration of distal aortic flow via collateral vessels, confirming distal aortic lumenization. Nevertheless, we cannot completely exclude aortic abnormalities distal to the occlusion.

We speculate that rather than affecting a specific part of the aorta, pthr1 knockdown exerts its effects at a specific time during embryonic development, at which point that portion of the aorta is developing and hence most sensitive. Human aortic coarctation can occur at various sites, including preductally and postductally in the aortic arch but also more distally, including in association with Alagille syndrome.34 Although the most obvious phenotype in our studies and in human coarctation is the localized occlusion, it is entirely possible that there are more subtle defects affecting arterial formation generally; this would be supported by the 5-fold increased risk of cerebral aneurysms in patients with aortic coarctation.35

Although we have shown that pthr1 is expressed in isolated endothelial cells, the ubiquitous expression of both the receptor and pthrp make nonendothelial cell autonomous explanations possible. Again, we can only speculate on these potential...
Figure 6. pthrp knockdown induces an identical aortic defect to pthr1 knockdown associated with defective Notch signaling. A. In situ hybridization for pthrp of 24 hpf zebrafish embryo showing ubiquitous trunk expression. B. When pthrp was knocked down in Flt1:GFP embryos by morpholino antisense, this induced an aortic occlusion attributable to lack of endothelium (arrow) identical in appearance and site to that seen in pthr1 morphants (Figure 2). Scale bar represents 100 um. C. Penetration of abnormal aortic phenotype in pthrp morphants compared with control morphants. D. pthrp knockdown induces a localized defect in hypochondral Notch signaling (arrow) identical to that seen in pthr1 morphants. MO indicates morpholinos.

We attempted to place PTHR1 within the Shh-VEGF-Notch pathway. Both pthr1 and pthrp knockdown induced a localized defect in hypochondral Notch signaling at the site of the future aortic occlusion. Global upregulation of Notch signaling significantly rescued these aortic occlusions, suggesting that pthr1/pthrp signaling controls Notch expression to orchestrate correct aortic formation, at least at the site of the observed reduction in Notch signaling and subsequent aortic defect. Pthr1 is unlikely to lie upstream hedgehog in this pathway, as a reduction in pth1 expression would be expected if hedgehog signaling is perturbed by pthr1 knockdown. Equally, the failure to rescue the phenotype by small molecule induction of VEGF (a manipulation which completely rescues the gridlock mutant) suggests pthr1 does not lie upstream VEGF to drive aortic formation.

Many questions remain about the contribution of pthr1 to aortic formation, particularly whether this is a cell autonomous effect, and the mechanism of downregulation of Notch signaling. The reason for the localized nature of the aortic defect is unclear, given the ubiquitous nature of pthr1 and pthrp expression. We are currently attempting to dissect these mechanisms. Nevertheless, our study is the first to prove a role for PTHR1 in aortic formation and to link PTHR1 with Notch signaling during vascular development.

We were unable to rescue the phenotype by mRNA injection, but are confident that the morphant phenotype is specific to pthr1 knockdown rather than off target effects. This is based on the observations that 2 nonoverlapping (start and splice) MOs induce the same phenotype; knockdown of the ligand induces the same phenotype (which we have never observed with multiple other MOs); and that the phenotype can be rescued by upregulation of Notch signaling. We have been unsuccessful in identifying stable mutants of pthr1 or pthrp by TILLING, although the use of zinc finger nucleases may now make this possible. Nevertheless, the data obtained using MO seem sufficiently robust to support our conclusions. Indeed, the partial nature of the gene knockdown achieved with MO may be a better model of the effect of hypomorphic or haploinsufficient human mutations, such as those responsible for Alagille syndrome than the total gene deletion achieved using murine knockouts. It is noteworthy that the Hey2 mutation responsible for the gridlock mutant is hypomorphic and in fact reducing Hey2 expression still further leads to widespread failure of aortic formation without a localized occlusion.

Although the gridlock mutant was originally described as a model of human aortic coarctation, the mouse Hey2 knockout does not display a coarctation, nor has any human case of aortic coarctation been associated with defects in Hey2. Given the incidence of CoA in Blomstrand chondrodysplasia, the pthr1 morphant has arguably a better claim to being a model of CoA. However, although coarctation simply means occlusion, we do not contend the abnormality seen in pthr1 morphants is the same as in human CoA. We do however consider it likely that some conserved function of PTH1R underlies both the CoA in Blomstrand chondrodysplasia and the defects seen in our study, and that this is likely to mechanistically be linked to the Notch pathway.

Previous work has shown that pthr1 signaling induces Notch signaling in other organ systems, such as the osteoblast and periodontal ligament, but ours is the first report of a similar function in the vasculature. Because Alagille syndrome is also associated with defective Notch signaling, we speculate that the Notch pathway may represent a final common pathway of aortic development that could be affected even in non-Mendelian or sporadic CoA. Supporting this is the finding that Notch mutations can be found in a significant proportion of adults with bicuspid aortic valve, a common congenital abnormality that frequently coexists with CoA. We consider that this pathway is therefore an excellent candidate for examination during future attempts to delineate the causative mechanisms of congenital defects in aortic formation.

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Disclosures

None.
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Significance

We show that parathyroid hormone receptor 1 is required for aortic formation via a Notch-dependent mechanism. This provides insight into the aortic coartation seen in Blomstrand chondrodysplasia (caused by parathyroid hormone receptor 1 mutations) and underlines the importance of the Notch pathway for aortic formation. Our study also highlights the usability of zebrafish for reverse genetic studies examining effects on vascular formation.
Loss of Function of Parathyroid Hormone Receptor 1 Induces Notch-Dependent Aortic Defects During Zebrafish Vascular Development


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**Supplemental Movie I.** Light microscopy of 2dpf control morphant embryo. Arrow indicates aorta.

**Supplemental Movie II.** Digital subtraction movie of 2dpf control morphant embryo.

**Supplemental Movie III.** Light microscopy of 2dpf PTHR1 morphant embryo. Thick arrow indicates aorta, thin arrow indicates site of occlusion.

**Supplemental Movie IV.** Digital subtraction movie of 2dpf PTHR1 morphant embryo.

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**Supplemental Figure I.** PTHR1 morphants without aortic abnormalities do not demonstrate aberrant PTHR1 transcripts.

PTHR1 morphants at 48hpf were separated into groups with either normal or abnormal aortic formation. Total RNA was extracted and rt-PCR for PTHR1 performed. A: unsorted PTHR1 morphants. B: PTHR1 morphants with normal aortae. C: PTHR1 morphants with abnormal aortae. Aberrently spliced mRNA can only be detected in those PTHR1 morphants with abnormal aortic formation, indicating that the morpholino has not been effective in those embryos with normal aortae.
Materials and Methods
All studies conformed to the institutions ethical requirements and were performed under UK Home Office license 40/3434.

Zebrafish husbandry and transgenic lines
Adult zebrafish were housed in groups of 40 mixed males and females at 28°C on a 12hr light/dark cycle. To obtain embryos, adults were either paired or clutches from the entire tank were obtained by placement of a marble tank. We used the following transgenic lines: Fli1:GFP expressing GFP in endothelial cytoplasm, Flk1:GFP-NLS in endothelial nuclei, GATA1:dsRED expressing dsRED in erythrocytes, Tg(CSL:Venus)qmc61 expressing the YFP derivative Venus driven by concatemerised CSL binding sites. CSL is a transcription factor that mediates upregulation of Notch responsive genes; this transgenic therefore expresses Venus at sites of Notch signalling, hsp70:Gal4/UAS:NICD, which upregulates the Notch intracellular domain (and hence Notch signalling) in response to heatshock.

Isolation of zebrafish endothelial cells
Endothelial cells were isolated by FACS from dissociated Flk1:GFP-NLS embryos as described previously.

Morpholino antisense knockdown
We used the following morpholino antisense oligonucleotides (MO) (Gene-Tools); pthr1 translation blocking: ATCCCGACGCAAGTTCACGCAAATG, pthr1 splice blocking: GAAAACCTTTGGAAC TTACCAGACG, PTHrP splice blocking: AAAGCCACAGACACTTACATTCGGC, Control: CCTCTTACCTCAGTTACAATTTATA Each MO was injected into one-cell embryos (0.5nl of 0.83mmol). Vascular development was assessed in groups of 30-40 embryos by stereomicroscopy, spinning-disk confocal microscopy, and digital motion analysis as previously published. All experiments were performed at least twice (in triplicate for assessment of aortic defects).

In situ hybridisation and rt-PCR
pthr1 and ptc1 expression was assessed by rt-PCR and in situ hybridisation either alone or with co-immunostaining as described previously. The following primers were used for PCR; PTHR1 Forward: CAG CA C ATT TGC GTG AAC TT Reverse: GAA ACA GGT GCA TGT GGA TG, PTHR1 Forward: CCA GCA GTC AGT TGG TCA GA Reverse: AAG GTC AGC AGC ACC TTG AT. Quantitative rt-PCR for ptc1 was performed as previously described.

Active caspase 3 staining
Control and pthr1 MO-injected flk1:EGFP-NLS embryos were fixed overnight in 4% paraformaldehyde (PFA) in phosphate buffered saline (PBS). Following washes in PBS containing 0.1% Tween 20 (PBST) and in 1% dimethylsulfoxide in PBST (PDT), embryos were permeabilised in 0.3% Triton X-100 in PDT, at room temperature for 20 min. After washes in PDT, the embryos were incubated in blocking solution (5% fetal calf serum and 2 mg/ml bovine serum albumin in PDT) at room temperature for 1 hour. The embryos were then incubated at 4°C overnight with rabbit anti-human/mouse active caspase 3 antibody (R&D Systems), diluted 1:200 in blocking solution. Following washes in PDT, the embryos were incubated in blocking solution at room temperature for 1 hour before incubation for 2 hours at room temperature in Alexa Fluor 546 goat anti-rabbit secondary antibody (Life Technologies), diluted 1:500 in blocking solution. The embryos were then extensively washed in PBST and mounted in Vectashield mounting medium for fluorescence (Vector Laboratories). Imaging was performed using an Olympus FV1000 laser scanning confocal microscope with a 40x (numerical aperture (NA) 1.0) oil immersion objective.

The effect of small molecule VEGF induction on pthr1 morphants
Groups of 30-40 pthr1 morphants were incubated in various doses of the VEGF inducer GS4012 (Calbiochem) or DMSO from immediately post morpholino injection (2 cell stage) to 2dpf as previously described. The percentage of each group with abnormal aortic development was observed.
blinded by stereomicroscopy. Each group was considered as a single replicate and repeated at least three times.

**The effect of Notch induction on pthrl or pthrp morphants**

*hsp70:Gal4/UAS:NICD* transgenic or wildtype embryos were injected with the *pthrl* or *pthrp* morpholino. At 12hpf, groups of 30-40 morphants were placed in thermal cycler tubes in a heatblock. After initial incubation at 22°C, embryos were heated for 10 minutes at 40°C to activate the heatshock responsive transgene. The percentage of each group with abnormal aortic development was observed blinded by stereomicroscopy. Each group was considered as a single replicate and repeated at least twice.