Lrp4 and Wise interplay controls the formation and patterning of mammary and other skin appendage placodes by modulating Wnt signaling

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SUMMARY
The future site of skin appendage development is marked by a placode during embryogenesis. Although Wnt/β-catenin signaling is known to be essential for skin appendage development, it is unclear which cellular processes are controlled by the signaling and how the precise level of the signaling activity is achieved during placode formation. We have investigated roles for Lrp4 and its potential ligand Wise (Sostdc1) in mammary and other skin appendage placodes. Lrp4 mutant mice displayed a delay in placode initiation and changes in distribution and number of mammary precursor cells leading to abnormal morphology, number and position of mammary placodes. These Lrp4 mammary defects, as well as limb defects, were associated with elevated Wnt/β-catenin signaling and were rescued by reducing the dose of the Wnt co-receptor genes Lrp5 and Lrp6, or by inactivating the gene encoding β-catenin. Wise-null mice phenocopied a subset of the Lrp4 mammary defects and Wise overexpression reduced the number of mammary precursor cells. Genetic epistasis analyses suggest that Wise requires Lrp4 to exert its function and that, together, they have a role in limiting mammary fate, but Lrp4 has an early Wise-independent role in facilitating placode formation. Lrp4 and Wise mutants also share defects in vibrissa and hair follicle development, suggesting that the roles played by Lrp4 and Wise are common to skin appendages. Our study presents genetic evidence for interplay between Lrp4 and Wise in inhibiting Wnt/β-catenin signaling and provides an insight into how modulation of Wnt/β-catenin signaling controls cellular processes important for skin placode formation.

KEY WORDS: Wnt/β-catenin signaling, Lrp4, Sostdc1, Wnt antagonists, Mammary placodes, Skin appendages, Vibrissae, Limb

INTRODUCTION
Skin appendages such as teeth, hair and mammary glands develop from the surface ectoderm and underlying mesenchyme during embryogenesis. Despite the differences in the final structures, these skin appendages arise through similar morphological processes and tissue interactions in the early stages of their development (Mikkola and Millar, 2006). The future site of appendage development is initially marked by a thickening of the epithelium, which gives rise to a more localized placode. Subsequently, invagination of the placodal epithelium and condensation of the underlying mesenchymal cells leads to bud formation. Interactions within and between epithelial and mesenchymal tissues are essential for the proper growth and patterning of placode development. Genetic disruptions of genes encoding components of signaling pathways (Wnt, FGF, BMP, Eda, etc.) often cause developmental defects in multiple skin appendages, suggesting that patterning processes are shared among these appendages at the molecular level (Pispa and Thesleff, 2003; Mikkola and Millar, 2006).

Although many aspects of early patterning are similar, the spatial and temporal dynamics of placode development appear to be unique among the appendages. For example, hair placode formation begins with broad, regularly spaced epithelial thickenings, which are gradually refined to smaller circular placodes (Schmidt-Ullrich and Paus, 2005). By contrast, mammary placodes develop along the mammary lines, two lines of transient epithelial thickening, which appear between the fore- and hindlimb buds. Within one day, five pairs of mammary placodes form in a defined order as the mammary lines resolve (Robinson, 2007; Cowin and Wysolmerski, 2010) (Fig. 1C). The molecular and cellular basis of this transition is still unclear. However, earlier morphological studies in rabbits and recent cell-tracing experiments in mice suggested that the formation and growth of mammary placodes involve migration and reassembly of the mammary epithelial cells (Propper, 1978; Lee et al., 2011). This dynamic mode of placode formation suggests that mammary glands may have adopted a distinct molecular mechanism for placode induction.

Genetic studies in mouse have provided insights on signaling pathways required for embryonic mammary development (Robinson, 2007). In particular, Wnt signaling plays an important role in formation of mammary placodes. In the Wnt/β-catenin signaling pathway, interaction of Wnt ligands with Frizzled (Fz) receptors and the Wnt co-receptors Lrp5 and Lrp6 initiates a series of intracellular events leading to stabilization and nuclear accumulation of β-catenin. Subsequently, β-catenin forms complexes with TCF/LEF transcription factors and activates expression of target genes (MacDonald et al., 2009). Ectopic expression of the Wnt inhibitor Dickkopf 1 (Dkk1) blocks placode formation (Chu et al., 2004) and lack of Lef1, Lrp5 or Lrp6 disrupts normal placode development (van Genderen et al., 1994; Boras-Granic et al., 2006; Lindvall et al., 2006; Lindvall et al., 2009). It has been shown that Wnt/β-catenin signaling is initially activated in a broad domain along the mammary line, coincident with the expression pattern of a number of Wnt genes, but rapidly

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becomes restricted to mammary placodes (Chu et al., 2004; Veltmaat et al., 2004). This suggests that spatiotemporal control of the signaling activity is tightly coupled to placode formation. However, little is known about how precise control of Wnt signaling is achieved during embryonic mammary development.

Modulation of Wnt/β-catenin signaling in the extracellular space is often mediated by secreted Wnt antagonists, which interact with Wnts, Fz receptors or Lrp5/6 co-receptors (MacDonald et al., 2009). For example, Dkk1, Sost and Wise (Sostdc1 – Mouse Genome Informatics) can bind to the extracellular domain of Lrp5/6 and inhibit Wnt signaling presumably by disrupting the formation or activity of Wnt-induced Fz-Lrp5/6 complexes (Seménov et al., 2001; Itasaki et al., 2003; Li et al., 2005; Seménov et al., 2005). Another layer of complexity was added by recent findings on a low-density lipoprotein (LDL) receptor-related protein, Lrp4. The extracellular domain of Lrp4 resembles that of Lrp5/6, but its intracellular domain is distinct from that of Lrp5/6, suggesting that it may have different inputs on Wnt signaling (Herz and Bock, 2002; Weatherbee et al., 2006). In humans, LRP4 mutations cause limb, kidney and tooth malformations in Cenani-Lenz syndrome and are associated with bone overgrowth in two isolated cases of sclerosteosis (Li et al., 2010; Leupin et al., 2011). The role for Lrp4 appears to be conserved in mammals as mice deficient for Lrp4 also display defects in limbs, kidney and teeth (Johnson et al., 2005; Weatherbee et al., 2006; Ohazama et al., 2008).

In Lrp4 mutant mice, limb and tooth defects were associated with abnormal Wnt signaling activity. Furthermore, Lrp4 can antagonize activation of Wnt signaling when overexpressed in cultured cells, and this inhibitory activity is lost in mutant proteins (Johnson et al., 2005; Li et al., 2010). However, studies in bone and kidney development revealed no apparent elevation of Wnt signaling in Lrp4 mutants (Choi et al., 2009; Karner et al., 2010). In addition, Lrp4 is implicated in regulation of Bmp signaling in some contexts and functions as a co-receptor for Agrin in the neuromuscular junction (Kim et al., 2008; Ohazama et al., 2008; Zhang et al., 2008). Therefore, whether Lrp4 directly inhibits the Wnt pathway or controls another pathway to indirectly affect Wnt signaling in vivo is unclear.

Similar to Lrp5/6, Lrp4 can bind in vitro to Dkk1, Sost and Wise, suggesting that roles for Lrp4 in Wnt signaling may be modulated by binding of these antagonists (Ohazama et al., 2008; Choi et al., 2009; Karner et al., 2010). This is consistent with the observation that Lrp4 facilitates the Wnt inhibitory function of Sost in vivo bone mineralization (Leupin et al., 2011). In addition to this potential cell-autonomous role as a membrane receptor, Lrp4 is also postulated to modulate Wnt signaling by releasing its extracellular domain, and hence sequestering Wnt antagonists (Ohazama et al., 2008; Pinson et al., 2000; Brault et al., 2002; Simon-Chazottes et al., 2006; Weatherbee et al., 2006; Ahn et al., 2010; Ferrer-Vaquer et al., 2010). All experiments involving mice were approved by the Institutional Animal Care and Use Committee of the Stowers Institute for Medical Research (Protocol 2010-0062).

**Generation of Lrp4-mtLacZ, K14-tTA, TCF-tTA and teto-Wise transgenic mice**

For Lrp4-lacZ BAC reporter, a mouse BAC clone, RP23-276H15, was modified to contain an 134 kb genomic region that covers the whole Lrp4-coding region and neighboring upstream (36 kb) and downstream (44 kb) sequences using the bacterial recombination technology (Lee et al., 2001). lacZ was then inserted in frame into the first coding exon of Lrp4. The K14-tTA was generated by inserting the K14 promoter (Ahn et al., 2010) and a synthetic intron (IVS) (Clontech) upstream of VP22-tTA-SV40pA (Gossen and Bujard, 1992). For TCF-tTA, the K14 promoter of K14-tTA was removed except the basal promoter region (~120 to +13) and replaced with the multiple TCF-binding sites from TOPFLASH vector (Millipore). To make teto-O-Wise, G-CaMP2 elf teto-O-G-CaMP2 (He et al., 2008) was replaced with a Wise ORF, and then IRES-eGFP was subcloned between Wise and SV40pA. Transgenic founders were generated by pro-nuclear injection of linearized constructs into C57Bl/10JxCBA-F1 embryos.

**β-Gal staining, in situ hybridization and BrdU analysis**

To detect β-galactosidase activity, embryos were fixed in either 0.1% parafomaldehyde/0.2% glutaraldehyde (E11.5-E13.5) or 4% paraformaldehyde (PFA) (E14.0 or older) for 30-60 minutes on ice. After several washes in phosphate-buffered saline, samples were stained in X-Gal for 4-20 hours at 4°C or at room temperature. Whole-mount in situ hybridization was performed with embryos fixed in 4% PFA overnight according to standard protocols using DIG-labeled antisense riboprobes. Histological samples were paraffin wax-embedded after post-fixation in 4% PFA, sectioned at 8 μm and counterstained with nuclear Fast Red. For analysis of cell proliferation and cell death, embryos were harvested 2 hours after intraperitoneal injection of BrdU (50 μg/g body weight) into pregnant females, sectioned and stained with a mouse anti-BrdU antibody (Amersham), a mouse E-cadherin antibody (BD Biosciences) or a rabbit caspase 3 antibody (Cell Signaling).

**Confocal microscopy and cell counting**

Fluorescent images were obtained by the LSM 710 confocal microscope (Carl Zeiss). Nuclei with fluorescence above basal level were counted according to standard protocols using DIG-labeled antisense riboprobes. For analysis of cell proliferation and cell death, embryos were harvested 2 hours after intraperitoneal injection of BrdU (50 μg/g body weight) into pregnant females, sectioned and stained with a mouse anti-BrdU antibody (Amersham), a mouse E-cadherin antibody (BD Biosciences) or a rabbit caspase 3 antibody (Cell Signaling).

**RESULTS**

**Abnormal development of the mammalian glands in Lrp4 mutant mice**

Lrp4 is known to be expressed in placodes of skin appendages such as mammary glands, hair follicles and vibrissae (Weatherbee et al., 2006; Fliniaux et al., 2008). This prompted us to look into potential roles for Lrp4 in development of these tissues. Mice homozygous for null alleles of Lrp4 (Lrp4mut and Lrp4mut*) die after birth, but mice homozygous for a hypomorphic allele (Lrp4mdig) survive to reach adulthood (Simon-Chazottes et al., 2006; Weatherbee et al., 2006). Our analyses of both Lrp4mut/mdig and Lrp4mdig/mdig females revealed a variety of abnormalities in the number, position and morphology of nipples (Fig. 1A,B and data not shown). In Lrp4 mutant females, nipples 2 and 3 were frequently fused and the...
individual nipples were enlarged compared with those of control females. In addition, ectopic nipples were present in the region between nipples 3 and 4, and around nipple 4 (yellow arrowheads in Fig. 1B). The ectopic nipples were smaller than normal nipples and were associated with little or no fat pads, suggesting that they are non-functional (data not shown).

**Lrp4 is essential for patterning of the mammary placodes**

The mammary defects in *Lrp4* mutants suggest that Lrp4 plays a role in embryonic mammary development. The number and position of the nipples and associated mammary glands is primarily determined around embryonic day 12 (E12) when the mammary placodes develop (Cowin and Wysolmerski, 2010). We used the TopGal reporter mouse line (DasGupta and Fuchs, 1999) to follow the progress of mammary development and to monitor changes in the activity of Wnt/β-catenin signaling (Fig. 1C,D,E). Consistent with the previous report (Chu et al., 2004), in control embryos, TopGal-expressing epithelial cells were spread along the mammary lines at E11.5, and within a day they sequentially became restricted to placodes in a defined order (3, 1/4, 5 and, finally, 2). TopGal expression was gradually lost in the inter-placodal regions; after E12.5, TopGal expression was seen only in the epithelial cells of the mammary buds. In *Lrp4*mdig/mdig embryos, TopGal-expressing cells were more loosely organized around the developing placodes at E12.0, suggesting that placode assembly was delayed (compare Fig. 1D with 1E). This is particularly apparent in placodes 3 and 4 at this stage. Consistent with a delay, the mutant placodes displayed broader but shallower epithelial invagination at E12.5, which is typical of an earlier stage placode. Furthermore, there were ectopic TopGal-expressing cells spread along the mammary line. A large proportion of these cells were found around the underdeveloped placodes, especially placodes 2, 3 and 4. It appeared that some of these cells later give rise to supernumerary placodes (arrows in Fig. 1E) in the interplacodal region, which correspond to the site of supernumerary nipples. Similar changes were observed in *Lrp4*mdig/mdig and *Lrp4*mitt/mitt mice, indicating that the observed defects are loss-of-function phenotypes (supplementary material Fig. S1).

We investigated whether the abnormal mammary patterning in *Lrp4* mutants is associated with changes in the number of mammary epithelial cells using the TCF/LEF:H2B-GFP reporter, which marks mammary placodes similar to TopGal (Ferrer-Vaquer et al., 2010). Confocal imaging of the placode 2/3 region revealed a 40% increase in the total number of GFP-expressing cells (Fig. 2A-C; supplementary material Movies 1, 2). Together, these data indicate that Lrp4 is required for facilitating the assembly of mammary placodes and for limiting the number of mammary epithelial cells.

**Reduced proliferation of the misplaced mammary epithelial cells causes placode fusion**

Although mammary placodes 2 and 3 were developmentally delayed and morphologically abnormal in *Lrp4* mutants, they were centered at fairly normal positions at E12.0 (Fig. 1E). However, afterwards the distance between the two placodes was reduced compared with controls, leading to fusion later in development (Fig. 1E). To
investigate the underlying basis of this placode fusion, we examined the rate of cell proliferation and cell death. As previously reported (Balinsky, 1950), in control mice non-mammary epithelial cells surrounding the placodes were actively proliferating whereas the placodes themselves displayed a very low level of proliferation (Fig. 2D). By contrast, in Lrp4mdig/mdig mice, cell proliferation was greatly reduced in the interplacodal region (Fig. 2E; supplementary material Fig. S2). The interplacodal region continued to show reduced proliferation and was thickened at E13.5 in the mutants (Fig. 2F,G,J,K). Combined with the TopGal and TCF/LEF::H2B-GFP expression data, our results indicate that cells in the interplacodal region in Lrp4 mutants possess mammary fate.

With respect to cell death, in control mice, a small number of apoptotic cells were observed mostly around the neck of the buds, but not in the interplacodal epithelium (Fig. 2H). In Lrp4 mutants, more apoptotic cells were observed in the interplacodal region and also around the sites of invagination (Fig. 2I). Together, these results suggest that placode fusion in the mutants is largely due to relatively slow growth of ectopic mammary epithelial cells in the interplacodal region that forms part of the large extended placode, but removal of some epithelial cells by cell death also contributes to the fusion.

**Reduction in the dose of the Wnt co-receptors ameliorates the Lrp4 mutant defects in limb and mammary patterning**

To examine which signaling pathways were misregulated in the mammary placodes of Lrp4 mutants, placodes 2 and 3 were dissected from E12.5 embryos and expression analysis was performed using qPCR assays designed for components of Wnt, FGF, TGFβ/BMP and Eda pathways (supplementary material Fig. S3). Differential expression of genes in Wnt (Dkk1, Dkk4 and Lef1) and TGFβ/BMP (Bmp3, Msx1 and Msx2) pathways suggests that signaling activity of the two pathways is changed in Lrp4 mutants. The increased number and abnormal distribution of cells expressing the Wnt reporters (Figs 1, 2) and Lef-1 (supplementary material Fig. S3) in Lrp4 mutants raises the possibility that elevation of Wnt/β-catenin signaling is causally related to the mammary defects. To explore this idea, we examined genetic interactions between Lrp4 and the Wnt co-receptor genes Lrp5 and Lrp6. In crosses between Lrp4 and Lrp5/6 mutants, we first focused on examining limb defects as a means to score for genetic interactions (Fig. 3A). All the known Lrp4 mutants have been characterized by abnormal patterning of the apical ectodermal ridge (AER) and polysyndactyly, whereas Lrp5; Lrp6 compound mutants displayed limb defects in a dose-dependent manner (Holmen et al., 2004; Johnson et al., 2005; Simon-Chazottes et al., 2006; Weatherbee et al., 2006). At E13.5, TopGal-expressing cells were normally confined to AER as a thin line, but in Lrp4 mutants these cells were scattered in the distal limb buds owing to broadening of AER. Interestingly, inactivating two copies of Lrp5 or single copy of Lrp6 ameliorated the AER defects of Lrp4 mutants and fairly normal limb patterning was observed in Lrp4mdig/mdig; Lrp5+/–; Lrp6+/– mice. Loss of Lrp6 resulted in severe limb defects with a stronger effect on hind limbs (Pinson et al., 2000; Zhou et al., 2010). Such limb defects of Lrp6-null mice were significantly rescued in Lrp4mdig/mdig; Lrp5+/–; Lrp6–/– mice (n=5) (Fig. 3C,C′), indicating that Lrp4 and Lrp6 act antagonistically.

It has been shown that embryonic mammary development is delayed or severely impaired in Lrp5–/– and Lrp6–/– mice, respectively, in association with reduced Wnt signaling activity. (Lindvall et al., 2006; Lindvall et al., 2009). We observed that reduced doses of Lrp5 and Lrp6 can rescue the mammary defects of Lrp4 mutants (Fig. 3B,B′). When both copies of Lrp5 or a single copy of Lrp6 were inactivated in Lrp4 mutants, TopGal expressing cells were more confined around the sites of bud formation, indicating amelioration of Lrp4 mutant phenotypes. Furthermore, in Lrp4mdig/mdig; Lrp5+/–; Lrp6–/– mice, the buds appeared to be fairly normal, and buds 2 and 3 were fully separated in the majority of cases (Fig. 3D). These genetic interactions indicate that the abnormal limb and mammary development in Lrp4 mutants is largely due to elevated Wnt signaling and support the idea that Lrp4 inhibits Wnt/β-catenin signaling in vivo.

**Lrp4 facilitates placode formation and restricts mammary fate by inhibiting Wnt/β-catenin signaling**

We investigated whether the normal timing of placode initiation is restored in Lrp4mdig/mdig; Lrp5+/–; Lrp6–/– mice. Indeed, the compound mutants displayed placodes of almost normal morphology and size with few TopGal-expressing cells in the interplacodal region at E12.5 (Fig. 4A-C′). This suggests that a reduction in Wnt/β-catenin signaling can compensate for loss of Lrp4 function and facilitate placode formation in Lrp4 mutants.
To further explore a role for Wnt/β-catenin signaling in controlling the number of mammary epithelial cells, we inactivated the β-catenin gene (Ctnnb1) in the epithelium after placode initiation using a conditional allele of β-catenin combined with a Cre line driven by a Keratin 14 promoter (K14cre). K14cre can induce recombination in a subset of epithelial cells along the mammary line at E11.5-E12.0 (Fig. 4D,E). By E12.5, Cre activity is detected in most epithelial cells in and around the mammary buds (Fig. 4F,F′/H11032). In β-cateninfx/-;K14cre mice, all the buds formed at their normal position, consistent with the late onset of Cre activity, but they were smaller at E12.5 and remained growth-retarded afterwards (Fig. 4G,H,G′/H11032; supplementary material Fig. S4). This suggests that Wnt/β-catenin signaling is required for producing a sufficient pool of the mammary precursor cells and for facilitating growth of the buds at later stages.

We then tested whether inactivation of Ctnnb1 has effects on the Lrp4 mutant phenotypes (Fig. 4I,J,I′/H11032, J′). Interestingly, a greater reduction in placode size was observed in Lrp4 mutants than in control mice when Ctnnb1 was inactivated. Lrp4mutindig;β-cateninfx/K14cre mice often developed a variable number of small placodes in the placode 2/3 region. We interpret this to mean that due to the delay in placode formation in Lrp4 mutants, Ctnnb1 was inactivated at a relatively earlier stage of placode development, resulting in further reduction in mammary precursor cells. These genetic analyses further support the idea that Wnt/β-catenin is essential for inducing or maintaining the mammary fate in the epithelial cells before placode assembly. Taken together, these data suggest that Lrp4 normally facilitates placode formation and limits the number of mammary epithelial cells by inhibiting Wnt/β-catenin signaling.

Lrp4 is required for development of hair and vibrissal follicles
We next investigated whether our findings in mammary gland development reflect related roles for Lrp4 in other skin appendages.

Fig. 3. Genetic interaction of Lrp4 with Lrp5 and Lrp6. TopGal expression at E13.5. A low level of broad β-galactosidase activity is detectable from the Lrp6 mutant allele. (A-B′) Reduced dosages of Lrp5 and Lrp6 rescue the limb (A) and mammary (B′) defects of Lrp4 mutants. A proximal (left, dorsal to the right) and a dorsal (right) view of a forelimb bud are shown with anterior to the top (A). (C,C′) Lrp4 and Lrp6 compensate for loss of each other in limbs. Note that hindlimb defects of Lrp6mut mice were rescued by inactivation of Lrp4, but other defects such as loss of tail remain the same (arrows). (D) Separation of mammary bud #2 and 3 by reduced dosages of Lrp5 and Lrp6 in Lrp4 mutants.

Fig. 4. Lrp4 facilitates placode initiation and controls the number of mammary epithelial cells via inhibition of Wnt/β-catenin signaling. (A-C′) Reduced dose of Lrp5 and Lrp6 restores normal timing of placode initiation and reduces ectopic TopGal-expressing cells in Lrp4 mutants. (D-F′) Detection of Cre activity from K14cre transgene. (G-J′) Conditional inactivation of Ctnnb1 in control mice results in smaller mammary buds. In Lrp4 mutants, inactivation of Ctnnb1 results in separated, but much smaller, buds.
Primary hair follicles were marked by Wnt10b transcripts at E14.5 in control mice, but in the Lrp4 mutant skin, Wnt10b was undetectable (Fig. 5A). Our Lrp4-lacZ BAC reporter line marked newly forming hair placodes at E13.5 and continued to express in the primary hair follicles (Fig. 5B,C), mimicking endogenous Lrp4 expression pattern (Fliniaux et al., 2008). In Lrp4 mutants, Lrp4-lacZ expression was not observed at E13.5, and hair placodes were less developed at E14.5, indicating that hair follicle development is delayed (Fig. 5C,E).

Groups of vibrissae develop in different regions of the mouse head (Yamakado and Yohro, 1979), and supernumerary vibrissal placodes were observed for each group in Lrp4 mutants (Fig. 5H-J; supplementary material Fig. S5). In particular, we detected extra interramal vibrissal follicles, which form along a transverse line under the chin at E14.5 (Fig. 5H-I). One day earlier, there was a delay in morphogenesis of the follicles in Lrp4 mutants with less condensed domains of TopGal expression (Fig. 5F-G'). In general, these phenotypes were milder and less penetrant in Lrp4/mdig/mdig mice compared with Lrp4/mm/mm mice (data not shown). Our analyses revealed that Lrp4 is required for timely formation of hair and vibrissal follicles, and suggest that Lrp4 normally facilitates morphogenesis of these skin placodes similar to its role in mammary placodes.

**Wise is required for development of mammary glands and vibrissae**

As Wise is a potential ligand for Lrp4 and mice deficient for Wise or Lrp4 displayed similar tooth defects, we investigated roles for Wise in the mammary glands and other skin appendages. Earlier studies have shown that, in developing skin appendages, Wise is excluded from the epithelial signaling centers where Lrp4 is expressed (Laurikkala et al., 2003; Weatherbee et al., 2006). During mammary placode formation, Lrp4 was expressed in the placodal epithelial cells similar to Lef-1, whereas Wise expression was strong in the surrounding epithelial and mesenchymal cells (Fig. 6A,A'). Comparison of TopGal, which marks the epithelial signaling centers, and our Wise-lacZ reporter further demonstrates that the complementary expression pattern of Lrp4 and Wise is a common feature of skin appendage formation (supplementary material Fig. S5).

In Wise-null females, we observed changes in the position and number of nipples (Fig. 6B). In control females, there was only a modest level of variation in the distance between nipples 2 and 3 (data not shown). However, in the majority of Wise-null females the distance was greatly reduced, and with a low frequency (4/18) the two nipples were fused or juxtaposed next to each other. In addition, Wise-null females frequently displayed supernumerary nipples around normal ones. We next examined changes in TopGal expression in Wise-null mice (Fig. 6C,D). In the mutants at E12.0, the placodes appeared modestly enlarged, but formed at the normal positions with no clear sign of delay in placode assembly. However, by E12.5, mutant placodes were further enlarged with an increased number of TopGal-expressing cells. Some of these TopGal-expressing cells were observed outside the placodes, in particular in the region between placodes 2 and 3, and formed a bridge connecting the two placodes. Histological sections revealed that the expanded TopGal expression was associated with abnormal morphology of the mammary epithelium in the mutant. The distance between the two placodes/buds became gradually reduced in most mutants, often leading to fusion by E14.5 (4/12) consistent with the adult nipple phenotypes. Similar to the observation in Lrp4/mdig/mdig mice, this abnormal spacing between the placodes was associated with reduced proliferation in the interplacodal region (supplementary material Fig. S5). These data indicate that Wise and Lrp4 have a similar role in controlling the distribution and number of the mammary epithelial cells, but Wise is largely dispensable for placode initiation.

In addition to the mammary defects, Wise-null mice displayed supernumerary vibrissal follicles with a frequency lower than that of Lrp4/mm/mm mice (supplementary material Fig. S5; data not shown). Overall, our data suggest that Lrp4 and Wise are required for common processes in skin appendage development, but Lrp4 has additional roles. During the preparation of this manuscript, Närhi et al. independently reported similar defects in mammary glands and vibrissae of Wise-null mice (Närhi et al., 2012). Relatively milder mammary defects, such as lack of fusion described by Närhi et al., are probably due to difference in strain background.
We genetically tested whether changes in Wnt/β-catenin signaling account for the Wise-null mammary defects. We first found that removing both copies of Lrp5 significantly rescues the abnormal spacing and ectopic TopGal expression of Wise-null mammary buds (Fig. 6E,F). In addition, epithelial inactivation of Ctnnb1 eliminated the ectopic TopGal expression around the buds and restored the normal spacing between the buds 2 and 3 in Wise-null mice (Fig. 6E,F). These genetic interactions suggest that elevated Wnt/β-catenin signaling is the primary cause of mammary defects in Wise-null mice.

To complement and validate predicted roles for Wise based on loss-of-function analyses, we investigated whether overexpression of Wise using the keratin 14 promoter (K14-Wise) (Ahn et al., 2010) can reduce the number of placodal epithelial cells. K14-Wise embryos showed defects in development of hair/vibrissal follicles, mammary placodes and limbs with reduced TopGal expression (supplementary material Fig. S6). Owing to the challenge in maintaining viable K14-Wise mice, we established a bi-transgenic system in which expression of tetracycline-controlled transactivator (tTA) is driven by the keratin 14 promoter (K14-tTA) in a driver line and tTA activates expression of Wise together with eGFP in an expressing line (tetO-Wise) (Fig. 7A) (Gossen and Bujard, 1992). Using a strong (32) or a moderate (87) K14-tTA driver, the mammary defects of K14-Wise embryos were reproduced (Fig. 7B-E). Wise overexpression led to a significant reduction in the number of mammary epithelial cells present around the placodes (Fig. 7B’C’). Importantly, Wise overexpression in the epithelium was sufficient to restore the normal morphology and spacing of the placodes in Wise-null mice (Fig. 7D’G’). Using the promoter with multiple TCF-binding sites (TCF-tTA), similar mammary defects were observed even when Wise was overexpressed specifically in the placodes (Fig. 7H’K’). As Wise is not normally expressed in the placodes, these gain-of-function phenotypes are consistent with the non-cell-autonomous function of Wise as a secreted protein. Together, our loss- and gain-of-function analyses suggest that Wise controls the number and distribution of the mammary epithelial cells during placode formation by inhibiting Wnt/β-catenin signaling.

**Wise requires Lrp4 to exert its function in vivo**

The overall similarities in skin defects and elevated Wnt signaling in Lrp4 and Wise mutants raise the issue of whether Lrp4 and Wise act through a common or parallel pathway. To genetically test this idea, we generated combinatorial mutants of the two genes. No mammary defect was observed in transheterozygotes, and defects in double homozygous mutants were indistinguishable from those of Lrp4mdig/mdig mice during embryonic mammary development (Fig. 8A-C). A similar genetic interaction was observed with Lrp4mitt (data not shown). This epistasis analysis suggests that inactivating Wise does not exacerbate the defects in Lrp4 mutants.

Considering the close genetic interaction of both genes with the components of Wnt/β-catenin pathway, this lack of synergy or additive effect between the two mutants suggests that Lrp4 and Wise may be acting on the same pathway to inhibit Wnt/β-catenin signaling and Lrp4 acts downstream of Wise. Alternatively, it is possible that Lrp4 and Wise function independent of each other, but Lrp4 has a greater role in modulating the level of signaling activity. To distinguish between these possibilities, we overexpressed Wise in Lrp4 mutants. Elevated Wise expression would rescue the Lrp4 mutant phenotypes if Wise and Lrp4 function primarily in an independent manner. However, overexpression of Wise resulted in no changes in the limb and mammary defects of Lrp4 mutants (Fig. 8D-I; Fig. 7G’I’). Although Wise overexpression reduced the number of vibrissal follicles in control mice, Lrp4mdig/mdig;K14tTA;tetO-Wise mice still displayed supernumerary vibrissal follicles (Fig. 8J-M). Wise overexpression also disrupted TopGal expression in the tongue, consistent with the essential role of Wnt signaling in the taste papilla development (Iwatsuki et al., 2007) (Fig. 8J’L’). However, in Lrp4mdig/mdig;K14tTA;tetO-Wise mice, only minor changes in TopGal expression were observed in the tongue (Fig. 8K’M’). These data suggest that, in the mammary placodes and other contexts, Wise depends on Lrp4 for its function; they also support the idea that Lrp4 acts downstream of Wise to inhibit Wnt signaling.

**Wise controls the number and distribution of the mammary epithelial cells via inhibition of Wnt/β-catenin signaling**

We genetically tested whether changes in Wnt/β-catenin signaling account for the Wise-null mammary defects. We first found that removing both copies of Lrp5 significantly rescues the abnormal spacing and ectopic TopGal expression of Wise-null mammary buds (Fig. 6E,F). In addition, epithelial inactivation of Ctnnb1 eliminated the ectopic TopGal expression around the buds and restored the normal spacing between the buds 2 and 3 in Wise-null mice (Fig. 6E,F). These genetic interactions suggest that elevated Wnt/β-catenin signaling is the primary cause of mammary defects in Wise-null mice.
DISCUSSION

Our genetic analyses have revealed that Lrp4 and Wise play stage-specific roles for proper patterning and morphogenesis of the murine mammary glands and other skin appendages through their ability to modulate Wnt/β-catenin signaling. Lrp4 has an early role in facilitating placode initiation and together Lrp4 and Wise have later roles in induction and/or maintenance of precursor cells. Through loss-, gain-of-function and epistasis analyses, we found that Wise requires Lrp4 to exert its activity. Together, our data suggest a model whereby Wise and Lrp4 work in concert to modulate the activity of Wnt signaling though a common mechanism. These findings have important implications for a mechanistic understanding of how Wnt antagonists participate in the precise control of Wnt signaling to regulate cellular processes involved in ectodermal placode formation.

Lrp4 and Wise control patterning of the mammary placodes

Development of mammary glands provides an opportunity to study spatiotemporal patterning of ectodermal organs as multiple placodes form along the mammary lines in a fairly well-defined order. Our analyses of Lrp4 and Wise mutant mice have provided insight on the cellular processes that control the transition from stretches of thickened epithelium into precisely spaced placodes.

First, initiation of the placodes requires assembly of the precursor cells. In Lrp4 mutants, even when comparable number of cells were present around the site of placode formation, they were loosely assembled with a smaller degree of invagination compared with those of control mice. This delay in placode assembly suggests that Lrp4 normally facilitates aggregation of the precursor cells.

Second, the number of the precursor cells needs to be tightly controlled for proper morphogenesis of individual placodes and maintenance of spacing between them. The significant increase in the number of Wnt reporter-positive cells in Lrp4 and Wise mutants suggests that both Lrp4 and Wise have a role in limiting the mammary fate to a defined number of epithelial cells. This may be achieved by suppressing maintenance of mammary fate in existing precursor cells or by blocking induction of new precursor cells as mammary epithelial cells tend to proliferate at a very low rate.

In addition, migration of the mammary precursor cells may play an important role in placode initiation and morphogenesis. The sustained presence of the precursor cells in the interplacodal regions of Lrp4 and Wise mutants suggest that these cells fail to migrate to the normal sites of placode formation. These ectopic precursor cells then interfere with morphogenesis of normal placodes and give rise to supernumerary placodes. The extent of migration along the mammary line is not well characterized. It is possible that cell movement is limited to cells near the sites of placode formation and cells farther away from the placodes lose their potential to become mammary epithelial cells.

Disruption in any of the above processes would lead to defects in the number, morphogenesis and position of the mammary placodes. Mutant phenotypes suggest that initially Lrp4 is predominantly required for assembly of the placodes, and later both Lrp4 and Wise play a role in the number of the precursor cells.

Lrp4 and Wise are required for development of other skin appendages

Consistent with the idea that the molecular mechanisms for early morphogenesis are shared among the skin appendages, both Lrp4 and Wise mutants display similar abnormalities in patterning of hair and vibrissal follicles, with stronger defects observed in Lrp4 mutants. Interestingly, the formation of supernumerary vibrissal follicles is preceded by delayed placode morphogenesis with a
broader distribution of the Wnt-active precursor cells in Lrp4 mutants. A delay in placode formation was also observed in the primary hair follicles of Lrp4 mutants. These delays are reminiscent of the defects observed during the mammary placode formation. Focalization of the epithelial precursor cells and associated Wnt activity is commonly seen during the formation of the skin placodes as well as AER (Mikkola and Millar, 2006; Fernandez-Teran and Ros, 2008). It is possible that Lrp4 and its ligands modulate Wnt signaling in those precursor cells to control cellular processes such as cell movement, cell shape change, cell-cell adhesion and cell proliferation, which are important for patterning and morphogenesis of the skin placodes (Jamora et al., 2003).

Lrp4 and Wise inhibit Wnt/β-catenin pathway during mammary development

We showed that the mammary defects of Lrp4 and Wise mutants can be rescued by reducing the dose of Lrp5/6 and Ccnb1. This genetic interaction indicates that elevated Wnt/β-catenin signaling is responsible for the mammary defects and suggests that Lrp4 and Wise directly antagonize Wnt/β-catenin signaling instead of acting indirectly via another signaling pathway. This is consistent with the previous studies that provided genetic evidence that Wise functions as a Wnt inhibitor in tooth development (Munne et al., 2009; Ahn et al., 2010).

Our genetic analyses also demonstrate that Wnt/β-catenin signaling is essential for induction and/or maintenance of mammary precursor cells, but its activity needs to be tightly controlled to achieve a proper number of these cells (Fig. 9A). Early inhibition of Wnt/β-catenin signaling would lead to loss or reduction of the precursor cells disrupting placode formation as seen in K14-Dkk1 (Chu et al., 2004) and K14-Wise mice. Conversely, elevated Wnt/β-catenin signaling in Lrp4 and Wise mutants results in increase in the number of mammary epithelial cells. Another important implication of our study is that a temporal reduction of Wnt/β-catenin signaling is necessary to facilitate initiation of mammary placodes and this seems to be applicable to other skin appendages. Thus, our study provides additional insight into the diverse roles played by Wnt signaling throughout placode development and underscores the importance of Wnt inhibitory function of Lrp4 and Wise in these processes.

Wise requires Lrp4 to modulate Wnt/β-catenin signaling

Similar to other LDL receptor-related proteins, Lrp4 is implicated in regulating different signaling pathways (May et al., 2007; Willnow et al., 2007). With its multiple ligand binding motifs, Lrp4 has the ability to bind to secreted Wnt and Bmp antagonists (Ohazama et al., 2008; Choi et al., 2009). Interestingly, in both
humans and mice, Lrp4 mutations phenocopy defects caused by deficiency of individual Wnt antagonists in a tissue-specific manner. For example, limb defects of Lrp4 mutants are similar to those of Dkk1 mutant mice (MacDonald et al., 2004), and bone overgrowth of humans with LRP4 mutations is reminiscent of bone defects caused by SOST and DKK1 mutations (Balemans et al., 2001; Morvan et al., 2006). Last, Lrp4 and Wise mutant mice share defects in the skin appendages (Ohazama et al., 2008) (this study). These observations imply that interplay between Lrp4 and the Wnt antagonists may play an important role in modulating Wnt/β-catenin signaling in many developmental and physiological contexts.

Although genetic evidence for such interplay has been lacking, our observation that Wise gain-of-function phenotypes depend on Lrp4 in various tissue contexts provides an important insight on this issue. Based on our loss- and gain-of-function analyses, we propose that Lrp4 and Wise act through a common mechanism where Lrp4 lies downstream of Wise in a pathway leading to inhibition of Wnt/β-catenin signaling (Fig. 9B). In this model, Lrp4 is required to mediate or potentiate the Wnt inhibitory function of Wise and possibly other Wnt antagonists. This model is consistent with the lack of synergy or additive effects between Lrp4 and Wise mutants in our epistasis analyses. The earlier Wise-independent role for Lrp4 and the relatively milder mammary defects of Wise-null mice would be attributed to function of Lrp4 alone or compensation by other antagonists. It remains to be explored how Lrp4, the Wnt antagonists and Lrp5/6 interact with each other to compensate by other antagonists. It remains to be explored how Lrp4, the Wnt antagonists and Lrp5/6 interact with each other to

mammary placode development and is essential for initiation of mammary gland morphogenesis. Development 131, 4819-4829.


Lrp4 and Wise pattern mammary placodes


Yamakado, M. and Yohro, T. (1979). Subdivision of mouse vibrissae on an embryological basis, with descriptions of variations in the number and arrangement of sinus hairs and cortical barrels in BALB/c (nu+/; nude, nu/nu) and hairless (hr/hr) strains. Am. J. Anat. 155, 153-173.


Fig. S1. Similar mammary defects in different Lrp4 mutant mice. (A-D) Allelic combinations of Lrp4 mutations result in abnormal patterning of mammary placodes as shown by TopGal expression. Ectopic TopGal-expressing cells are present in the interplacodal regions of mutant mice (arrows).

Fig. S2. Reduced number of proliferating cells in the interplacodal epithelium of Lrp4 mutant mice. Relative number of BrdU-positive epithelial cells between mammary placodes 2 and 3 at E12.5 on stained sections. Average number of labeled cells in control mice is 27.8. Data are mean±s.d.
Fig. S3. Gene expression analyses of \textit{Lrp4} mutant mammary placodes. (A) Real-time PCR was performed with TaqMan assays (Life Technologies) using cDNA from mammary placodes 2/3 and surrounding epithelial and mesenchymal tissues dissected from E12.5 embryos. Twelve to 14 dissected areas (the area marked with rectangles in B) from control and mutant embryos were pooled for RNA extraction. Error bar was calculated from four replicates for each probe using DataAssist (Life Technologies). (B,C) \textit{In situ} hybridization shows increases in \textit{Lef1} (B) and \textit{Msx1} expression.
Fig. S4. β-Catenin is required for growth of mammary buds. (A-D’) Ectodermal inactivation of the gene encoding β-catenin leads to hypoplastic mammary buds.
Fig. S5. Lrp4 and Wise are required for skin appendage development. (A,B) Complementary expression pattern of TopGal and Wise-lacZ in the mystacial (red circles), supra- and sub-orbital (green circles) vibrissal follicles, mammary buds (pink circles) and hair follicles (yellow circles). The Wise-lacZ construct was generated by inserting a lacZ-SV40pA in-frame into the first coding exon of Wise in the 24 kb EcoRI-SalI genomic fragment from a mouse BAC clone, RP23-98E22. (C-E) BrdU staining is reduced in the epithelium between mammary buds 2 and 3 (arrows) in Lrp4 and Wise mutants at E13.5. (F-H) TopGal expression reveals supernumerary mystacial (open arrowheads) and supra-orbital (yellow arrowheads) vibrissal follicles in Lrp4 and Wise mutants at E14.5.
Fig. S6. Overexpression of Wise disrupts development of limbs and skin appendages. (A) The K14-Wise construct. (B-E) K14-Wise mice display hair loss and limb abnormalities. (F,G) Histological sections show disruption in the formation of primary hair follicles in K14-Wise mice. (H-I') Abnormal development of mammary placodes and limb buds in K14-Wise mice.