The lipoprotein receptor LRP1 modulates sphingosine-1-phosphate signaling and is essential for vascular development

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ABSTRACT
Low density lipoprotein receptor-related protein 1 (LRP1) is indispensable for embryonic development. Comparing different genetically engineered mouse models, we found that expression of Lrp1 is essential in the embryo proper. Loss of LRP1 leads to lethal vascular defects with lack of proper investment with mural cells of both large and small vessels. We further demonstrate that LRP1 modulates Gi-dependent sphingosine-1-phosphate (S1P) signaling and integrates S1P and PDGF-BB signaling pathways, which are both crucial for mural cell recruitment, via its intracellular domain. Loss of LRP1 leads to a lack of S1P-dependent inhibition of RAC1 and loss of constraint of PDGF-BB-induced cell migration. Our studies thus identify LRP1 as a novel player in angiogenesis and in the recruitment and maintenance of mural cells. Moreover, they reveal an unexpected link between lipoprotein receptor and sphingolipid signaling that, in addition to angiogenesis during embryonic development, is of potential importance for other targets of these pathways, such as tumor angiogenesis and inflammatory processes.

KEY WORDS: Lipoprotein receptor, Sphingolipid, Angiogenesis

INTRODUCTION
During vertebrate embryonic development the formation of blood vessels by vasculogenesis and angiogenesis leads to the establishment of blood circulation (Adams and Alitalo, 2007). For the circulation to be adequately maintained throughout development and in postnatal life, blood vessels need to mature, i.e. they need to be invested with mural cells for support and stability (Gaengel et al., 2009). This involves the differentiation of pericytes and vascular smooth muscle cells, collectively called mural cells, from mesenchymal precursors, their recruitment to developing blood vessels, and their adequate proliferation. Some crucial mechanisms that regulate this complex process have been identified: PDGF-BB secreted by endothelial cells and acting via PDGF receptor-β (PDGFRβ) on mural cells plays an essential role in recruiting pericytes/vascular smooth muscle cells and maintaining vascular stability (Hellstrom et al., 1999; Bjarnegard et al., 2004). A related function, which is likely to involve modulation of the PDGF-BB–PDGFRβ signaling axis, is carried out by sphingosine-1-phosphate (S1P) and the components of its signaling network (Liu et al., 2000; Hobson et al., 2001; Mizugishi et al., 2005). Of the five S1P receptors, S1P1 (also known as EDG1 or S1PR1) seems to play the predominant role during vascular development. It is highly expressed on endothelial cells and to a lesser extent also on vascular smooth muscle cells, on which S1P2 (EDG5 or S1PR2) is more prominent (Allende and Proia, 2002; Kluk and Hla, 2002; Ryu et al., 2002).

The transmembrane receptor LRP1 is a member of the low density lipoprotein (LDL) receptor family of lipoprotein receptors. It is expressed ubiquitously in the adult and has dual functions in endocytosis and signal transduction (May et al., 2005; Lillis et al., 2008). Examination of mice lacking LRP1 in smooth muscle cells, including differentiated vascular smooth muscle cells, revealed that the receptor is essential for the integrity of the vascular wall. On the one hand, it confers protection from cholesterol-induced atherosclerosis independently of systemic cholesterol levels (Boucher et al., 2003). On the other hand, it controls PDGF-BB and TGFβ signaling in vascular smooth muscle cells and thus prevents their overproliferation and disruption of their normal layering (Boucher et al., 2007). Its role during vascular development is less clear owing to the early embryonic lethality of conventionally genetically engineered Lrp1-deficient mice (Herz et al., 1992). Although the initial hypothesis that Lrp1−/− embryos die before implantation into the uterus was amended to embryonic lethality during early to mid-gestation (Herz et al., 1993), its actual function during embryonic development is yet to be elucidated. Also, it is unclear whether LRP1 exerts its essential functions in the embryo proper or whether its main role is in the supporting extramembranous tissues, where it could serve in cargo transport across the placenta owing to its ability to endocytose extracellular ligands.

Here, we examined mice that lack Lrp1 either completely or in the embryo proper only. We show that Lrp1 has an essential role in the embryo proper and that Lrp1 expression in the supporting tissues is insufficient to rescue embryonic development. Morphological and immunohistochemical analyses of Lrp1−/− embryos reveal an essential role of LRP1 in blood vessel maturation, as proper investment with mural cells does not occur in these animals. The vascular defects result in widespread hemorrhage and subsequent circulatory failure and ultimately in the death of the embryos at ~E13.5. In vitro examination of mesenchymal cell migration and signal transduction in both fibroblasts and endothelial cells reveals a regulatory role of LRP1 at the endothelial barrier. In contrast to the embryonic lethality of Lrp1−/− mice, conditional Lrp1−/− animals with a smooth muscle-specific deletion of Lrp1 exhibit only mild vascular defects. This indicates that the loss of LRP1 in smooth muscle cells is responsible for the embryonic lethality of the Lrp1−/− mice.

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in Gi-dependent S1P signaling and in the crosstalk of the S1P and PDGF-BB pathways, which requires the LRP1 intracellular domain and seems to underlie the vascular developmental defect observed in \( Lrp1^{-/-} \) animals.

**RESULTS**

**LRP1 plays an essential role during development of the embryo proper**

In order to clarify the role of LRP1 during embryonic development, we crossed mice with floxed \( Lrp1 \) alleles to knock-in mice that express Cre recombinase under the control of the Meox2 promoter. The Meox2 promoter is activated in the epiblast (Tallquist and Soriano, 2000) and thus leads to Cre expression and subsequent recombination of floxed alleles in all tissues of the embryo proper, whereas the extraembryonic tissues are spared.

Comparison of conditionally \( Lrp1 \)-deficient MeoxCre-LRP1\(^{rec/lox} \) embryos with embryos with completely recombined \( Lrp1 \) alleles (LRP1\(^{rec/rec} \)) confirmed a lack of LRP1 protein in extraembryonic membranes and the embryo proper of LRP1\(^{rec/rec} \) offspring. By contrast, in MeoxCre-LRP1\(^{rec/lox} \) LRP1 is preserved in the extraembryonic tissues but is almost completely absent from the embryo proper (Fig. 1A). Neither genotype was found in newborn offspring from suitable matings and genotyping of timed embryos revealed that LRP1\(^{rec/rec} \) embryos die after E11.5 with no living LRP1\(^{rec/rec} \) conceptus left after E13.5 (Table 1). MeoxCre-LRP1\(^{rec/lox} \) embryos show a similar decline that begins after E12.5, with complete loss by E14.5.

These findings indicate that preservation of LRP1 in the extraembryonic tissues cannot rescue \( Lrp1^{-/-} \) embryos from their lethal developmental defects and point to an essential developmental role for LRP1 in the embryo proper.

**LRP1 is expressed ubiquitously during embryonic development**

E9.5-12.5 wild-type embryos were examined by whole-mount *in situ* hybridization with an antisense probe specific for the *Lrp1* mRNA. Comparison of these embryos with *Lrp1*\(^{-/-} \) controls and wild-type controls stained with a sense probe revealed ubiquitous expression of *Lrp1* mRNA during all stages examined (Fig. 1B). Western blotting confirmed LRP1 expression in the developing brain as well as in heart, liver, and intestine (Fig. 1C). Interestingly, the LRP1 protein already exhibited the organ-dependent variation in apparent size that is observed in adult animals and occurs due to differential glycosylation (May et al., 2003).

**Severe vascular defects underlie the embryonic lethality of *Lrp1* deficiency**

Macroscopic morphological analysis of *Lrp1*\(^{-/-} \) LRP1\(^{rec/rec} \) embryos revealed extensive hemorrhage (Fig. 2A-C). Bleeding
and Eosin (HE)-stained sections confirmed the macroscopic microscopic examination, compared with wild-type embryos (Fig. 2H,I), the aorta in Lrp1-deficient embryos was grossly dilated with a thin and disorganized smooth muscle cell layer (Fig. 2I,K). Areas of interrupted endothelial integrity could be identified where bleeding into the perivascular soft tissue had occurred (Fig. 2L). Immunohistochemical analysis with an anti-desmin antibody confirmed the absence of an organized tunica media in the Lrp1-deficient embryos (Fig. 2N) as compared with LRP1-containing embryos (Fig. 2M). Examination of sections from wild-type embryos with antibodies directed against LRPI and smooth muscle actin (SMA) revealed that LRPI is abundantly expressed in aortic smooth muscle cells (Fig. 3A, upper panels), whereas only very little LRPI could be detected in the aortic endothelium by co-staining with anti-LRPI and anti-CD31 (also known as PECAM1) as an endothelial marker (Fig. 3D). The thickness of the aortic wall was quantified after staining of sections from Lrp1-deficient and LRPI-containing control embryos with an anti-SMA antibody (Fig. 3B,C). Comparison of both the number of smooth muscle cell layers (Fig. 3Aa,c) and the media thickness (Fig. 3Cb,d) revealed no significant difference between Lrp1-deficient and control embryos at E11.5. At E12.5, however, a significantly thinner tunica media was noted in the absence of LRPI.

On further examination, an additional defect of small vessel architecture was identified. Electron microscopy images of capillaries in the brain of E12.5 animals showed that, in the absence of LRPI, pericytes are missing (Fig. 4Ab-d), whereas they are easily identified by their characteristic processes and location within the endothelial basement membrane in the presence of LRPI (Fig. 4Aa). Examination by confocal microscopy after staining with antibodies directed against the pericyte marker PDGFRβ and the endothelial marker CD31 revealed the almost complete absence of PDGFRβ-positive and CD31-negative pericytes in the Lrp1-deficient animals (Fig. 4Ba, quantification in Fig. 4Bb). Similar results were obtained after immunostaining for SMA as a pericyte marker (supplementary material Fig. S1). At E11.5, the number of putative pericytes was still low in both the Lrp1-deficient and in control animals. Immunohistochemical analysis with anti-LRPI showed expression of LRPI in capillary vessels, both in pericytes and in endothelial cells (Fig. 4Bc).

Taken together, Lrp1-deficient embryos apparently fail to recruit (or maintain) mural cells, i.e. pericytes and vascular smooth muscle cells, to developing vessels of different sizes.

In addition to the vascular developmental defects, the developmental delay of several other structures was observed, which possibly occurred secondary to the circulatory failure (supplementary material Fig. S2A,B). Nevertheless, somite number and crown-rump length at E11.5 and E12.5, respectively, did not show a significant difference between Lrp1-deficient and control embryos (supplementary material Fig. S2C).

**LRP1 modulates the crosstalk between S1P and PDGF-BB pathways in migrating mesenchymal cells**

Collectively, the alterations observed in the Lrp1−/− embryos resembled those described for mice with defective S1P signaling, i.e. those genetically engineered for homozygous loss of the S1P receptor S1P1 (Liu et al., 2000). The homozygous S1P− receptor-deficient embryos were analyzed by immunohistochemistry with an anti-desmin antibody. Bound antibody was visualized with a chromogenic substrate for horseradish peroxidase via the avidin/extravidin system. Bracket indicates the smooth muscle cell layers of the aortal wall. Scale bars: 100 µm in A-I; 20 µm in J-N.

was evident from E11.5 and often became severe by E12.5. Microscopic examination of paraffin-embedded and Hematoxylin and Eosin (HE)-stained sections confirmed the macroscopic findings (Fig. 2D-G). In addition, LRPI−/− embryos showed anasarca and their cardinal veins and jugular veins appeared distended. In summary, this morphology was compatible with extensive hemorrhage and secondary circulatory failure leading ultimately to the death of the embryos.

Further investigation into the cause of the profuse bleeding in Lrp1-deficient embryos revealed an underlying vascular defect. On
Lrp1-deficient and control embryos at E11.5 (supplementary material Fig. S3A-D). Subsequently, at E12.5, when hemorrhage was already evident, both S1P1 and S1P2 were lost from the aortic endothelium (supplementary material Fig. S3A,C). As this could not explain the vascular defects in the absence of LRP1, we examined S1P downstream signaling events in the absence and presence of LRP1. Migration of Lrp1-deficient and wild-type murine embryonic fibroblasts (MEFs) was studied in a transwell assay, both in the basal state and after treatment with S1P, PDGF-BB or co-treatment with both factors. The Lrp1-deficient cells showed increased migration compared with their wild-type counterparts in the basal state (Fig. 5A,C). Treatment with S1P did not significantly alter motility of either cell line and treatment with PDGF-BB comparably induced migration of both Lrp1-deficient and wild-type cells. If both PDGF-BB and S1P were applied, S1P significantly reduced PDGF-BB-induced cell motility in the wild-type cells. By contrast, in LRP1-deficient cells S1P did not significantly alter PDGF-BB-induced migration (Fig. 5B,C). To rule out underlying LRP1-independent clonal differences in the cell lines, we repeated the migration assay with Lrp1-deficient cells stably retransfected with either an LRP1 expression vector or with the empty plasmid backbone. Again, in the presence of LRP1, S1P significantly inhibited the PDGF-BB-dependent induction of cell migration, whereas it did not in the absence of LRP1 (Fig. 5D).

The LRP1 intracellular domain mediates modulation of S1P–PDGF-BB crosstalk
Interestingly, retransfection of the LRP1 intracellular domain was sufficient to restore the S1P effect on PDGF-BB-induced cell migration (Fig. 5D,E), indicating that modulation of cytoplasmic signaling events, rather than extracellular binding of either ligand, underlies the regulatory role of LRP1. When cells were retransfected with an expression plasmid for an LRP1 intracellular domain in which the two NPxY protein interaction motifs had been mutated, S1P did not reduce PDGF-BB-induced cell motility (Fig. 5E). This finding further corroborates the role of the LRP1 intracellular domain and its interaction with cytoplasmic scaffolding and signaling molecules in proper S1P action.

S1P downregulates PDGF-BB-induced cell migration via activation of S1P2-dependent pathways in LRP1-containing cells
S1P regulates the migratory activity of mesenchymal cells primarily through its G protein-coupled receptors S1P1 and S1P2 (Okamoto et al., 2000; Hobson et al., 2001; Kluk and Hla, 2001; Goparaju et al., 2005; Mizugishi et al., 2005). Signaling via S1P1 involves the activation of RAC1 via Gi and stimulates migration (Hobson et al., 2001; Kluk and Hla, 2001), whereas activation of S1P2 via Gq and G12/13 leads to an increase in RHOA activity with a concomitant reduction in RAC1 activation and reduction in cell migration (Okamoto et al., 2000; Goparaju et al., 2005; Mizugishi et al., 2005). To test whether, in our experimental system, the inhibitory effect exerted by S1P on PDGF-BB-induced cell migration in LRP1-containing cells is mediated by S1P2 as previously described, we pre-treated the cells with the S1P2 antagonist JTE-013. As expected, treatment with S1P no longer reduced PDGF-BB-induced cell migration in LRP1-expressing cells after blockade of S1P2. Instead, S1P induced further migration under these conditions, presumably by activating S1P1. In LRP1-deficient cells, where S1P did not alter PDGF-BB-induced cell migration, pre-treatment with JTE-013 had no effect on the number of migrating cells after co-stimulation with S1P and PDGF-BB (Fig. 6A). To further elucidate why S1P cannot
inhibit PDGF-BB-induced cell migration via S1P2 in LRP1-deficient cells, we compared the expression levels of S1P1 and S1P2 mRNAs in both LRP1-containing and LRP1-deficient cells by quantitative RT-PCR. The mRNAs of both receptors were equally abundant in the two cell lines (Fig. 6B). In addition, neither S1P1 nor S1P2 directly interacted with LRP1 in co-immunoprecipitation experiments (supplementary material Fig. S4).

We next examined activation of the S1P2 downstream effector RHOA in the two cell lines after treatment with S1P and S1P/PDGF-BB co-treatment. In the former, S1P/PDGF-BB co-treatment led to a significant reduction in RAC1 activity compared with PDGF-BB-induced RAC1 activity. This S1P-induced decrease in RAC1 activity did not occur in the LRP1-deficient cells (Fig. 6D). In the context of cell migration, RAC1 is regulated by S1P via S1P2, leading to a reduction in RAC1 activity, and via S1P1 and activation of the heterotrimeric Gi protein, resulting in an increase in RAC1 activity (Hobson et al., 2001; Goparaju et al., 2005). To test whether the failure to constrain RAC1 activity was due to increased activation of S1P1 in LRP1-deficient cells, we employed the selective S1P1 antagonist W146 in the transwell migration assays. Pre-treatment with W146, however, did not alter the migratory behavior of LRP1-containing or LRP1-deficient cells, indicating that the dysregulation of migration in the LRP1-deficient cells does not occur at the S1P1 receptor level (Fig. 7B). We therefore tested whether downstream inhibition of Gi by pertussis toxin would restore the inhibitory effect of S1P in the LRP1-deficient cells. Pre-treatment with pertussis toxin augmented the inhibitory effect of S1P on cell migration in both LRP1-containing and LRP1-deficient cells, such that...
single treatment with S1P led to a reduction in cell migration. The inhibitory effect on PDGF-BB-induced cell migration was enhanced in LRP1-containing cells and, in addition, was restored in LRP1-deficient cells (Fig. 7A), indicating that overactive Gi-mediated signaling prevented the S1P inhibitory effect in non-pertussis toxin-treated LRP1-deficient cells. Similar results were obtained when RAC1 activity was measured in LRP1-deficient versus LRP1-containing cells. Treatment with S1P in addition to PDGF-BB
Relative expression of effect of S1P in the absence of LRP1 (Fig. 7C). Immunocytochemical deficient cells. Pretreatment with pertussis toxin restored the inhibitory reduced RAC1 activity in the presence of LRP1, but not in LRP1-deficient cells. Pretreatment with pertussis toxin restored the inhibitory effect of S1P in the absence of LRP1 (Fig. 7C). Immunocytochemical analysis of LRP1-containing and LRP1-deficient cells with an antibody against Gi-GTP confirmed an excess of activated Gi after S1P and PDGF-BB co-treatment in LRP1-deficient cells (Fig. 7D). LRP1 thus functions as an integrator of signaling input, regulating the activity of heterotrimeric Gi protein and, subsequently, that of small GTPases involved in cytoskeleton remodeling in migrating cells. Immunocytochemical analysis of the LRP1-containing MEFs showed localization of LRP1 on filopodial protrusions and on lamellipodia (Fig. 7E), where it would be correctly located to fulfill its regulatory functions during cell migration.

To examine whether LRP1 also modulates Gi-dependent integration of S1P and PDGF-BB signals in endothelial cells, we used human umbilical cord venous endothelial cells (HUVECs), which contain very little LRP1 in their native state (Fig. 8A). We compared levels of Gi-GTP before and after treatment with S1P and/or PDGF-BB in HUVECs transfected with an expression plasmid for LRP1 or with the empty plasmid vector. Transfection of LRP1 decreased basal levels of Gi-GTP in HUVECs (Fig. 8Aa,b). After treatment with S1P there was significantly more active Gi in vector-transfected control cells, whereas PDGF-BB induced comparable levels of Gi-GTP in both groups (Fig. 8Bc-f). Co-treatment with S1P significantly reduced Gi-GTP in PDGF-BB-treated HUVECs only when LRP1 was overexpressed (Fig. 8Bg,h), indicating that the molecular interaction described in fibroblasts also takes place in endothelial cells.

Similar results were obtained when SV40-transformed endothelial cells (SVEC4-10), which do express LRP1, were transfected with siRNA to silence LRP1 expression (Fig. 8C). Basal levels of Gi-GTP were higher in these cells, which was exaggerated after transfection of LRP1 siRNA. Single treatment with S1P or PDGF-BB effected little change in the already high Gi-GTP levels, whereas after S1P/PDGF-BB co-treatment Gi-GTP levels were constrained only in the presence of LRP1, and silencing of Lrp1 led to further augmentation of Gi-GTP in SVEC4-10 cells (Fig. 8D).

In summary, our current findings show that LRP1 plays an essential role for embryonic development in the embryo proper. LRP1 is necessary for the correct investment of developing vessels with mural cells. In its absence disturbed vessel architecture leads to extensive hemorrhage and secondary circulatory failure. Our in vitro data indicate that LRP1-dependent modulation of S1P–PDGF-BB crosstalk, which has been shown to be crucial in the regulation of cell migration and vascular development, might underlie the essential role of LRP1 in vessel maturation. LRP1 is located on lamellipodia of mesenchymal cells and mediates integration of S1P and PDGF-BB signaling input via its intracellular domain at the level of heterotrimeric Gi protein, leading to subsequent influence on RAC1 activity and cell migration (Fig. 9).

**DISCUSSION**

In this study we have unveiled an unexpected role of the lipoprotein receptor LRP1 in blood vessel maturation. The developmental phenotype of LRP1-deficient mice resembles that of mice with genetic defects in S1P signaling, and our in vitro studies reveal a hitherto unknown function of LRP1 in modulating S1P signaling, specifically in supporting its inhibitory effect on PDGF-BB-induced cell migration via Gi-dependent regulation of Rho family GTPase activity.

**LRP1 expression in extraembryonic tissues cannot rescue Lrp1-deficient embryos**

In the Lrp1-deficient strain examined here, E11.5-12.5 was identified as the time of lethality of Lrp1-deficient embryos (Table 1). A previous study did not find viable Lrp1−/− embryos.
beyond E12.5, and their number was smaller than expected from E9.5 on (Herz et al., 1993). The exact nature of the genetic inactivation of \textit{Lrp1} differed in this and our current study. It is thus conceivable that a difference exists in the genomic information that is lost in addition to the sequences coding for the LRP1 protein, e.g. information carried by non-coding RNAs. In both cases, however, loss of LRP1 was complete and differences in the time of embryonic lethality between the two strains are also likely to stem from variations in the genetic background of the lines.

The widespread expression and multifunctionality of LRP1 theoretically enable it partake in diverse developmental tasks (May et al., 2005; Lillis et al., 2008). These include a role in nutrient transport in the placenta in analogy to its LDLR gene family relative, the insect vitellogenin receptor (Barber et al., 1991), as opposed to a role in the embryo proper. Here we showed that the presence of LRP1 in the placenta and other extraembryonic tissues is not sufficient to rescue conditionally \textit{Lrp1}-deficient animals that lack LRP1 in the embryo proper, indicating that the predominant function of LRP1 during development is in the latter. It is of note, however, that in the MeoxCre-LRP1\textsuperscript{lox/lox} conditionally \textit{Lrp1}-deficient embryos, where recombination takes place in epiblast-derived tissues, LRP1 is also lost in the epiblast-derived extraembryonic mesoderm, including the visceral mesoderm of the yolk sac and the allantoic and chorionic mesoderm of the chorio-allantoic placenta. Thus, a role for LRP1 in these tissues cannot be excluded, especially for the formation of the fetal part of the placental vasculature, but a predominant function as a nutrient transporter is still unlikely, as one would expect this to occur on the labyrinthine syncytiotrophoblast, which is in direct contact with maternal blood.

The slight delay in lethality in the conditionally \textit{Lrp1}-deficient embryos might also be attributable to the incomplete recombination of the floxed \textit{Lrp1} allele in the conditional line (Fig. 1). It was noted during the initial characterization of the Meox2Cre line in combination with a reporter strain that recombination was mosaic, occurring in 95% of cells in the embryo proper (Tallquist and Soriano, 2000).

\textbf{Lrp1} deficiency in the embryo proper leads to defects in vessel maturation and subsequent circulatory failure

Morphological analysis of \textit{Lrp1}-deficient embryos revealed that, around the great arterial vessels, the smooth muscle cell layers of...
the tunica media are greatly reduced and disorganized compared with wild-type embryos (Fig. 2H-L). Additionally, electron microscopy analysis of brain capillaries showed an absence of pericytes in the \( Lrp1 \)-deficient embryos (Fig. 4Ab-d). The initial description of conventionally engineered \( Lrp1 \)-deficient embryos included evidence of hemorrhage (Herz et al., 1993). By contrast, genetically engineered mice that lack \( Lrp1 \) in smooth muscle cells, including those of the vascular wall, show considerable thickening of the tunica media with an increase in smooth muscle cells (Boucher et al., 2003). This discrepancy is likely to be explained by two crucial differences in the mouse strains examined. First, to obtain mice that lack \( Lrp1 \) in smooth muscle cells only, Cre recombinase was expressed under the control of the \( Sm22 \) (\( Tagln \)) promoter (Boucher et al., 2003). Thus, recombination of \( Lrp1 \) takes place only after differentiation of the smooth muscle lineage, whereas in our study LRP1 is already lost in the mesenchymal precursor that gives rise to both types of mural cells, i.e. pericytes and smooth muscle cells. Second, in our study LRP1 is also lacking in endothelial cells, which play a crucial role in the investment of developing vessels with mural cells (Bjarnegard et al., 2004).

Defects in the investment of blood vessels with mural cells have been described in genetically engineered mice with dysregulation of various signaling pathways (Adams and Alitalo, 2007). The crucial roles of PDGF-BB and PDGFR\( \beta \) in this process have been demonstrated through analysis of knockout mice (Soriano, 1994; Lindahl et al., 1997; Tallquist et al., 2003). Both types of animals, however, die perinatally, considerably later than the \( Lrp1 \)-deficient animals (Liu et al., 2000). They exhibit a defect in mural cell investment of their blood vessels, which was attributed to the lack of normal crosstalk between S1P and PDGF receptor pathways (Hobson et al., 2001).

**Fig. 8. LRP1 modulates S1P signaling in endothelial cells.** (A) HUVECs, as well as \( Lrp1 \)-deficient fibroblasts stably retransfected with an LRP1 expression plasmid (LRP1) or with empty plasmid vector (Vector) were cultured. Whole cell lysates were subjected to western blotting against LRP1, with actin as a loading control. (B) HUVECs transiently transfected with an LRP1 expression plasmid (HUVEC+LRP1) or with the empty plasmid vector (HUVEC+Vector) were treated with 1 \( \mu \)M S1P and/or with 50 ng/ml PDGF-BB for 1 min or were left untreated and G\( \alpha \) activation was detected by immunocytochemistry. The cells were stained for activated G\( \alpha \)-GTP (red) and LRP1 (green), with DAPI as counterstain. (C) SVEC4-10 cells were transfected with siRNA targeted at the mouse \( Lrp1 \) sequence (LRP1 siRNA) or firefly luciferase sequence (control siRNA). Knockdown of LRP1 was assayed by western blotting from whole cell lysates. (D) Transiently transfected SVEC4-10 cells were treated with 1 \( \mu \)M S1P and/or 50 ng/ml PDGF-BB for 2 min or left untreated. The cells were immunostained for G\( \alpha \)-GTP (red) and LRP1 (green), with DAPI counterstain. Scale bars: 10 \( \mu \)m in B; 20 \( \mu \)m in D.

**Fig. 9. Schematic model of LRP1 acting via G\( \alpha \) to modulate S1P–PDGF-BB crosstalk.** LRP1 restrains the activation of G\( \alpha \), which integrates input from several signaling pathways and mediates the promigratory effect of S1P-activated S1P1. Red line indicates the cell membrane.
Owing to the phenotypic similarities between Lrp1-deficient mice and those with a genetic defect in S1P signaling, we hypothesized that LRP1 might modulate S1P-induced cellular responses. As LRP1 is already known to interact with and regulate PDGFRβ signaling (Boucher et al., 2002; Loukinova et al., 2002), we specifically tested whether LRP1 modulates S1P–PDGF-BB crosstalk.

**LRP1 is necessary for S1P to modulate PDGF-BB-induced cell migration**

When migration of MEFs expressing or lacking Lrp1 was compared, it transpired that, although PDGF-BB induced similar maximal rates of migration in both cell lines, S1P could modulate, i.e. reduce, this effect only in the presence of LRP1 (Fig. 5B). Several signaling properties of LRP1 might underlie its role in mediating the S1P effect on PDGF-BB-induced cell migration. First, LRP1 itself negatively regulates the internalization and degradation of PDGF protein and regulates its internalization and degradation (Boucher et al., 2002; Loukinova et al., 2002). Nevertheless, we found that Lrp1-expressing and Lrp1-deficient MEFs show comparable migration toward a PDGF-BB gradient and that both the presence of LRP1 and treatment with S1P were necessary to reduce this effect (Fig. 5). Thus, it seems more likely that LRP1 targets S1P signaling in this context. S1P has several transmembrane receptors, all of which are G protein-coupled. S1P1 has the best-documented role in angiogenesis, where it is essential for vessel maturation through interaction with mural cells (Allende and Proia, 2002). Endothelial cell-specific conditional ablation of S1P1 expression proved that S1P1 is essential in this cell type (Allende et al., 2003). No studies concerning a mural (precursor) cell-specific ablation have been published so far, so its role in this cell type is less clear. As investment with pericytes/smooth muscle cells requires their interaction with endothelial cells, such an interaction might well be essential in mural precursors, which are targets of PDGF-BB during vascular development, as well. Although it was initially shown that S1P, via the S1P1 receptor, augments PGDF-BB-induced cell migration (Hobson et al., 2001), it had long been known that S1P could inhibit the PDGF-BB-induced migration of smooth muscle cells (Bormfeldt et al., 1995) and it was subsequently demonstrated that it has a dose-dependent effect on the migration of this cell type (Boguslawski et al., 2002). S1P2 has been identified as a negative regulator of RAC1 activation and cell migration (Okamoto et al., 2000). It thus seems that integration of the activity of different S1P receptors, as well as other signaling input, results in the final response in terms of cell migration and mural/endothelial cell interaction during vessel maturation.

It is conceivable that the exact mechanism that results in defective mural cell coverage differs in small and large vessels, as there is a difference in LRP1 expression between these vessel types: in brain capillaries LRP1 was abundantly identified in both endothelial cells and pericytes in control embryos, whereas in the aortal endothelium there was very little LRP1 but strong LRP1 expression in the smooth muscle cell layers (Fig. 4 and Fig. 3, respectively). This could mean that LRP1 exerts its regulatory role in both endothelial cells and pericytes in capillaries, whereas in the large vessel type it seems more likely that its role is confined to cells of the smooth muscle layer.

**Lack of LRP1 results in the failure of S1P to downregulate RAC1 activity in PDGF-BB-treated cells due to inadequate activity of Gi**

A central player both in S1P signaling pathways and in the regulation of cell migration is the heterotrimeric G protein Gi. It receives input both from S1P1, which signals mainly via Gi, and to a lesser extent from S1P2, which also uses Gq and G12/13 (Daum et al., 2009). In addition, PDGF-BB has been described to signal via Gi in airway smooth muscle cells (Conway et al., 1999). Our experiments showed that in the LRP1-containing cells S1P exerts its influence on PDGF-BB-induced cell migration via S1P2 (Fig. 6A). In the absence of LRP1, S1P was still able to induce RHOA activity (Fig. 6C), which has been shown to play an important role in the negative regulation of migration by S1P (Goparaju et al., 2005), although it failed to decrease PDGF-BB-induced cell migration. As it also failed to downregulate RAC1 activity (Fig. 6D), one might speculate that there is not a lack of anti-migratory activity but a surplus of promigratory input in the LRP1-deficient cells. Indeed, inhibition of Gi by pertussis toxin restored the S1P-dependent decrease in PDGF-BB-induced cell migration (Fig. 7A) and RAC1 activity (Fig. 7C) in the LRP1-deficient cells. Apparently, the increased Gi activity in the LRP1-deficient cell line does not stem from a preponderance of S1P1 activation by S1P, as blockade of S1P1 by the antagonist W146 had no influence (Fig. 7B) on cell migration in the transwell assay. Furthermore, co-immunoprecipitation experiments did not show direct interaction of LRP1 with S1P1 (nor S1P2) (supplementary material Fig. S4) and expression levels of S1P1 (and S1P2) are comparable regardless of the presence of LRP1 (Fig. 6B; supplementary material Fig. S3). The exact molecular mechanism by which LRP1 modulates Gi activity remains to be elucidated. As we could show that LRP1 exerts its influence via its intracellular domain, with the NPxY protein interaction motifs being necessary for this activity (Fig. 5D,E), it might control the assembly of the intracellular signaling scaffold, where Gi is activated. The localization of LRP1 in lamellipodia (Fig. 7E) would suit such a role and, interestingly, LRP1 has been found to modulate signaling processes via pertussis toxin-sensitive G proteins in the context of focal adhesion disassembly (Orr et al., 2002), ApoE4-induced neuronal apoptosis (Hashimoto et al., 2000) and LRP1-dependent signaling processes in macrophages (Misra et al., 1994).

Thus, the unexpected role of LRP1 in the modulation of S1P signaling is likely to have an impact not only on vascular development, as shown here, but also on S1P action in other contexts, such as tumor angiogenesis and the pathogenesis of atherosclerosis.

**MATERIALS AND METHODS**

**Chemicals**

PDGF-BB was purchased from Sigma-Aldrich, sphingosine-1-phosphate was from Biomol, JTE-013 was from Cayman Chemical, W146 from Avanti Polar Lipids, (2-hydroxypropyl)-β-cyclodextrin from Tocris Bioscience and pertussis toxin from Biozol. W146 was solubilized in 10 mM Na2CO3/2% (2-hydroxypropyl)-β-cyclodextrin to provide a 5 mM stock solution.

**Animals**

Mice carrying a loxP-marked Lrp1 allele were described previously (Rohllmann et al., 1996). To obtain epiblast-specific recombination of the floxed allele, these mice were bred to animals heterozygous for a knock-in of the viral Cre recombinase into the Meox2 locus (Tailuart and Vortmeyer, 2000). Embryos completely deficient for Lrp1 were obtained by mating mice heterozygous for the recombinated Lrp1 allele derived from the MeoxCre-Lrp1lox line (Lrp1lox/lox, Lrp1lox/lox).

Animals were kept under standard laboratory conditions. Experiments were carried out according to the principles of good laboratory animal care and were approved by the Regierungspräsidium Freiburg.

**DEVELOPMENT**


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Preparation of organ lysates and western blot analysis
Organs were dissected from embryos as indicated in the Results section and homogenized in cold lysis buffer [PBS (pH 7.4) containing 0.5% Triton X-100 and EDTA-free protease inhibitor cocktail (Roche)]. After centrifugation (4 min, 17,000 g at 4°C) supernatants were subjected to SDS-PAGE and western blotting according to standard procedures. Preparation of membrane fractions was as described (Marschang et al., 2004). LRPI was detected with an LRPI antiserum directed against the C-terminus (Herz et al., 1988). After incubation with an HRP-conjugated secondary antibody, bound antibodies were visualized by enhanced chemiluminescence (ECL) using Immobilon Western Chemiluminescence HRP Substrate (Millipore).

Whole-mount in situ hybridization
Transcription of sense and antisense probes was performed using the DIG RNA Labeling Kit (Roche) followed by purification with Mini Quick Spin RNA columns (Roche). Whole-mount in situ hybridization was then performed according to Belo et al. (1997). For cloning of the Lrp1 cDNA fragment see supplementary Methods.

Paraffin sections and immunohistochemistry
Embryos were dissected from pregnant mice at the time points indicated, fixed in 4% paraformaldehyde (PFA) overnight and embedded in paraffin according to standard procedures; 5 µm sections were cut and rehydrated for further analysis. They were either stained with Hematoxylin-Eosin or subjected to immunohistochemical analysis (IHC). For detection with primary antibodies, paraffin sections were incubated in Tris-EDTA buffer (10 mM Tris, 1 mM EDTA, 0.05% Tween 20, pH 9.0) for 20 min at 95-100°C. Then slides were washed in PBS with 0.025% Triton X-100 and blocked with 5% donkey serum and 2% BSA in PBS containing 0.1% Triton X-100 for 2 hours at room temperature. Incubation with primary antibodies was overnight at 4°C. Alexa Fluor 488- or 555-conjugated secondary antibodies diluted 1:500 were used (A-21206, A-31572, A-21202, A-31570, A-11055, A-21432, Life Technologies). Sections were mounted in ProLong Gold (Invitrogen) and images were obtained. For details of the antibodies used, detection of anti-desmin and image acquisition see supplementary Methods.

Electron microscopy
E12.5 embryos were fixed by perfusion with 0.9 % NaCl followed by 4% PFA, 0.1% glutaraldehyde and 0.2% picric acid in 0.1 M phosphate buffer (pH 7.4) and postfixed overnight after dissection. Brains were then excised and cut in 0.1 M phosphate buffer using a Vibratome. After osmication (1% OsO4) and dehydration in a graded series of alcohols and propylene oxide the sections were embedded in Durcopan (Fluka). Ultrathin sections were cut on a Leica EM UC6 ultramicrotome, mounted on formvar-coated slot nickel grids, and stained with uranyl acetate and lead citrate. Analysis and documentation were performed on a Philips CM 100 electron microscope equipped with a digital camera device (Gatan, Oirus SC600).

Cell culture and stable transfection of MEFs
MEFs derived from wild-type or Lrp1-deficient embryos were maintained in DMEM with glucose 4.5 g/l, 2 mM L-glutamine (Invitrogen), 100 U/ml penicillin, 100 µg/ml streptomyein sulfate (Invitrogen) and 8% FCS (Sigma Aldrich).

Mutant Lrp1 plasmids and generation of stable transfectants have been described previously (Zurhove et al., 2008). In addition, mutations of the two NPxY motifs in the LRPI cytoplasmic domain to AAAA were introduced into the cDNA by overlapping PCR using mutated primers (Zurhove et al., 2008; see supplementary Methods).

Culture and transient transfection of primary HUVECs and SVEC4-10 cells
HUVECs were cultured in Vascular Cell Basal Medium (ATCC) supplemented with Endothelial Cell Growth Kit-VEGF (ATCC) at 37°C in a 5% CO2 atmosphere. HUVECs were transiently transfected (for details see supplementary Methods) at ~70% confluency with an Lrp1 expression plasmid or empty vector (Zurhove et al., 2008).

SVEC4-10 cells were cultured in DMEM with glucose 4.5 g/l, 2 mM L-glutamine (Invitrogen) and 10% FCS (Sigma-Aldrich). Transfection with siRNA was performed with Lipofectamine 2000 (Invitrogen) according to the manufacturer’s instruction (see supplementary Methods for sequence information). The cells were incubated for 48 h before further analysis.

Transwell assays
All experiments were performed in duplicate and repeated independently at least three times. Insert membranes (PET, 0.3 cm2, 8 µm pore size; BD Falcon) were incubated with poly-D-lysine (0.05 mg/ml; Sigma) for 1 h at 37°C and subsequently with collagen I (0.01%; Sigma) overnight at 4°C. 100,000 cells per insert were seeded in DMEM (4.5 g/l glucose, 0.1% FBS) and allowed to attach for 1 h. Then, chemoattractants (1 µM S1P or 50 ng/ml PDGF-BB) were added to the lower chamber and cells were allowed to migrate through the membrane for 5 h. They were then fixed with 4% PFA, permeabilized with 0.01% Triton X-100 and stained with DAPI (1 µg/ml). Cells on the upper side of the membrane were removed using a cotton swab. Images of five random fields per insert were taken with an Olympus BX-50 fluorescence microscope. Cells were counted using ImageJ (NIH). Statistical analysis employed Student’s t-test.

Quantitative real-time PCR
RNA was extracted from MEFs grown to 95-100% confluence with Trizol (Invitrogen) and then treated with RNase-free DNase I (Fermentas). For cDNA synthesis, random primers (Promega), M-MLV reverse transcriptase (Promega), RNase inhibitor (Promega) and dNTPs (Fermentas) were used. The real-time PCR reaction was set up with 2x Absolute QPCR SYBR Green Mix with Fluorescein (Abgene) on a single-color real-time PCR detection system (Bio-Rad MyQ with MyQ Optical System Software version 1.0). For primer sequences see supplementary Methods. To compare expression levels, the ∆∆Ct method was used. Ct values were standardized with respect to Gapdh. For all experiments, samples were assayed at least in duplicate and the mean of Ct was used for further calculations. Experiments were repeated independently eight times.

G-Lisa assays
Chemiluminescence-based RAC1 (cat. #BK126) and RHOA (cat. #BK121) G-Lisa activation assays were performed according to the manufacturer’s (Cytoskeleton) instructions. Briefly, 450,000 MEFs were seeded per 60 mm dish in DMEM (4.5 g/l glucose) with 0.1% FCS. After 24 h, cells were stimulated with S1P (1 µM), PDGF-BB (50 ng/ml) or both for 1 min. Then they were washed with ice-cold PBS and lysed using the lysis buffer provided with the kit. After adjustment to a protein concentration of 1 mg/ml, the luminescence of lysates was measured with a FLUOstar OPTIMA plate reader (BMG Labtech) with 100 ms integration time.

Immunocytochemistry
MEFs, HUVEC’s or SVEC4-10 cells cultured on glass cover slips were fixed with 4% PFA, permeabilized and blocked with 5% donkey serum and 1% albumin in PBS containing 0.1% Triton X-100. Incubation with primary antibodies was overnight at 4°C: anti-LRP1 monoclonal antibody (50 µg/ml; Calbiochem, 438192) or affinity purified LRPI antiserum directed against the C-terminus; rat anti-AR2P (1:500; Abbcom, ab47654); anti-active Gi2 GTP monoclonal antibody (1:100; New East Biosciences, 26901). Alexa Fluor 555- or 488-labeled secondary antibodies (Invitrogen) were used at 1:1000. Nuclear counterstaining was performed with DAPI (0.1 µg/ml). Coverslips were mounted in aqueous mounting medium (Thermo Scientific) and examined with a Zeiss Axiplan 2 imaging microscope with ApoTome or Leica TCS SP5.

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Competing interests
The authors declare no competing financial interests.

Author contributions
P.M. conceived the study. C.N., P.H., S.M.G., K.Z., G.A. and P.M. designed the experiments. G.A. performed electron microscopy. C.N., P.H. and S.M.G. performed all other experiments. All authors analyzed the data. C.N., H.H.B., J.M.F. and P.M. wrote the manuscript.

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Author contributions
P.M. conceived the study. C.N., P.H., S.M.G., K.Z., G.A. and P.M. designed the experiments. G.A. performed electron microscopy. C.N., P.H. and S.M.G. performed all other experiments. All authors analyzed the data. C.N., H.H.B., J.M.F. and P.M. wrote the manuscript.

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Author contributions
P.M. conceived the study. C.N., P.H., S.M.G., K.Z., G.A. and P.M. designed the experiments. G.A. performed electron microscopy. C.N., P.H. and S.M.G. performed all other experiments. All authors analyzed the data. C.N., H.H.B., J.M.F. and P.M. wrote the manuscript.

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Supplemental Figures

Supplemental Figure 1

Supplemental Figure 1

Capillaries in the telencephalon of E12.5 *Lrp1*-deficient (K.O.: LRP1^{rec/rec}) and control (Con.: LRP1^{lox/lox}) embryos were stained by the pericyte markers α-PDGFRβ (red) and α-SMA (green).

a’, b’, and c’: enlarged insets of a, b, and c. An arrow indicates PDGFRβ and SMA-positive pericytes and an arrowhead SMA singly-positive pericytes. In K.O. tissues, SMA or PDGFRβ-positive pericyte-like structures were rare.
Supplemental Figure 2
Supplemental Figure 2

A) HE-stained paraffin section through the eye of an E12.5 wildtype embryo (left) and of an E12.5 \textit{Lrp1}-/- embryo (right).

B) Branchial arches of an E10.5 wildtype embryo (left) and an E11.5 \textit{Lrp1}-/- embryo (right).

Ca) The number of somite pairs was counted in E11.5 control (LRP1\textsuperscript{lox/lox}) and \textit{Lrp1}-/- (K.O.) embryos. Control and K.O. embryos had 43-46 and 44-46 pairs of somites, respectively. There was no significant difference between the two genotypes (Student’s t-test, n=4 each, n.s.: not significant).

b) The body length of E12.5 control (LRP1\textsuperscript{lox/lox}) and \textit{Lrp1}-/- (K.O.) embryos was measured as crown-rump length. There was no significant difference in length between the two genotypes (Student’s t-test, n=3 each, n.s.: not significant).

c) Left: representative image of an E11.5 embryo stained with 0.02% cresyl violet for better identification of somites. Middle: enlarged inset from left image with somites labelled as i, ii, iii and iv. Right: representative image of E12.5 embryo with crown-rump length indicated.
Supplemental Figure 3

**S1P1 and S1P2 expression patterns in the absence and presence of LRP1.**

A, B, C, and D) Dorsal aorta (A and C) and brain capillaries in the telencephalon (B and D) from MeoxCreLRP1<sup>rec/lox</sup> (conditional LRP1 K.O.: K.O.) and LRP1<sup>lox/lox</sup> (control: Con.) E11.5 and E12.5 embryos were stained with antibodies against the endothelial marker CD31 (green) and S1P1 (A and C, red) or S1P2 (B and D, red), respectively. Scale bars, 20 µm (A and C) and 10 µm (B and D). Arrowheads: Co-localization of CD31 and S1P1 and
S1P2, respectively. Representative images from n=2 per genotype for E11.5 and n=3 per genotype for E12.5 embryos.
**Supplemental Figure 4**

**LRP1 does not co-immunoprecipitate with S1P1 or S1P2**

A) Brain lysates from mice lacking LRP1 neurally (NesCreLRP1<sup>lox/lox</sup> (Nakajima et al., 2013), K.O.) and control animals (LRP1<sup>lox/lox</sup>, Con.) were prepared as follows. Brain tissue from adult mice was homogenized in lysis buffer (50 mM Tris-HCl (pH7.5), 150 mM NaCl, 1 mM MgCl<sub>2</sub>, 1 mM CaCl<sub>2</sub>, 1% Triton-X100 containing protease and phosphatase inhibitors) and then passed through a 26G needle 10 times. The homogenate was centrifuged and the supernatant was precleared by incubating with Protein A/G plus agarose and rabbit IgG for 30 min on ice. To the precleared lysate antibodies against LRP1 or IgG were added. Immune complexes were precipitated with Protein A/G plus agarose, followed by detection by Western blotting with an antibody against S1P1 (Cat. No. MABC94, Millipore).

B) LRP1 expressing (WT) and Lrp1-deficient (K.O.) MEF cells were used for co-immunoprecipitation. MEF were lysed in the same lysis buffer as described above and
centrifuged for 15 min at 16000 rcf at 4°C. The supernatant was incubated on ice for 1 hour with an antibody against LRP1 (Herz et al., 1988) or IgG, respectively. Bound proteins were further analyzed by Western blotting with an antibody against S1P2 (Cat. No. MABC95, Millipore).
Supplementary Methods

Whole-mount in situ hybridization: A 543 bp fragment of the LRP1-cDNA was PCR-amplified with the following primers: forward 5’-TTCGGCTTACGACGCGCATCC-3’, reverse 5’-ACTGAAAGCTTGGCGTCTGCC-3’. The fragment was cloned into pCR 2.1 TOPO (Invitrogen, Karlsruhe, Germany) resulting in random orientation.

Paraffin sections and immunohistochemistry: IHC was carried out with α-desmin IgG (dilution 1:12, AB6322, Abcam, Cambridge, UK) anti-PDGFRβ (1:100, 3169, Cell Signaling), anti-CD31 (1:100, sc-1506, Santa Cruz), anti-SMA (1:400, CP47, Merck), anti-LRP1 (1:200, 2703-1, Epitomics) anti-S1P1 (1:250, MABC94, Millipore), anti-S1P2 (1:250, MABC95, Millipore) as first antibodies. Detection of α-desmin was carried out with biotinylated goat α-mouse Ig, a horseradish peroxidase-coupled avidin product (both from the Mouse Extravidin Staining Kit, Sigma Aldrich) and the NovaRED Substrate Kit for Peroxidase (Vector Laboratories, Peterborough, UK). Images were obtained with a confocal Zeiss LSM 510 Meta laser scanning microscope, equipped with a C-Apochromat 63x/1.2 W Corr or with a Leica TCS SP5 equipped with a HCX PL APO 63x/1.4 oil CS (Leica, Germany).

Culture and transient transfection of primary human umbilical vein endothelial cells (HUVEC) and SV40-transformed endothelial cells (SVEC4-10): For transfection of HUVEC’s 1 µg DNA was mixed with 3 µl polyethyleneimine 1 mg/ml (Sigma Aldrich), diluted in 100 µl OptiMEM (Invitrogen) and incubated at room temperature for 10 min prior to the addition to HUVEC in 1.5 ml medium for 24 h.
siRNA was from Life Technologies: mouse LRP1 siRNA GCAUCUGAGACUAUCAAtt, (Fears et al., 2005) and firefly luciferase siRNA as a negative control CGUACGGAAUACUUUGAt (Masson et al., 2009).

**Quantitative real-time PCR:** The following primers were used: edg1-forward 5'-CGGTGTAGACCCAGAGTCCT-3', reverse 5'-TTTTCCATTGGCTGGAGAGG-3', edg5-forward 5'-CCCAACTCCGGGACATAGA-3', reverse 5'-ACAGCCAGTGGTTGTTTTTG-3', gapdh-fw 5'-TGTGTCGTCGGATCTGA-3', rev 5'-CCTGCTTCACCACTCTTGTGAT-3'.