Intraflagellar transport 27 is essential for hedgehog signaling but dispensable for ciliogenesis during hair follicle morphogenesis

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ABSTRACT

Hair follicle morphogenesis requires precisely controlled reciprocal communications, including hedgehog (Hh) signaling. Activation of the Hh signaling pathway relies on the primary cilium. Disrupting ciliogenesis results in hair follicle morphogenesis defects due to attenuated Hh signaling; however, the loss of cilia makes it impossible to determine whether hair follicle phenotypes in these cilia mutants are caused by the loss of cilia, disruption of Hh signaling, or a combination of these events. In this study, we characterized the function of Ift27, which encodes a subunit of intraflagellar transport (IFT) complex B. Hair follicle morphogenesis of Ift27-null mice was severely impaired, reminiscent of phenotypes observed in cilia and Hh mutants. Furthermore, the Hh signaling pathway was attenuated in Ift27 mutants, which was in association with abnormal ciliary trafficking of SMO and GLI2, and impaired processing of Gli transcription factors; however, formation of the ciliary axoneme was unaffected. The ciliary localization of IFT25 (HSPB11), the binding partner of IFT27, was disrupted in Ift27 mutant cells, and Ift25-null mice displayed hair follicle phenotypes similar to those of Ift27 mutants. These data suggest that Ift27 and Ift25 operate in a genetically and functionally dependent manner during hair follicle morphogenesis. This study suggests that the molecular trafficking machineries underlying ciliogenesis and Hh signaling can be segregated, thereby providing important insights into new avenues of inhibiting Hh signaling, which might be adopted in the treatment of targeted therapies for Hh-dependent cancers, such as basal cell carcinoma.

KEY WORDS: Intraflagellar transport, Ift27, Hedgehog signaling, Cilia, Hair follicle, Skin, Mouse

INTRODUCTION

The development of the skin starts with the commitment of single-layered surface ectoderm to stratification controlled by the transcription factor TRP63 (Candi et al., 2008, 2007), followed by the terminal differentiation of epidermal keratinocytes (Blanpain et al., 2006). The induction of hair follicle formation is initiated by the terminal differentiation of epidermal keratinocytes (Blanpain et al., 2008, 2007), followed by reciprocal interactions between epidermal keratinocytes and folliculogenic dermal papilla cells mediated by molecular signaling pathways, notably canonical Wnt signaling (Schmidt-Ullrich and Paus, 2005), which requires hedgehog (Hh) signaling (Schmidt-Ullrich and Paus, 2005). Prior studies demonstrated that disrupting genes involved in Hh signaling could result in complete arrest of hair follicle development (Chiang et al., 1999; Mill et al., 2003; St-Jacques et al., 1998; Woo et al., 2012), revealing Hh signaling as an indispensable signaling mechanism during early stages of hair follicle morphogenesis.

In vertebrates, the primary cilium, which is an antenna-like cellular protrusion, serves as the venue for Hh signaling (Corbit et al., 2005; Huangfu and Anderson, 2005; Wong et al., 2009). When the Hh signaling pathway is inactive, Hh receptor PTCH1 occupies the ciliary membrane, suppressing SMO. Upon binding of ligand, such as sonic hedgehog (SHH), the suppression by PTCH1 is relieved, permitting SMO to be activated (Rohatgi et al., 2007; Wang et al., 2009a), thereby activating Gli transcription factors and the expression of downstream target genes (Haycraft et al., 2005; Kim et al., 2009; Tukachinsky et al., 2010). In addition, the primary cilium is essential for the proteolytic processing of Gli factors into transcriptional repressors in the absence of the ligand (Haycraft et al., 2005; Huangfu and Anderson, 2005). A number of recent studies demonstrated that disrupting cilia formation results in developmental arrest of hair follicles by suppressing Hh signaling (Chen et al., 2015; Dai et al., 2013, 2011; Lehman et al., 2009). These studies confirmed the integral role of primary cilia in mediating the epithelial-mesenchymal crosstalk required for hair follicle morphogenesis. However, the loss of the ciliary axoneme in these mutants made it impossible to understand whether the attenuated Hh signaling was caused by the loss of cilia, defective trafficking of Hh components, or a combination of both.

The assembly of the ciliary axoneme and the processing of Hh signals require intraflagellar transport (IFT) (Huangfu et al., 2003). IFT is an evolutionarily conserved intracellular trafficking mechanism, which was first characterized in Chlamydomonas reinhardtii (Kozminski et al., 1993). All IFT proteins identified in Chlamydomonas are found in mammals (Cole and Snell, 2009; Follit et al., 2009). The IFT system comprises IFT-A and IFT-B protein complexes. Both IFT-A and IFT-B are essential for cilia assembly and maintenance, as well as the transduction of molecular signals. IFT-B seems to be more fundamental for ciliary assembly, whereas IFT-A plays a role in retrograde transport and the entry of some G-protein-coupled receptors into cilia (Cole et al., 1998; Follit et al., 2009; Rosenbaum and Witman, 2002). Disrupting subunits of IFT complexes could result in the loss of the ciliary axoneme and attenuated Hh signaling (Houde et al., 2006; Huangfu et al., 2003).

IFT27 belongs to the IFT-B complex (Qin et al., 2007). In contrast to other IFT proteins, IFT27 does not have homologs in Caenorhabditis elegans or Drosophila melanogaster, which do not rely on primary cilia to process Hh signals, suggesting that IFT27 might possess unique roles in ciliogenesis and Hh signaling in comparison to other IFT proteins. IFT27 is a small Rab-like GTPase...
that is capable of forming a heterodimer with IFT25 (HSPB11) (Bhogaraju et al., 2011; Cole, 2003; Wang et al., 2009b). In a previous study, we discovered that IFT25 is dispensable for cilia assembly but remains essential for the trafficking of Hh signaling molecules in cilia (Keady et al., 2012). It is particularly intriguing to know whether these intracellular trafficking molecules are essential for the transduction of molecular signals in the context of epithelial-mesenchymal interaction during the development of multicellular organs.

Here, we examined the role of Ift27 during embryonic development of the skin and found that disrupting Ift27 expression blocks hair follicle morphogenesis. The hair follicle phenotype was associated with attenuated Hh signaling in Ift27 mutant skin. Accordingly, primary dermal fibroblasts isolated from Ift27 mutants were unable to respond to Hh pathway activation. Interestingly, the formation of primary cilia was unaffected in Ift27 mutant cells and we found that disrupted Hh signaling was associated with the abnormal ciliary accumulation of SMO in Ift27 mutant cells. Moreover, the ciliary localization of IFT25 was disrupted in Ift27 mutant cells, and Ift25 mutant mice displayed hair follicle phenotypes similar to those of Ift27 mutants. Thus, data obtained from this study suggest that Ift27 and Ift25 may operate in a molecularly and functionally interdependent fashion during hair follicle formation through regulating ciliary trafficking of Hh pathway components.

RESULTS
Expression of Ift27 in the mouse skin and hair follicle
To understand the relevance of Ift27 in skin development, we examined Ift27 expression at the transcriptional and translational levels. Ift27 mRNA and protein were expressed throughout embryonic skin development (supplementary material Fig. S1A; Fig. 1A,B). Interestingly, IFT27 levels decreased significantly in P28 skin (P<0.05), which is concomitant with the completion of hair follicle morphogenesis and the entrance into the first hair cycle. Furthermore, quantitative RT-PCR and in situ hybridization demonstrated that Ift27 mRNA is expressed in both epidermis and dermis (supplementary material Fig. S1B; Fig. 1C,C'), including follicular keratinocytes and dermal papilla cells of developing hair follicles (Fig. 1C,C').

By contrast, Ift27 mRNA and protein were undetectable in hair follicles or skin of homozygous Ift27−/− mutants (Fig. 1C,D,E). Thus, the homozygous Ift27−/− mutants are essentially Ift27-null mutants and are hereafter referred as Ift27−/−. Throughout this study, phenotypes observed in heterozygous mice (Ift27+/−) were indistinguishable from those of wild-type littermates (data not shown), and the wild-type littermates (Ift27+/+) were used as controls.

Disrupting Ift27 blocks the differentiation of follicular keratinocytes but not epidermal keratinocytes
The dorsal skin of mutant embryos was examined for developmental abnormalities. Hematoxylin and Eosin (H&E) staining of E14.5 and E15.5 skin did not reveal any apparent defects in Ift27−/− embryos (supplementary material Fig. S2A and Fig. S3A). Furthermore, immunofluorescence labeling of TRP63, KRT14, KRT1, LOR (Fig. 2B; supplementary material Fig. S2B,C and Fig. S3B), BrdU labeling (Fig. 2C; supplementary material Fig. S3G,H and Fig. S4A) and TUNEL assay (data not shown) revealed normal epidermal stratification, differentiation, proliferation and apoptosis in Ift27−/− skin throughout early (E14.5) and late (E18.5) stages of epidermal development. The expression levels of canonical Wnt and Notch target genes and the activation of BMP and TGFβ signaling pathways were also unchanged in Ift27−/− skin (supplementary material Fig. S4B-E). These observations suggest that Ift27 is unlikely to be involved in embryonic development of the epidermis. However, the E18.5 Ift27−/− skin displayed a striking hair follicle phenotype, in which the majority of hair follicles were substantially reduced in size (Fig. 2A). Therefore, we focused our investigation on the formation of hair follicles.

Classification of the developmental stages of hair follicles based on morphological features described by Paus et al. (1999) revealed that the development of hair follicles in Ift27−/− skin was significantly delayed. Specifically, in E18.5 control skin, the percentage of stage 1-2, 3-4 and stage 5-6 hair follicles was 29.3±17.9%, 41.8±9.7% and 28.8±21.3%, respectively. In the Ift27−/− skin, up to 90.1% of hair follicles remained in stage 1-2 (P<0.001), whereas only 0.7% developed beyond stage 5 (P<0.01) (Fig. 2D). Interestingly, the number of hair follicles (irrespective of their differentiation stages) was only slightly reduced in Ift27−/− skin at E18.5 (P=0.11;
Fig. 2. Skin and hair follicle phenotypes of Ift27−/− embryos. (A) Representative histology (H&E staining) of E18.5 control (Ift27+/+) and Ift27−/− dorsal skin. (B) Expression of differentiation markers of the epidermis at E18.5. There is no apparent difference in the expression profiles of KRT1 and LOR in control and Ift27−/−. (C) BrdU+ cells in the basal layer of the interfollicular epidermis of E18.5 Ift27+/+ and Ift27−/−. (D) Distribution of the developmental stages of hair follicles of E18.5 dorsal skin. A minimum of 100 hair follicles were analyzed; n≥2. (E) Number of hair follicles in E15.5 and E18.5 control and Ift27−/− dorsal skin per microscopy field (100×); n≥4. (F) BrdU+ follicular keratinocytes in stage 2 hair follicles of E18.5 control and Ift27−/−. (G,H) Representative images (G) and statistical analysis (H) of double immunofluorescence labeling of AE13 (red) and KRT75 (green) of hair follicles in E18.5 control and Ift27−/− skin. (I,J) Representative gross appearance (I) and histology (H&E staining, J) of skin transplants at 35 days post-transplantation. *P<0.05, **P<0.01. Scale bars: 50 µm in A,B,G; 100 µm in J.

Fig. 2E), but the number of proliferating cells in Ift27−/− hair follicles was markedly reduced (P<0.01; Fig. 2F; supplementary material Fig. S4A). Thus, the data obtained so far suggested that delayed hair follicle development in Ift27−/− embryos was likely to be associated with impaired responses to mitogenic signals.

Examination of hair follicle differentiation markers, such as KRT75 (companion cell layer) and AE13 (hair cortex), demonstrated that 3.4±0.8 and 3.1±0.9 wild-type hair follicles (per microscopic field) expressed these markers, respectively (Fig. 2G,H), compared with only 0.1±0.2 and 0.2±0.2 hair follicles in Ift27−/− skin (P<0.001; Fig. 2G,H). This observation strongly suggests that delayed hair follicle development in Ift27−/− skin is caused by abnormal follicular keratinocyte differentiation.

By contrast, the induction of hair follicle formation was indistinguishable between Ift27−/− and control skin. Specifically, the number and expression pattern of KRT17+ hair germs in E15.5 Ift27−/− skin were comparable to those in wild-type littermates (supplementary material Fig. S3C). Moreover, the expression of LEF1 (supplementary material Fig. S3D), a marker for the activation of canonical Wnt signaling, and of NGFR (formerly known as p75NTR) (supplementary material Fig. S3E), alkaline phosphatase (AP) activity (supplementary material Fig. S3F) and the number of BrdU+ follicular keratinocytes (supplementary material Fig. S3G,H) were comparable in early stage control and Ift27−/− hair follicles.

Because Ift27−/− mice die shortly after birth we could not determine whether the development of hair follicles was temporarily delayed or impermissible in these animals. To address this question, dorsal skin of E18.5 Ift27+/+ and Ift27−/− embryos was transplanted onto nude (Foxn1nu) mice for further development and maturation. Ift27−/− skin was able to engraft. However, there was a drastic reduction in the number of hairs in the Ift27−/− skin (Fig. 2I). H&E staining of tissues collected 5 weeks post-grafting confirmed that the hair phenotype was due to the lack of hair follicles (Fig. 2J). Thus, disrupting Ift27 blocked hair follicle development.

Hh signaling is perturbed in Ift27−/− skin

The hair follicle phenotype of Ift27−/− mice was reminiscent of that of Hh mutants (Chiang et al., 1999; Gat et al., 1998; Mill et al., 2003; St-Jacques et al., 1998; Woo et al., 2012). Consistently, in situ hybridization and quantitative RT-PCR revealed that Ift27−/− hair (E15.5 and E18.5) had significantly reduced expression levels of Hh target genes, such as Gli1 and Ptc1, in follicular keratinocytes and dermal papilla cells (Fig. 3A-C; supplementary material Fig. S5A,B). Interestingly, the expression of Shh was essentially indistinguishable between control and Ift27−/− embryos (P=0.08; Fig. 3C; supplementary material Fig. S5C). Moreover, western blotting revealed reduced processing of full-length GLI3 (GLI3-FL) to GLI3 repressor (GLI3-R) in skin biopsied from E18.5 Ift27 mutants (Fig. 3D), which led to an increased GLI3-FL/GLI3-R ratio (Fig. 3D). These findings suggest that perturbation of the Hh pathway is likely to have occurred downstream of ligand but upstream of Gli transcription factors.
To further determine how Ift27 participates in transducing Hh signals during hair follicle development, primary dermal fibroblasts were treated with SMO agonist (SAG) and the expression of Hh-responsive genes examined. SAG treatment drastically induced the expression of Hh target genes (Ptch1, Gli2) in control cells, a response that was attenuated in Ift27−/− cells (Fig. 3E-G). Moreover, primary dermal fibroblasts isolated from E18.5 mouse embryos. Thus, data obtained from primary dermal fibroblasts were consistent with in vivo findings, thereby strengthening the idea that IFT27 participates in Hh signaling downstream of SMO activation. Moreover, primary dermal fibroblasts of Ift27−/− mice demonstrated increased GLI3-FL levels and an increased GLI3-FL/GLI3-R ratio (supplementary material Fig. S6), suggesting that the processing of Gli transcription factors was disrupted in Ift27−/− cells.

**Formation of the ciliary axoneme is unaffected in Ift27−/− skin**

Because Hh signaling requires primary cilia and the formation of cilia requires IFT, we speculated that Ift27 might be essential for Hh signaling by controlling ciliogenesis in follicular keratinocytes and dermal papilla cells. Immunofluorescence labeling with a number of ciliary markers, namely ARL13B, ADCY3 (ACIII) and acetylated α-tubulin, revealed indistinguishable patterns of primary cilia in wild-type and Ift27−/− embryos (Fig. 4A; supplementary material Fig. S7; data not shown). Scanning electron microscopy of primary keratinocytes isolated from control and Ift27−/− embryos also revealed primary cilia of comparable appearance (supplementary material Fig. S8). Thus, these observations suggested that neither the formation of the ciliary axoneme nor the localization of ciliary membrane-associated proteins, such as ARL13B and ADCY3, was affected in Ift27−/− cells.

Skin transplants generated from control embryos contained an abundance of ciliated follicular keratinocytes (supplementary material Fig. S9A). Remarkably, cells in the epidermal invaginations of Ift27+/− skin transplants also contained well-ciliated keratinocytes (supplementary material Fig. S9B). These cells are proposed to be keratinocytes that are committed to the follicular fate but have failed to develop into hair follicles because of disrupted Hh signaling or primary cilia formation (Chen et al., 2015; Chiang et al., 1999; Dai et al., 2013, 2011; Gat et al., 1998; Mill et al., 2003; St-Jacques et al., 1998). Thus, the congregation of these ciliated keratinocytes in the epidermal invaginations of Ift27+/− skin transplants not only confirmed this speculation but also strengthened our previous observation that Ift27 is essential for Hh signaling (Fig. 3) but not for primary cilia formation (Fig. 4).

To further examine the ciliogenic potential of Ift27−/− cells, primary keratinocytes were treated with cytochalasin D (cyto D), a compound capable of elongating the ciliary axoneme. Twenty-four hours after cyto D treatment (0.5 µM), the number of ciliated cells remained unchanged in both wild-type and Ift27−/− keratinocytes (supplementary material Fig. S9A). Remarkably, cells in the epidermal invaginations of Ift27−/− skin transplants also contained well-ciliated keratinocytes (supplementary material Fig. S9B). These cells are proposed to be keratinocytes that are committed to the follicular fate but have failed to develop into hair follicles because of disrupted Hh signaling or primary cilia formation (Chen et al., 2015; Chiang et al., 1999; Dai et al., 2013, 2011; Gat et al., 1998; Mill et al., 2003; St-Jacques et al., 1998). Thus, the congregation of these ciliated keratinocytes in the epidermal invaginations of Ift27+/− skin transplants not only confirmed this speculation but also strengthened our previous observation that Ift27 is essential for Hh signaling (Fig. 3) but not for primary cilia formation (Fig. 4).

To gain insight into how Ift27 regulates the Hh pathway, we examined the ciliary localization of Hh pathway components in primary dermal fibroblasts isolated from E18.5 mouse embryos. Similar to what was observed in Ift27+/− keratinocytes, Ift27−/− primary dermal fibroblasts were capable of forming primary cilia.
in vitro (Figs 5 and 6). In control dermal fibroblasts, SMO is essentially undetectable in the ciliary axoneme when the Hh pathway in inactive (cells treated with DMSO, Fig. 5A, upper panel). Upon pathway activation (SAG treatment), control cells robustly accumulated SMO in the cilium (Fig. 5A,B). By contrast, SMO abnormally accumulated in cilia of Ift27−/− dermal fibroblasts even when the Hh pathway was inactive (Fig. 5A, lower panel). This suggested that the ciliary exit of SMO was defective in Ift27−/− cells.

In SAG-treated control fibroblasts GLI2 accumulated at the ciliary tip (Fig. 5C,D), which was consistent with an activated Hh pathway as documented previously (Kim et al., 2009). By contrast, ciliary tip accumulation of GLI2 was severely disrupted in SAG-treated Ift27−/− dermal fibroblasts (Fig. 5C,D). This result was not only consistent with the suppressed Hh pathway observed in vivo and in vitro (Fig. 3) but also suggested defective trafficking of Hh components in Ift27−/− cells in response to Hh pathway activation.

**IFT27 and the expression and localization of other IFT proteins**

Since the loss of Ift27 does not seem to impact ciliogenesis, we further determined whether the expression and ciliary localization of known ciliogenic IFT proteins are affected in Ift27−/− cells. First, double immunofluorescence labeling and western blotting confirmed the loss of expression and of the ciliary localization of IFT27 in Ift27−/− cells (Fig. 6A,E). Subsequently, we found that the expression patterns of IFT88 and IFT140, which belong to the IFT-B and IFT-A complexes, respectively, were unaffected in Ift27−/− cells (Fig. 6C,D). Specifically, IFT88 was enriched in the axoneme and basal body, whereas IFT140 was predominantly localized at the basal body (Fig. 6C,D). The expression level of IFT140 was unchanged in Ift27−/− cells as confirmed by western blotting (Fig. 6E). By contrast, in Ift27−/− cells the ciliary localization of IFT25 was essentially undetectable (Fig. 6B) and its expression was significantly reduced by 35% (Fig. 6E,F). These data suggested that IFT27 is not required for the expression and localization of IFT proteins that are involved in cilia formation but selectively regulates the stability and localization of its binding partner IFT25, which is also dispensable during cilia formation.

**Ift25 mutants phenocopy the hair follicle phenotypes of Ift27−/− mice**

To confirm the functional relevance of IFT25 during hair follicle formation, we examined the skin of Ift25-null (Ift25−/−) mice (Keady et al., 2012). As expected, Ift25−/− mice displayed a hair follicle phenotype almost identical to that of Ift27−/− cells (Fig. 7A). Specifically, although the total number of hair follicles remained unaffected (Fig. 7B), the hair follicles of E18.5 Ift25−/− embryos
expression of IFT27 (A), IFT25 (B), IFT88 (C) and IFT140 (D) in ANOVA). These data suggested that necessary warrant functionality.
ciliogenesis, and that the presence of the ciliary axoneme does not for transducing the Hh signals may be separated from those of components. These findings demonstrate that the processes required ciliary axoneme but are essential for processing Hh signaling.

discovered that a subset of IFT proteins, specifically IFT27 and IFT25, are not required for the formation and maintenance of the ciliary axoneme but are essential for processing Hh signaling. In the current study, we further dissected the ciliogenic processes in the context of hair follicle morphogenesis, and discovered that a subset of IFT proteins, specifically IFT27 and IFT25, are not required for the formation and maintenance of the ciliary axoneme but are essential for processing Hh signaling components. These findings demonstrate that the processes required for transducing the Hh signals may be separated from those of ciliogenesis, and that the presence of the ciliary axoneme does not necessarily warrant functionality.

If27−/− and If25−/− mice die shortly after birth due to severe developmental abnormalities in vital organs, such as the heart, spinal cord and lung (Egutheter et al., 2014; Keady et al., 2012). These developmental anomalies were linked to disrupted Hh signaling (Egutheter et al., 2014; Keady et al., 2012). The extensive phenotypic outcome in If27−/− and If25−/− mice suggests that this subset of IFT proteins might be widely required in the embryonic development of complex organ systems. The recent identification of a loss-of-function mutation in IFT27 (C99Y) in Bardet-Biedl syndrome (BBS) demonstrated that IFT27 indeed plays an important role in human development and health (Aladhamesh et al., 2014). The hair follicle phenotype observed in the germline mutant If27−/− mice is reminiscent of that previously reported for Hh and primary cilia germline mutants (Chen et al., 2015; Chiang et al., 1999; Dai et al., 2011; Gat et al., 1998; Mill et al., 2003; St-Jacques et al., 1998; Woo et al., 2012). Interestingly, when Hh or ciliary genes were disrupted in a tissue-specific fashion, i.e. in the epidermal lineage (Dai et al., 2013) or in mesenchymal cells (Lehman et al., 2009; Woo et al., 2012), the resultant phenotypes were almost identical to those in germline mutants (Chen et al., 2015; Chiang et al., 1999; Dai et al., 2011; Gat et al., 1998; Mill et al., 2003; St-Jacques et al., 1998; Woo et al., 2012). These findings strongly suggest that disrupting Hh signaling or cilia formation/function in either or both tissue compartments of the hair follicle will, individually or collectively, contribute to hair follicle morphogenesis defects.

IFT27 and IFT25 are subunits of the IFT-B complex (Follit et al., 2013; Rosenbaum and Witman, 2002). Direct interactions between these two proteins have been demonstrated previously (Bhogaraju et al., 2011; Keady et al., 2012; Wang et al., 2009b). In this study, we further demonstrated that the stability and subcellular localization of these proteins are required for the morphogenesis of hair follicles, such that disrupting the expression of either of them

Fig. 6. Distribution of IFT-B and IFT-A proteins in If27−/− cells. (A-D) The expression of IFT27 (A), IFT25 (B), IFT88 (C) and IFT140 (D) in If27+/− and If27−/− primary dermal fibroblasts by colabeling by acetylated α-tubulin (red). Ciliary localization is shown in single channel and merged. (E) Expression levels of IFT27, IFT25 and IFT140 in dermal fibroblasts by western blotting; n=3. (F) Quantification of IFT25 as shown in E. The IFT25 protein level was significantly reduced in If27−/− primary dermal fibroblasts. *P<0.05. Scale bar: 5 µm.

displayed severe developmental delay (Fig. 7A,C; P<0.01, two-way ANOVA). These data suggested that If27 and If25 engage in a functional association during hair follicle morphogenesis.

DISCUSSION
Hedgehog signaling is required for the crosstalk between follicular keratinocytes and dermal papilla cells during hair follicle development. Activation of the Hh signaling pathway requires the primary cilia. A number of recent studies unequivocally demonstrated that the primary cilium is essential for hair follicle morphogenesis; disrupting ciliogenesis results in the arrest of hair follicle development due to disrupted Hh signaling (Chen et al., 2015; Dai et al., 2011; Lehman et al., 2009). Thus, the formation of the ciliary axoneme is prerequisite for its function; disrupting cilia formation inevitably disrupts its function, including the transduction of Hh signals. In the current study, we further dissected the ciliogenic processes in the context of hair follicle morphogenesis, and discovered that a subset of IFT proteins, specifically IFT27 and IFT25, are not required for the formation and maintenance of the ciliary axoneme but are essential for processing Hh signaling components. These findings demonstrate that the processes required for transducing the Hh signals may be separated from those of ciliogenesis, and that the presence of the ciliary axoneme does not necessarily warrant functionality.

If27−/− and If25−/− mice are characterized by extensive phenotypic outcome in important organs, such as the heart, spinal cord and lung (Egutheter et al., 2014; Keady et al., 2012). These developmental anomalies were linked to disrupted Hh signaling (Egutheter et al., 2014; Keady et al., 2012). The extensive phenotypic outcome in If27−/− and If25−/− mice suggests that this subset of IFT proteins might be widely required in the embryonic development of complex organ systems. The recent identification of a loss-of-function mutation in IFT27 (C99Y) in Bardet-Biedl syndrome (BBS) demonstrated that IFT27 indeed plays an important role in human development and health (Aladhamesh et al., 2014). The hair follicle phenotype observed in the germline mutant If27−/− mice is reminiscent of that previously reported for Hh and primary cilia germline mutants (Chen et al., 2015; Chiang et al., 1999; Dai et al., 2011; Gat et al., 1998; Mill et al., 2003; St-Jacques et al., 1998; Woo et al., 2012). Interestingly, when Hh or ciliary genes were disrupted in a tissue-specific fashion, i.e. in the epidermal lineage (Dai et al., 2013) or in mesenchymal cells (Lehman et al., 2009; Woo et al., 2012), the resultant phenotypes were almost identical to those in germline mutants (Chen et al., 2015; Chiang et al., 1999; Dai et al., 2011; Gat et al., 1998; Mill et al., 2003; St-Jacques et al., 1998; Woo et al., 2012). These findings strongly suggest that disrupting Hh signaling or cilia formation/function in either or both tissue compartments of the hair follicle will, individually or collectively, contribute to hair follicle morphogenesis defects.

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could result in hair follicle morphogenesis arrest. It is worth noting that the Ift25 and Ift27 mutant mice were able to survive to term, whereas other IFT-B mutants, such as Ift88<sup>−/−</sup>, are unable to survive beyond mid-gestation (Huangfu et al., 2003). The relatively mild phenotypes in the former suggested that IFT25 and IFT27 might have more restricted functions, such as in transducing Hh signals as shown herein, in comparison to IFT88, which is essential for ciliogenesis in a wide range of cell types. Interestingly, disrupting Ift88 resulted in similar hair follicle phenotypes (Lehman et al., 2009) to those of the Ift25 and Ift27 mutants described herein. Because these hair follicle phenotypes were attributed to attenuated Hh signaling, these studies collectively suggest that the core function of primary cilia during hair follicle morphogenesis is the transduction of Hh signals.

The ciliogenic capability of Ift27<sup>−/−</sup> cells was further examined using cyto D, which is capable of elongating the ciliary axoneme. Ift27<sup>−/−</sup> dermal fibroblasts treated with cyto D showed a comparable capacity to elongate the ciliary axoneme as control cells. Similarly, neither the expression nor localization of known ciliogenic IFT proteins, such as IFT88 and IFT140, nor the trafficking of ciliary membrane-associated proteins, such as ARL13B and ADCY3, was affected in Ift27<sup>−/−</sup> cells. These data suggested that Ift27 is not involved in the machinery required for ciliary length maintenance nor the trafficking of key ciliogenic proteins in mammalian primary cells. A recent study on the flagellum of Trypanosoma brucei suggested that IFT27 is involved in both anterograde and retrograde trafficking (Huet et al., 2014). Whether IFT27 performs cellular functions beyond trafficking Hh components remains to be determined in mammalian cells.

IFT27 was recently shown to play a crucial role in facilitating ciliary exit of the BBSome (Eguether et al., 2014; Ng et al., 2012), and Ift27-deficient mouse embryonic fibroblasts are unable to maintain low levels of SMO in the cilia when the Hh pathway is inactive (Eguether et al., 2014). In this study, we further demonstrated that suppressed Hh signaling in Ift27<sup>−/−</sup> primary dermal fibroblasts is also associated with abnormal accumulation of SMO in the cillum. However, ciliary accumulation of SMO does not necessarily correlate with pathway activation (Rohatgi et al., 2009). Thus, data obtained in this study suggest that disrupted Hh signaling in Ift27<sup>−/−</sup> cells may be associated with abnormal trafficking of Hh pathway components in the primary cilium.

The primary cilium is essential for the processing of Gli transcription factors. It is well documented that in the absence of Hh ligands GLI3-FL is processed to its repressor form GLI3-R, resulting in a relatively low GLI3-FL:GLI3-R ratio (Niewiadomski et al., 2014). Data obtained from this study demonstrated that disrupting Ift27 results in an attenuated Hh pathway and, counterintuitively, an elevated GLI3-FL level, suppressed GLI3-R level, and increased GLI3-FL:GLI3-R ratio. We speculate that these changes in Ift27<sup>−/−</sup> cells do not necessarily correspond to activation of the Hh pathway. Rather, they might merely reflect that IFT27 is required for proper processing of GLI3-FL. These data are in line with the well-documented observation that ligand-induced activation of the Hh pathway, and thus the production of GlI activators (but not GLI3-R), plays a predominant role during hair follicle morphogenesis (Mill et al., 2003). Thus, despite the elevated GLI3-FL level or increased IFT27<sup>−/−</sup>:GLI3-R ratio, the net outcome of disrupting Ift27 is Hh pathway suppression and impaired hair follicle morphogenesis. Moreover, Hh pathway activity is modulated by multiple phosphorylations of Gli transcription factors (both activators and suppressors) (Niewiadomski et al., 2014). Thus, data obtained from this study support the notion that Ift27 is involved in both anterograde and retrograde trafficking of IFT27 can be attributed primarily to its function in processing Hh signals. Whether IFT27 participates in the transduction of other molecular signals in the skin remains to be empirically determined.

In summary, this study demonstrated an essential role of Ift27 in mediating Hh signaling during follicular keratinocyte proliferation and differentiation but not the differentiation program of the interfollicular epidermis. Although the full spectrum of Ift27 functions remains to be uncovered, the rather restricted function of IFT27 during embryonic skin development provides important insight into a novel avenue of targeting Hh signaling, such as in the targeted therapy for basal cell carcinoma (BCC), in which tumors not only originate from the hair follicles but are also dependent on hyperactive Hh signaling (Epstein, 2008; Kasper et al., 2012). Because IFT27 is likely to mediate Hh signaling through regulating the ciliary localization of SMO and the processing of Gli transcription factors, targeting IFT27 might prevent the development of drug resistance caused by acquired mutations in the SMO receptor following Vismodegib treatment (Yauch et al., 2009).

**MATERIALS AND METHODS**

**Generation of Ift27<sup>−/−</sup> mice and skin transplantation**

Ift27-targeted embryonic stem cells ([Ift27]<sub>Wt</sub>/Ift27<sub>−/−</sub>EUCOMM/Mfng>) were obtained from the EUCOMM project and used to create Ift27<sup>−/−</sup> mutant mice (Eguether et al., 2014). Homozygous mutants were obtained by crossing Ift27<sup>−/−</sup> mice. Genotypes of Ift27<sup>−/−</sup> mice were determined using the following primer pairs (5′-3′): F, GGGAGATGAGGGATTCTTCC; R1, TCCAACCTGACTCGGTGCTT; R2, CCCCTGAACTCGTAAAACATA. E15.5 and E18.5 embryos were obtained by timed mating. Full-thickness skin transplantation was performed as previously described (Dai et al., 2011). All procedures related to mice were approved by the IACUC of the University of Massachusetts Medical School and Stony Brook University.

**BrdU labeling and tissue processing**

Bromodeoxyuridine (BrdU) labeling was performed by intraperitoneally injecting 10 μg BrdU labeling reagent (Invitrogen) per gram body weight 2 hours prior to euthanasia. Skin specimens were obtained by removing the full-thickness dorsal skin with surgical tools and were fixed in 10% buffered formalin at 4°C overnight. Fixed skin specimens were processed and sectioned for routine histology analysis. For all analyses, a minimum of three embryos obtained from at least two different litters were examined. AP staining was performed as previously described (Tsai et al., 2010). Specifically, frozen skin sections were fixed in 4% paraformaldehyde, soaked in B3 buffer (0.1 M Tris pH 9.5, 0.1 M NaCl, 0.05 M MgCl<sub>2</sub>) for 10 min, then in NBT (1:200)/BCIP (1:267) solution (Roche) for 20 min, and imaged.

**Cell culture and in vitro assays**

The isolation of primary skin keratinocytes and dermal fibroblasts was conducted as described (Marshall et al., 2005). Briefly, E18.5 skin was digested by dispase II (Roche) to separate epidermis and dermis. Epidermis or dermis was then digested with trypsin or collagenase, respectively, to collect keratinocytes and dermal fibroblasts. Cells were used directly for
skin reconstitution or cultured in vitro. Keratinocytes were cultured in defined keratinocyte serum-free medium (Life Technologies) on collagen I-coated tissue culture plates. Fibroblasts were cultured in Dulbecco’s modified Eagle’s medium (4.5 g/l glucose) supplemented with 10% fetal bovine serum and 100 U/ml penicillin and 100 U/ml streptomycin. To examine cilia formation, cells were grown to near confluence and culture starved for 24 h before being treated with SAG (100 nM, Calbiochem) or cyto D (0.5 µM, Sigma) for an additional 24 h in serum-free medium.

Quantitative RT-PCR and western blotting

RNA isolation and quantitative RT-PCR analyses were performed as described previously (Dai et al., 2013). The following probes were used for TaqMan analysis: Ift27, ABI Mm00508912_m1; Pchl1, Mm00436026_m1; Gli1, Mm00409146_m1; Gli2, Mm01293111_m1; Smo, Mm01162710_m1; and Actb, Mm00607993_m1 (Life Technologies). Results were analyzed using the ΔΔCt method. Relative expression levels of target genes were determined by comparison with wild-type or treatment controls after normalizing to β-actin.

Protein was extracted either by homogenizing skin in cold RIPA lysis buffer (1% Triton X-100, 0.1% SDS, 50 mM Tris-HCl pH 7.4, 150 mM NaCl, 1% sodium deoxycholate, 2 mM EDTA, 50 mM NaF) supplemented with proteinase inhibitors or by digesting cells directly in RIPA lysis buffer. Cell lysates were cleared by centrifugation at 13,000 g for 20 min at 4°C; protein concentration was determined using the BCA Protein Assay Kit (Pierce). Nuclear fractionation was conducted using the NE-PER Nuclear and Cytoplasmic Extraction Kit (Thermo Scientific). Proteins were separated on a NuPage gel (Life Technologies) and transferred to Hybond nitrocellulose membranes (GE Healthcare). The following primary antibodies were used: β-actin (1:1000; Santa Cruz, sc-7437), IFT27 [1:1000; gift of G. Pazour, University of Massachusetts (Keady et al., 2012)], GLI1 (1:250; clone V812, Cell Signaling, 2534S), IFT25 [1:200; Proteintech, 15732-1-AP] and IFT140 [1:500 (Keady et al., 2012)], Gli3 (1:200; R&D Systems, G. Pazour, University of Massachusetts (Keady et al., 2012)], Gli1 (1:250; Abcam, ab11317 and ab11316), ARL13B (1:100; NeuroMab, #73-287), acetylated α-tubulin (1:1000; Sigma, A21304), α-tubulin (1:1000; Sigma, T6793), γ-tubulin (1:500; Abcam, ab11317 and ab11316), ARL13B (1:100; NeuroMab, #73-287), IFT27 and IFT140 [1:200 (Keady et al., 2012)], IFT25 (1:200; Proteintech, 15732-1-AP) and IFT40 [1:500 (Uitto, 2012)]. HRP-conjugated secondary antibodies (BD Biosciences), SuperSignal substrates (Thermo Scientific) and CL-XPosure film (Thermo Scientific) were used for detection. Quantification of signal was performed using ImageJ (NIH).

Immunofluorescence labeling and microscopy

Immunofluorescence labeling was performed as described previously (Dai et al., 2013). The following primary antibodies were used: TRP63 (1:100; Santa Cruz Biotechnology, sc-8431), KRT14 [1:1000 (Roop et al., 1987)], KRT1 [1:500 (Roop et al., 1987)], KRT17 [1:400; Abcam, ab111446], LOR [1:100; (Roop et al., 1987)], LEFI [1:100; Cell Signaling, 2230], NFGr (1:200; p75NTR, Promega, G3231), BrdU (1:20; Life Technologies, ABcam, ab11317 and ab11316), ARL13B (1:100; NeuroMab, #73-287), α-tubulin (1:1000; Sigma, T6793), γ-tubulin (1:500; Abcam, ab11317 and ab11316), ARL13B (1:100; NeuroMab, #73-287), IFT27 and IFT140 [1:200 (Keady et al., 2012)], IFT25 (1:200; Proteintech, 15732-1-AP) and IFT40 [1:500 (Uitto, 2012)]. HRP-conjugated secondary antibodies (BD Biosciences), SuperSignal substrates (Thermo Scientific) and CL-XPosure film (Thermo Scientific) were used for detection. Quantification of signal was performed using ImageJ (NIH).

Scanning electron microscopy (SEM)

For SEM, primary keratinocytes isolated from E18.5 mice were fixed overnight in 2.5% glutaraldehyde in 0.1 M phosphate buffer (pH 7.4). Cells were then post-fixed, dehydrated and gold coated through standard procedures (Bechtold, 2000). Samples were examined on a JOEL S-3000N scanning electron microscope (Hitachi).

Statistical analyses

All quantifications are presented as means±s.d. Student’s t-test was used unless stated otherwise. One-way ANOVA and two-way ANOVA were conducted using GraphPad Prism. P<0.05 was considered statistically significant.

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Competing interests

The authors declare no competing or financial interests.

Author contributions

N.Y., J.P.S., G.J.P. and J.C. designed experiments and analyzed data. L.L. and T.E. performed preliminary experiments. N.Y. and J.C. carried out the experiments, collected the data and wrote the manuscript.

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Supplementary material

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References


