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*Genes Dev.* 2010 24: 670-682
Access the most recent version at doi:10.1101/gad.1902910
The output of Hedgehog signaling is controlled by the dynamic association between Suppressor of Fused and the Gli proteins

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The transcriptional program orchestrated by Hedgehog signaling depends on the Gli family of transcription factors. Gli proteins can be converted to either transcriptional activators or truncated transcriptional repressors. We show that the interaction between Gli3 and Suppressor of Fused (Sufu) regulates the formation of either repressor or activator forms of Gli3. In the absence of signaling, Sufu restrains Gli3 in the cytoplasm, promoting its processing into a repressor. Initiation of signaling triggers the dissociation of Sufu from Gli3. This event prevents formation of the repressor and instead allows Gli3 to enter the nucleus, where it is converted into a labile, differentially phosphorylated transcriptional activator. This key dissociation event depends on Kif3a, a kinesin motor required for the function of primary cilia. We propose that the Sufu–Gli3 interaction is a major control point in the Hedgehog pathway, a pathway that plays important roles in both development and cancer.

[Keywords: Hedgehog signaling; Gli proteins; Suppressor of Fused; primary cilia; development; cancer]

Supplemental material is available at http://www.genesdev.org.

Received January 7, 2010; revised version accepted February 19, 2010.
Roles for Sufu: tethering Gli proteins in the cytoplasm, or leash Gli activity. Previous studies have suggested two mechanisms by which Hh inhibits Gli3R formation has not been established in mammals. In the presence of Shh, Gli3FL and Ci155 are converted into full-length transcriptional activator proteins (Gli3A or Ci155A). The biochemical mechanism of this activation process remains mysterious in both flies and mammals.

The regulation of Ci and Gli proteins in response to Smo activation has diverged significantly between mammals and flies. In flies, this regulation depends on a complex of three proteins: the kinase Fused, the protein Suppressor of Fused (Sufu), and the atypical kinesin Costal 2 (Cos2). Cos2 recruits the kinases PKA, GSK3, and CK1 to phosphorylate Ci155 and promote the formation of Ci75 (Zhang et al. 2005). When Hh is received, the Cos2 scaffolded complex is recruited to the Smo C-terminal tail (Lum et al. 2003), an interaction that inhibits Ci75 formation. Higher doses of Hh can promote conversion of Ci155 into the active Ci155A by an unknown reaction that depends on the kinase Fused [Ohlmeyer and Kalderon 1998, Wang and Holmgren 1999, Methot and Basler 2000]. A requirement for Sufu is seen only in Fused mutants, implying that Sufu is not absolutely required in flies for regulation of Hh signaling [Preat 1992].

In mammals, Gli regulation depends on the primary cilium, a solitary cell surface projection that functions as a major signaling center in the cell. Disruption of intraflagellar transport (IFT), the motor-driven transport mechanism that moves proteins along the cilium, prevents formation of Gli3R and reduces Gli2/3A function in embryos [Huangfu et al. 2003, Huangfu and Anderson 2005; Liu et al. 2005]. Most proteins in the Hh pathway, including Ptc1, Smo, Sufu, and the Gli proteins, localize to cilia, and it is likely that many of the critical reactions in the pathway occur within this specialized compartment [Corbit et al. 2005; Haycraft et al. 2005; Rohatgi et al. 2007].

In sharp contrast to its ancillary role in flies, Sufu plays a crucial negative role in mammalian Hh signaling. Genetic inactivation of Sufu leads to constitutive activation of Hh target genes in cultured cells and in mice [Cooper et al. 2005; Svard et al. 2006]. In humans, Sufu is a tumor suppressor gene; its inactivation can cause medulloblastomas and the Gorlin’s syndrome tumors [Taylor et al. 2002, Pastorino et al. 2009]. Sufu binds directly to the Gli proteins [Pearse et al. 1999, Stone et al. 1999], but we do not understand how Sufu antagonizes the function of the Gli proteins or how Hh signaling antagonizes Sufu to unleash Gli activity. Previous studies have suggested two roles for Sufu: tethering Gli proteins in the cytoplasm, or suppressing Gli transcriptional activity in the nucleus. The literature has conflicting reports on the relative importance of these mechanisms [Ding et al. 1999; Cheng and Bishop 2002; Svard et al. 2006]. The ability of Sufu to inhibit signaling is preserved in cells lacking IFT components, so Sufu function is probably independent of primary cilia [Chen et al. 2009; Jia et al. 2009]. Cells lacking Sufu contain very low steady-state levels of Gli2, Gli3FL, and Gli3R, raising the question of how these cells attain a high level of Hh target gene transcription [Chen et al. 2009; Jia et al. 2009].

In this study, we present experiments designed to illuminate the final steps along the path of Hh transduction—the regulation of GliA and GliR functions by Sufu. We focused our attention on Gli3 because it behaves most like the fly Ci protein. Our experimental approach is based on the analysis of endogenous proteins and their interactions in cultured fibroblasts in response to acute activation of Hh signaling, thus avoiding the pitfalls of overexpressed proteins or cells undergoing long-term adaptation to constitutive signal transduction. We find that the association of Sufu and Gli3 is regulated by Hh signaling, and that this critical interaction controls the balance between Gli3R versus Gli3A formation.

Results

Acute Hh pathway activation causes a decline in the stability of Gli3FL

Using antibodies that recognize endogenous Gli1, Gli3, or Ptc1, we assessed levels of these proteins in lysates from NIH3T3 fibroblasts treated with Shh [Fig. 1A]. The antibody to detect Gli3 recognized both Gli3FL and Gli3R, since it was directed against a common epitope in the N terminus of Gli3. Gli1 and Ptc1 are two early target genes induced by Hh signaling, and the levels of their protein and RNA products [Fig. 1A, B] increased in a time-dependent manner. As observed previously, Gli3R protein levels declined in response to Shh [Fig. 1A; Wang et al. 2000]. Current models predict that this decline in Gli3R should be accompanied by a concomitant increase in its precursor, Gli3FL. Instead, we found that Gli3FL protein levels also decreased in response to Shh [Fig. 1A]. The decrease in Gli3 levels in response to Shh was inhibited by SANT-1, a small molecule antagonist of Smo [Supplemental Fig. S1A]. Control experiments ensured that both forms of Gli3 were extracted efficiently from cells [Supplemental Fig. S1B].

To confirm this surprising concordant reduction in Gli3FL and Gli3R, cells were treated with Shh in the presence of increasing concentrations of Forskolin (Fsk). Fsk, an activator of adenylate cyclase (AC), can inhibit Hh signaling and induce formation of Gli3R because it activates PKA by raising cellular cAMP levels [Wang et al. 2000]. Fsk inhibited Hh signaling in a dose-dependent manner, assayed by Gli1 protein levels [Fig. 1C]. This inhibition was accompanied by increases in both Gli3FL and Gli3R protein levels [Fig. 1C, D]. Thus, both acute pathway activation by Shh and inactivation by Fsk led to
cycloheximide chase experiments were used to measure the half-life of Gli3FL in response to activation of Hh signaling. Since we were focused on events downstream from Smo and wanted to exclude confounding effects caused by feedback mechanisms that may operate upstream of Smo, we used the direct Smo activator SAG (Smo Agonist) (Chen et al. 2002). Smo activation by SAG reduced the half-life of Gli3FL but did not significantly change the half-life of Gli3R (Fig. 1E,F; Supplemental Fig. S1C). Thus, Hh signaling decreased levels of Gli3FL and Gli3R in fundamentally different ways: It induced the destabilization of Gli3FL, but it inhibited the production of Gli3R without affecting its stability.

**Sufu stabilizes Gli3FL**

Recent studies have shown that steady-state levels of Gli3FL and Gli3R are very low in sufu−/− embryos and cells (Chen et al. 2009, Jia et al. 2009). We asked if Sufu plays a role in regulating the synthesis or the degradation of Gli3FL. Sufu−/− cells were infected with a retrovirus carrying a gene for wild-type Sufu [sufu−/−:Sufu cells] or with an empty retrovirus [sufu−/−:vector cells]. Since Sufu is a negative regulator of the pathway, sufu−/−:vector cells showed high levels of Gli1 target gene expression (Fig. 2A). The reintroduction of Sufu or YFP-tagged Sufu extinguished signaling, suppressed Gli1 levels, and restored sensitivity of the cells to pathway activation (Fig. 2A). Compared with control cells, the steady-state levels of Gli3FL and Gli3R were much higher in sufu−/−:Sufu cells, showing that functional Sufu caused an accumulation of both forms of Gli3. We also confirmed that the endogenous Gli3 protein could form a complex with the reintroduced Sufu (Fig. 2B). Thus, the Sufu added back into sufu−/− cells was functional because it interacted with Gli3 and suppressed target gene transcription.

To determine if the difference in Gli3 levels in the presence or absence of Sufu was caused by a difference in synthesis or degradation, cycloheximide was used to block protein synthesis in sufu−/−:vector cells and sufu−/−:Sufu cells. The half-life of Gli3FL was drastically shorter (<30 min) in the absence of Sufu compared with the presence of Sufu (>8 h) (Fig. 2C,D, Supplemental Fig. S2A). Gli3FL degradation in cells lacking Sufu was likely mediated by the proteasome, since the addition of epoxomycin, a proteasome inhibitor, increased the steady-state levels of Gli3FL (Fig. 2E).

**Sufu potentiates the formation of Gli3R**

The low steady-state levels of Gli3R seen in sufu−/− cells could result from Sufu driving production of Gli3R, or because Sufu protects Gli3R from degradation. While steady-state levels of Gli3R were different (Fig. 2A), the half-life of Gli3R was identical in sufu−/−:vector and sufu−/−:Sufu cells (Figs. 2C, 3A; Supplemental Fig. S2A). Thus, Gli3FL was much more labile than Gli3R in the absence of Sufu (Supplemental Fig. S3A,B). In addition, the steady-state level of a Myc-tagged Gli3R protein introduced into sufu−/− cells by transfection did not increase when cotransfected with Sufu (Fig. 3B). Taken together,
these results suggest that Sufu controls the rate of Gli3R production and not the rate of its degradation.

Low Gli3R production could simply be due to the low amount of Gli3FL substrate available in the absence of Sufu. To address this issue, we overproduced Myc-tagged Gli3FL [Myc-Gli3FL] protein in sufu−/− cells. Increasing the levels of Myc-Gli3FL by overexpression did not lead to efficient production of Gli3R unless Sufu was coexpressed (Fig. 3C). The Gli3FL/Gli3R ratio was significantly lower (Fig. 3D) when Sufu was coexpressed, showing that the increase in Gli3R was not simply a consequence of higher expression levels of Gli3FL protein.

Since PKA is a major regulator of Gli3R production, we tested potential interactions between Sufu and PKA by treating sufu−/− cells with Fsk to hyperactivate PKA. Fsk treatment modestly increased the amounts of endogenous Gli3R produced in the absence of Sufu (Fig. 3E). However, Sufu was very inefficient at inducing the production of Gli3R from endogenous Gli3FL in the absence of Sufu. The levels of Gli3R in Fsk-treated sufu−/− cells remained far below those seen in sufu−/−:Sufu cells (Fig. 3E, Supplemental Fig. S3C). In fact, the small amount of Gli3R induced by Fsk in sufu−/− cells was insufficient to extinguish target gene transcription (Fig. 3F, Supplemental Fig. S3C). Thus, Sufu may play an important role in enhancing the ability of PKA to promote the processing of Gli3FL to Gli3R.

How could Sufu have such a dramatic effect on the half-life of Gli3FL but little effect on the half-life of Gli3R? One possibility is that Sufu binds only to the full-length protein but not to the truncated repressor fragment. Previous experiments using overexpressed or purified proteins showed that Sufu binds to both N-terminal and C-terminal regions of Gli3 [Pearse et al. 1999; Dunaeva et al. 2003]. We re-examined the association between Gli3 and Sufu, this time testing the interaction between endogenous proteins in extracts made from NIH3T3 cells. Immunoprecipitation of both Gli3FL and Gli3R from these extracts with an anti-Gli3 antibody pulled down Sufu, as predicted if Gli3 and Sufu proteins exist in a complex (Fig. 3G). Since the anti-Gli3 antibody recognizes Gli3FL and Gli3R, we could not determine whether Sufu interacts with one or both Gli3 proteins. However, when Sufu was immunoprecipitated from extracts with anti-Sufu, only Gli3FL coprecipitated with Sufu, even though it was present at much higher levels. To exclude the possibility that our polyclonal anti-Sufu antibody disrupted the Sufu–Gli3R complex, we used an anti-YFP antibody to isolate YFP-Sufu from extracts made from NIH3T3 cells infected with an empty retrovirus (vector) or with a retrovirus carrying either full-length Sufu or YFP-tagged Sufu. Cells were untreated or treated with SAG (100 nM; 12 h). [B] Anti-Gli3 immunoprecipitates from whole-cell lysates of sufu−/− cells or sufu−/− cells rescued with Sufu re-expression (sufu−/−:Sufu cells) were tested for the presence of Gli3 and Sufu protein by immunoblotting. ([C–E]) Gli3FL and Gli3R half-life in the presence or absence of Sufu was measured by treating sufu−/−:vector cells and sufu−/−:Sufu cells with cycloheximide (CHX; 100 μg/mL) for the indicated periods of time and then analyzing Gli3FL and Gli3R levels by immunoprecipitation (IP) from whole-cell lysates. Different exposures were necessary for samples from sufu−/−:vector and sufu−/−:Sufu cells to prevent signal saturation; equivalent exposures are shown in Supplemental Figure S2A. The fraction of Gli3FL remaining (t = 0) in the two cell types is plotted in D. [E] Gli3FL protein levels in sufu−/− cells increase when the proteasome is inhibited with epoxomycin (10 μM; 6 h).

Figure 2. Sufu stabilizes Gli3FL. (A) Levels of Gli3FL, Gli3R, Sufu, Gli1 (to assess target gene activation), and p38 (to ensure equal loading) were assayed in sufu−/− cells infected with an empty retrovirus [vector] or with a retrovirus carrying either full-length Sufu or YFP-tagged Sufu. Cells were untreated or treated with SAG (100 nM, 12 h). [B] Anti-Gli3 immunoprecipitates from whole-cell lysates of sufu−/− cells or sufu−/− cells rescued with Sufu re-expression (sufu−/−:Sufu cells) were tested for the presence of Gli3 and Sufu protein by immunoblotting. ([C–D]) Gli3FL and Gli3R half-life in the presence or absence of Sufu was measured by treating sufu−/−:vector cells and sufu−/−:Sufu cells with cycloheximide (CHX; 100 μg/mL) for the indicated periods of time and then analyzing Gli3FL and Gli3R levels by immunoprecipitation (IP) from whole-cell lysates. Different exposures were necessary for samples from sufu−/−:vector and sufu−/−:Sufu cells to prevent signal saturation; equivalent exposures are shown in Supplemental Figure S2A. The fraction of Gli3FL remaining (t = 0) in the two cell types is plotted in D. (E) Gli3FL protein levels in sufu−/− cells increase when the proteasome is inhibited with epoxomycin (10 μM, 6 h).
Hh signaling triggers the dissociation of Gli3FL and Gli2FL from Sufu

The dramatic effect of Sufu on the stability of Gli3FL (Fig. 2) led us to consider the possibility that the decline in Gli3FL stability seen when Hh signaling is activated (Fig. 1) was caused by the release of Gli3FL from Sufu. A recent report stated that there was no decrease in the Sufu–Gli interaction in response to Shh (Chen et al. 2009), but that experiment was done using overproduced quantities of both proteins that could have escaped limiting regulatory mechanisms in the cell.

The interaction between endogenous Gli3 and Sufu was tested by immunoprecipitating Gli3 from extracts made from NIH3T3 cells treated with SAG for increasing amounts of time. As expected, SAG treatment led to a decline in total Gli3FL levels (Fig. 4A). More interestingly, the amount of Sufu that coprecipitated with Gli3FL showed a time-dependent decline after initiation of signaling (Fig. 4A; Supplemental Fig. S4A). The amount of Sufu detected in Gli3 immunoprecipitates could decline simply because the total level of Gli3FL protein is decreasing, not because there is a change in association. This is not the case, for two reasons. First, the Sufu/Gli3FL ratio (Fig. 4B), which is proportional to the amount of Sufu pulled down per unit of Gli3FL, showed a time-dependent decline. Second, the amount of Sufu that coprecipitated with Gli3FL decreased in response to signaling even when Gli3FL degradation was prevented by treatment with the proteasome inhibitor MG132 (Fig. 4A,B).

We also examined if the signal-induced dissociation of Sufu from Gli3FL association also held for Gli2FL, often considered the major transcriptional activator in cells. Since we did not have antibodies to immunoprecipitate Gli2, we instead isolated endogenous Sufu and tested for the amount of coprecipitated Gli2 by immunoblotting. Similar to Gli3, the amount of endogenous Gli2 that coprecipitated with Sufu showed a time-dependent decline in response to SAG (Fig. 4C,D).

Fsk prevented both the decline in Gli3FL and the decline in Gli3R seen in response to Hh signaling (Fig. 1C). If Sufu association controls both events, an important prediction is that Fsk should block the SAG-induced dissociation of Gli3 and Sufu. Pretreatment of cells with Fsk completely blocked the SAG-induced dissociation of Gli3 and Sufu, as measured by the absolute levels of Sufu coprecipitated with Gli3 and by the Sufu/Gli3 ratio (Fig. 4E,F; Supplemental Fig. S4B).

Hh signaling leads to the phosphorylation and nuclear translocation of Gli3FL

A long-standing question in Hh signaling is how full-length Gli proteins are converted into transcriptional activators. A transcriptional activator must enter the nucleus to stimulate the transcription of target genes. Subcellular fractionation was used to determine the localization of endogenous Gli3 and Sufu in NIH3T3 cells without Hh pathway activation. Gli3FL and Sufu were found predominantly in the cytoplasm, while Gli3R was located in the nucleus (Fig. 5A). The presence of Sufu in the same compartment as Gli3FL but in a different compartment than Gli3R is in agreement with our observation that Sufu associates with Gli3FL but not Gli3R (Fig. 3G). It is also consistent with...
from estimated using the ratio of the Sufu signal to the Gli3FL signal. A time-dependent decrease in the amount of Sufu pulled down per unit of Gli3FL, MG132 was added 30 min before SAG. 

NIH3T3 cells treated with SAG (100 nM) for the indicated periods of time. 

Gli2FL that coprecipitates with anti-Sufu beads from lysates of NIH3T3 cells treated with SAG alone (100 nM) or SAG + MG132 (25 μM). MG132 was added 30 min before SAG. (B) A time-dependent decrease in the amount of Sufu pulled down per unit of Gli3FL, estimated using the ratio of the Sufu signal to the Gli3FL signal from A. (C,D) A time-dependent decrease in the amount of Gli2FL that coprecipitates with anti-Sufu beads from lysates of NIH3T3 cells treated with SAG (100 nM) for the indicated periods of time. 

(E,F) Fsk (20 μM) prevents the SAG-induced dissociation (100 nM; 6 h) of Sufu from Gli3, assayed by determining the amount of Sufu that coprecipitated with anti-Gli3 beads from lysates of NIH3T3 cells (shown in E). 

The ratio of the Sufu signal to the Gli3FL signal from E was plotted.

Figure 4. Hh signaling promotes the dissociation of Sufu from Gli3FL and Gli2FL. (A) A time-dependent decrease in the amount of Sufu that coprecipitates with Gli3 from lysates of NIH3T3 cells treated with SAG alone (100 nM) or SAG + MG132 (25 μM). MG132 was added 30 min before SAG. (B) A time-dependent decrease in the amount of Sufu pulled down per unit of Gli3FL, estimated using the ratio of the Sufu signal to the Gli3FL signal from A. (C,D) A time-dependent decrease in the amount of Gli2FL that coprecipitates with anti-Sufu beads from lysates of NIH3T3 cells treated with SAG (100 nM) for the indicated periods of time. 

(E,F) Fsk (20 μM) prevents the SAG-induced dissociation (100 nM; 6 h) of Sufu from Gli3, assayed by determining the amount of Sufu that coprecipitated with anti-Gli3 beads from lysates of NIH3T3 cells (shown in E). 

The ratio of the Sufu signal to the Gli3FL signal from E was plotted.

Regulation of Gli proteins by Sufu

In response to Smo activation by SAG, Gli3FL shifted from the cytoplasm to the nucleus, assessed by either absolute levels of Gli3FL in the nucleus [Fig. 5B] or the calculated fraction of total Gli3FL in the nucleus [Fig. 5C]. Gli2FL also moved from the cytoplasm to the nucleus in response to SAG (Supplemental Fig. S5A), although total Gli2 levels remained stable after signal activation (Supplemental Fig. S5C). In contrast, Sufu, Gli3R, and the standing pool of Gli1 did not show any change in subcellular localization in response to SAG (Fig. 5B; Supplemental Fig. S5A). The rise in nuclear Gli3FL was caused by increased nuclear import rather than decreased nuclear export because Leptomycin B, an inhibitor of nuclear export, did not enhance Gli3FL accumulation in the nucleus [Supplemental Fig. S5B].

The activation of Hh signaling led to both the nuclear translocation and destabilization of Gli3FL. These changes in the biochemical properties of Gli3FL may reflect its conversion into a transcriptional activator (Gli3A), since the activation of transcription factors is often coupled to their degradation (Collins and Tansey 2006). To determine whether the signal-induced nuclear translocation of Gli3FL is coupled to its degradation, cells were treated with SAG and the proteasome inhibitor MG132. MG132 stabilized Gli3FL in the nucleus, but had little effect on Gli3FL in the cytoplasm [Fig. 5B,C]. This suggested that Gli3FL is degraded in the nucleus, after Hh signaling drives its movement from the cytoplasm. To directly follow the dynamics and dissect the temporal order of Gli3FL nuclear translocation and degradation, levels of Gli3FL in the nucleus and cytoplasm were assessed at various times after SAG addition [Fig. 5D,E]. The rapid decline in cytoplasmic Gli3FL was accompanied by a concomitant increase in nuclear Gli3FL, showing that the initial event was translocation from the cytoplasm to the nucleus. This was followed by the degradation of the nuclear pool of Gli3FL. Notably, nuclear translocation of Gli3FL (<30 min) occurs before target gene transcripts can be detected (>2 h) [Fig. 1B].

The above studies support the view that the activator form of Gli3 is a labile species localized in the nucleus. This instability may be the reason that it has been difficult to detect endogenous Gli3 (and Gli155) in the nucleus after activating the pathway, especially when looking at late time points after signal initiation. In searching for a biochemical mark that might distinguish Gli3A from Gli3FL, we observed that Gli3FL extracted from the nucleus after treatment with SAG consistently migrated more slowly on SDS-PAGE gels compared with either cytoplasmic Gli3FL or nuclear Gli3FL extracted in the absence of SAG [Fig. 5B,F]. The gel migration difference suggested that nuclear Gli3FL was phosphorylated selectively in a signal-regulated manner.

The phosphorylation of Gli3FL induced by Smo activation was unexpected because previous work had suggested that Gli3FL [and Gli155] proteins are dephosphorylated in response to signaling [Chen et al. 1999]. Since we observed the opposite, Gli3FL was analyzed carefully using two different techniques to establish that the gel shift observed in the nuclear fraction was indeed caused by phosphorylation rather than a different post-translational modification. First, we used phosphate affinity SDS-PAGE [Kinoshita et al. 2009], a method in which gels incorporate Mn<sup>2+</sup>-Phos-tag. This dinuclear metal complex binds selectively to phosphomonoesters, and thus enhances only those gel shifts caused by phosphorylation events on proteins. The mobility of Gli3FL extracted from the nuclei of SAG-treated cells was significantly retarded on gels containing Phos-tag when compared with identical gels lacking Phos-tag [Fig. 5G]. The mobility of nuclear Gli3FL from SAG-treated cells was much slower than the mobility of cytoplasmic Gli3FL or the mobility of nuclear
Gli3FL in the absence of SAG (Fig. 5G), demonstrating that Gli3FL found in the nucleus in response to signaling has a unique pattern of phosphorylation. Second, the reduced mobility of nuclear Gli3FL seen in response to signaling could be reversed by phosphatase treatment (Fig. 5H), providing independent evidence for phosphorylation. Plots of Gli3FL mobility (Fig. 5H) suggested that cytoplasmic Gli3FL was also likely phosphorylated; however, the mobility, and hence the phosphorylation pattern, of nuclear Gli3FL was clearly different after SAG addition. In summary, conversion of Gli3 into a transcriptional activator was associated with its nuclear translocation, differential phosphorylation, and destabilization.

PKA is thought to inhibit both mammalian and Drosophila Hh signaling primarily by promoting formation of Gli3R [Wang et al. 2000; Smelkinson et al. 2007]. However, PKA activation stabilized Gli3FL [Fig. 1C], so we considered the possibility that PKA may also inhibit conversion of Gli3FL into Gli3A. Treatment of cells with Fsk inhibited the SAG-induced nuclear translocation [Figs. 6A; Supplemental Fig. S6A], phosphorylation [Supplemental Fig. S6A], and degradation of Gli3FL [Supplemental Fig. S4B]. These results are consistent with the ability of Fsk to prevent the signal-induced dissociation of SuFu from Gli3FL [Fig. 4]. To test whether the ability of PKA to inhibit formation of Gli3A influenced target gene transcription, cells were treated simultaneously with Shh and Fsk. Under these conditions, Gli1 was transcribed in a short pulse, presumably because the rapid activation of Gli1 transcription by Shh was followed by the slower kinetics of Fsk action [Fig. 6B]. This pulse was mirrored by changes in the level of Gli3FL, with unstable Gli3FL associated with high transcription and stable Gli3FL associated with low transcription [Fig. 6B]. During this experiment, Fsk inhibited Gli1 and Ptc1 transcription without increasing the levels of Gli3R. These experiments confirm that the unstable form of Gli3FL is a transcriptional activator, and that PKA can inhibit target gene induction by preventing the conversion of Gli3FL into Gli3A.

To dissect the relationship between SuFu dissociation, nuclear translocation, phosphorylation, and degradation, we took advantage of the observation that disrupation of
cytoplasmic microtubules blocks nuclear translocation of Gli2 (and target gene transcription) in response to Hh signaling (Kim et al. 2009). As for Gli2, the SAG-induced nuclear translocation of Gli3FL could be blocked by the microtubule-disrupting agent nocodazole (Fig. 6C,D, Supplemental Fig S6B). While nocodazole treatment also blocked the SAG-induced phosphorylation (Fig. 6C) and destabilization (Fig. 6E) of Gli3FL, it did not prevent the dissociation of Sufu from Gli3FL (Fig. 6E,F). Thus, cytoplasmic microtubules appear to be required at a step after Sufu–Gli3 dissociation, but before the coupled processes of nuclear translocation, phosphorylation, and degradation.

Sufu inhibits conversion of Gli3FL into a transcriptional activator

To show that Sufu works by preventing the nuclear translocation and activation of Gli3FL, we examined the subcellular localization of Gli3FL and Gli3R in sufu−/− cells. While sufu−/− cells have low total levels of Gli3FL (Fig. 2), a large fraction (>50%) of the Gli3FL is localized in the nucleus, consistent with the model that activated Gli proteins are highly unstable and are located in the nucleus (Fig. 7A,B). Gli3FL in nuclei of sufu−/− cells also migrated more slowly on SDS-PAGE gels than the Gli3FL present in the cytoplasm, suggestive of differential phosphorylation (Supplemental Fig. S7A). When Gli3FL degradation was inhibited with MG132 in sufu−/− cells, all of the additional Gli3FL accumulated in the nucleus (Fig. 7A,B). This supports the idea that Gli3A was degraded in the nucleus, either when Sufu protein was missing (Fig. 7A) or when Gli3FL was released from Sufu in response to Hh signaling (Fig. 5). The reintroduction of Sufu into sufu−/− cells extinguished target gene transcription and stabilized Gli3FL (Fig. 2A). Importantly, Sufu restoration into sufu−/− cells dramatically reduced the fraction of Gli3FL in the nucleus, despite the fact that the total level of Gli3FL was much higher in the presence of Sufu (Fig. 7C,D). Unlike Gli3FL, Gli3R was localized predominantly in the nucleus in the presence or absence of Sufu (Fig. 7C).

In summary, Gli3FL in sufu−/− cells has the same biochemical characteristics—nuclear location, instability, and differential phosphorylation—as wild-type fibroblasts treated with SAG, which both activates signaling and triggers the dissociation of Gli3 from Sufu. This finding provides an explanation for how sufu−/− cells can attain high target gene transcription despite containing low levels of Gli2 and Gli3 (Chen et al. 2009). Thus, Sufu inhibits Hh signaling in the cytoplasm by preventing conversion of Gli3FL into a transcriptional activator.

Dissociation of the Sufu–Gli3 interaction depends on the ciliary motor Kif3a

Cells and embryos with defective primary cilia are impaired in the production of activator and repressor forms of Gli proteins.
of the Gli proteins (Huangfu and Anderson 2006). The requirement for cilia was established by genetic studies in mice, and a large decrease in Gli3R was observed in lysates of embryos with ciliary defects (Huangfu and Anderson 2006). The steady-state level of Gli3Fl was similar in both cell types (Fig. 8D). This supports the idea, presented in two recent studies, that primary cilia are not required for Sufu to inhibit Gli proteins (Chen et al. 2009; Jia et al. 2009). We next analyzed how the Gli3–Sufu interaction changed after Hh pathway activation. SAG caused the dissociation of Gli3Fl from Sufu in kif3a+/+ cells, but SAG was unable to induce the dissociation of Gli3Fl from Sufu in cells lacking kif3a−/− [Fig. 8C,D]. Thus, the ability of Hh signaling to disrupt the Sufu–Gli3 interaction depends on Kif3a. Indeed, this is likely to be the major function of Kif3a and primary cilia in Hh signaling, because Kif3a is dispensable for target gene transcription in sufl−/− cells [Supplemental Fig. S8B; Chen et al. 2009].

Discussion

The main goal of Hh signaling is to alter the transcriptional program of the cell by influencing the balance between the activator and repressor functions of the Gli proteins. The dissociation of Sufu from Gli3 co-ordinately accomplishes the two main tasks of Hh signaling: inhibition of Gli3R formation, and promotion of Gli3A formation. We present our model for how the Sufu–Gli interaction, likely regulated by biochemical

We next tested the association between Gli3 and Sufu in both kif3a+/+ and kif3a−/− cells. In the absence of pathway stimulation, the Gli3–Sufu interaction was readily detected in cells from both genotypes [Fig. 8C], and the amount of Sufu precipitated per unit of Gli3Fl [the Sufu/Gli3 ratio] derived from Gli3 immunoprecipitates was similar in both cell types [Fig. 8D]. This supports the idea, presented in two recent studies, that primary cilia are not required for Sufu to inhibit Gli proteins (Chen et al. 2009; Jia et al. 2009). We next analyzed how the Gli3–Sufu interaction changed after Hh pathway activation. SAG caused the dissociation of Gli3Fl from Sufu in kif3a+/+ cells, but SAG was unable to induce the dissociation of Gli3Fl from Sufu in cells lacking kif3a−/− [Fig. 8C,D]. Thus, the ability of Hh signaling to disrupt the Sufu–Gli3 interaction depends on Kif3a. Indeed, this is likely to be the major function of Kif3a and primary cilia in Hh signaling, because Kif3a is dispensable for target gene transcription in sufl−/− cells [Supplemental Fig. S8B; Chen et al. 2009].

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Figure 8. Kif3a is required for Hh-induced dissociation of the Sufu–Gli3FL complex and nuclear translocation of Gli3FL. [A,B] Subcellular fractions generated from kif3a+/+ or kif3a−/− cells left untreated or treated with SAG (100 nM; 2 h) were assayed for Gli3FL, Gli3R, and Kif3a levels. [C,D] The amount of Sufu detected in Gli3 immunoprecipitates is unaffected by SAG treatment (100 nM; 2 h) in kif3a−/− cells, but drops significantly with SAG treatment in kif3a+/+ cells, seen both in the immunoblots [C] and by changes in the Sufu/Gli3FL ratio [D].
events at primary cilia, controls the formation of GliR and GliA.

**Gli3R formation**

In the absence of Hh signaling, the majority of Gli3FL is processed into Gli3R (Fig. 9A). In mammals, the efficient production of Gli3R depends on the association between Sufu and Gli3FL [Fig. 3]. While the association of Gli3FL with Sufu appears to be independent of primary cilia, the subsequent processing of Gli3FL into Gli3R depends on intact cilia [Fig. 8; Huangfu and Anderson 2005]. Sufu might promote Gli3 processing by recruiting it to primary cilia, although a recent report showed that overproduced Gli3 localized to cilia in sufu−/− cells [Chen et al. 2009]. Alternatively, the Gli3FL–Sufu complex may be a better substrate than Gli3FL for the biochemical reactions required for processing [Kise et al. 2009].

Once GliR is produced, its activity is independent of both Sufu and the primary cilium. Gli3R and Sufu proteins do not associate with each other in cells, and reside in separate subcellular compartments. The nuclear localization and half-life of Gli3R are unaffected by the loss of Sufu. The mechanism by which processing of Gli3FL into Gli3R leads to its dissociation from Sufu remains unknown, especially because prior work identified a Sufu-binding region in the N terminus of Gli3 [Pearse et al. 1999; Dunaeva et al. 2003]; however, our data suggest that endogenous Gli3R no longer has affinity for Sufu.

Activation of Hh signaling leads to a decrease in the levels of Gli3R, but the mechanism by which this occurs has been unclear in mammals. Our results support the model [Fig. 9B] that the dissociation of Sufu from Gli3FL drives the reduction in Gli3R synthesis seen in response to Hh signaling.

**Gli3A formation**

By studying Gli3 in the few hours after SAG treatment, we defined three properties that are associated with an increase in the transcriptional activity of Gli3FL: rapid nuclear translocation, phosphorylation, and destabilization (Fig. 9B). The activity of many transcription factors is often inversely related to their stability, in some cases to limit the duration of transcription, and in other cases because proteolysis is required for efficient transcription [Collins and Tansey 2006]. In flies, Hh has been proposed to promote the conversion of Ci155 into a labile transcriptional activator [Ohlmeyer and Kalderon 1998]. Thus, the destabilization of Gli3FL in response to signaling might reflect the conversion of Gli3FL to a transient but potent Gli3A. In terms of the mechanism of Gli3 degradation, work in flies and mammals has suggested that Gli3 or Ci155 stability may be regulated by Cul3-based E3 ubiquitin ligases that have a BTB domain-containing substrate recognition module [HIB in flies, SPOP in mammals] [Zhang et al. 2006; Chen et al. 2009].

The phosphorylation of Gli3FL seen after activation of signaling could control degradation, transcriptional activation, or both processes. Differential phosphorylation associated with Gli3A formation is seen only in the nucleus and occurs prior to degradation of Gli3 [Fig. 5D], suggesting that it may be controlled by a nuclear kinase. Dyrk1A is a nuclear kinase that has been implicated in the activation of Gli1, but the addition of Harmine, an inhibitor of Dyrk1A, had no effect on either nuclear translocation or phosphorylation of Gli3FL [Supplemental Fig. S5B; Mao et al. 2002; Seifert et al. 2008].

**Sufu restrains Hh signaling in the cytoplasm**

Our study suggests that the main locus for Sufu function in the cell is the cytoplasm, not the nucleus. The majority
of Sufu is present in the cytoplasm, and Sufu does not undergo any change in localization in response to Hh signaling. Experiments in sufu−/− cells, along with the observation that the association between Gli3 and Sufu is disrupted by Hh signaling, suggest that the main factor restraining the production of Gli3A is Sufu (Fig. 9B).

The mechanism by which Hh promotes this dissociation of Gli3 from Sufu is a major unresolved question. Some insights into this key step come from the finding that activation of PKA can prevent dissociation of the Gli3FL–Sufu complex, leaving Gli3FL stranded in the cytoplasm and unable to activate target genes. So, a decrease in PKA activity in response to Hh signaling may trigger dissociation of the Sufu–Gli3FL complex. There is some evidence that Smo activation can reduce PKA activity through the inhibitory Gai class of heterotrimeric G proteins (Riobo et al. 2006, Ogden et al. 2008). The dual involvement of Kif3a and PKA also suggests the interesting hypothesis that Hh signaling regulates Gli3–Sufu association by locally controlling the activity of PKA at the primary cilium (Barzi et al. 2010).

Future prospects

Our study provides a parsimonious model for control of the final, committed step in Hh signal transduction: activation of the Gli family of transcription factors. Unraveling the biochemical details of this activation process is an important goal. In addition, the reactions underlying Gli activation, such as phosphorylation or nuclear translocation, provide novel assays for both basic studies and small molecule and RNAi screens directed against this important pathway.

Materials and methods

Constructs and cell lines

All constructs described in the study were made from mouse genes. NIH3T3 cells were obtained from American Type Culture Collection, sufu−/− mouse embryonic fibroblasts (MEFs) were kindly provided by Rune Toftgard (Svard et al. 2006), and kif3a−/− and kif3a+/− MEFs were kindly provided by Pao-Tien Chuang (Corbit et al. 2008, Wilson et al. 2009). To make sufu−/− stable cells with Sufu or YFP-tagged Sufu added back, cDNAs encoding Sufu or Sufu tagged at its N terminus with YFP were cloned into pRetroX-PTuner retroviral expression vector (Clontech). The pRetroX-PTuner vectors include a ligand-responsive destrabilization domain (Clontech). Retroviral production and infection of sufu−/− fibroblasts was performed according to established protocols (Pear et al. 1993). The pRetroX-PTuner vectors include a ligand-responsive destabilization domain; however, this domain could not control Sufu or YFP-Sufu levels, and thus this feature was not used.

Full-length Gli3 (amino acids 1–1583) and Gli3 repressor (amino acids 1–740) were tagged on the N terminus with a 6-myc tag by cloning them into pCS2+ vector. N terminus with a 3× HA tag by cloning it into the pCS2+ HA vector.

Cell culture

Cells were grown to confluence in medium [high-glucose DMEM, 0.05 mg/mL penicillin, 0.05 mg/mL streptomycin, 2 mM glutamax, 1 mM sodium pyruvate, 0.1 mM MEM nonessential amino acid supplement] containing 10% FBS [Hyclone, defined grade], and then switched to medium containing 0.5% FBS for 12 h prior to all experiments. Cells were transfected using FugeneHD (Roche) per the manufacturer’s instructions.

Small molecules and recombinant proteins

SAG was obtained from Alexis; forskolin was obtained from BIOMOL; puromycin, cycloheximide, and nocodazole were obtained from Sigma; and Leptomycin B was obtained from EMD. The 293 EcR Shh cells [Taipale et al. 2000] were used to produce conditioned media containing processed and lipidated Shh [Supplemental Material]. This media was used at a dilution of one to four, with a final FBS concentration of 0.5%.

Antibodies

Anti-Gli1 [mouse monoclonal] was from Cell Signaling Technologies [catalog no. L42B10], anti-Gli2 [goat polyclonal] was from R&D systems [catalog no. AF3665], anti-Gli3 [goat polyclonal] was from R&D systems [catalog no. AF3690]; anti-p38, anti-Ki67, anti-LaminA, and anti-GFP [all rabbit polyclonal] was from Abcam [catalog nos. ab7952, ab11259, ab26300, and ab290]; and anti-Myc [9E10, mouse monoclonal] was from Roche. The anti-Sufu polyclonal antibody was produced [Josman Laboratories] in rabbits against full-length mouse Sufu protein and affinity-purified before use. Secondary antibodies conjugated to the horseradish peroxidase enzyme were purchased from Jackson Laboratories. The anti-Ptc1 rabbit polyclonal antibody, produced against a fragment of mouse Ptc1 from amino acids 1169 to 1435, has been described previously [Rohatgi et al. 2007].

Lysate production, immunoprecipitation, and Western blot analysis

For the production of whole-cell lysates, cells were lysed in Buffer A (50 mM Tris at pH 7.4, 300 mM NaCl, 2% NP-40 [v/v], 0.25% Deoxycholate [w/v], 10 mM N-ethyl maleimide, 1 mM DTT, a protease inhibitor cocktail [1× EDTA-free protease inhibitors from Roche]). When cells were treated with MG132 or cycloheximide, these drugs were maintained in the lysis buffers.

For immunoprecipitation, antibodies were coupled covalently to Protein A- or Protein G-coated magnetic beads [Dynal]. Anti-Gli3 or anti-Sufu-coupled beads were added to the clarified lysate. After overnight binding at 4°C, the beads were washed with Buffer A and eluted with 2× SDS sample buffer.

Subcellular fractionation

All subcellular fractionation experiments were performed on ice with freshly harvested cells. Cells were washed twice with phosphate-buffered saline [PBS] and twice with 10 mM HEPES [pH 7.4], and then were incubated for 10 min in 10 mM HEPES [pH 7.4]. The HEPES buffer was removed and SEAT buffer [10 mM Tris at pH 7.4, 250 mM sucrose, 1× EDTA protease inhibitor cocktail [Roche]] was added. Cells were lysed by 15 passages through a 25-G needle. Nuclei were separated from the post-nuclear supernatant [PNS] by centrifugation at 900g for 5 min and then washed once in SEAT buffer. The PNS was also resuspended at 900g for 5 min and then brought to 1× Buffer A, extracted for 1 h, and clarified by centrifugation at 20,000g for 1 h. The nuclei were extracted [same conditions as PNS] with 20 mM HEPES [pH 7.9], 1 mM MgCl2, 0.5 M NaCl, 0.2 mM EDTA, 20% glycerol, 1% Triton X-100, 1 mM DTT, benzamide, and a protease inhibitor cocktail. Lysates used for phosphorylation analysis included a phosphatase inhibitor cocktail [1× PhosphoSTOP
MnCl₂ were prepared and run according to a recently published protocol (Kinoshita et al. 2009). For phosphate affinity electrophoresis, Phos-tag gels containing phosphatase digestion, cytosolic and nuclear fractions were treated with 1 M protein phosphatase buffer, and 1 μM MnCl₂ for 1 h at room temperature. A 6% (100:1 acrylamide:bis-acrylamide) gel was used for the analysis of λ phosphatase digestion, cytosolic and nuclear fractions were treated with 1 μL (400 U) of λ protein phosphatase, 1 × λ protein phosphatase buffer, and 1 μM MnCl₂ for 1 h at room temperature. A 6% (100:1 acrylamide:bis-acrylamide) gel was used for the analysis of λ phosphatase-sensitive gel shifts in Figure 6C.

Data analysis
Films were scanned on the Epson Perfection V700 photo scanner into Photoshop at 600 dpi as grayscale TIFF files. Quantitative analysis of band intensities was performed with Total Lab 100 (Nonlinear Dynamics), and the data were transferred to GraphPad Prism for normalization, graphing, and curve fitting. All curves shown for the cycloheximide chase experiments represent best-fit single exponential decay curves. To calculate the fraction of Gli3FL in the nucleus or cytoplasm, we calculated the ratio of N/Nₐ for determination of its nucleocytoplasmic distribution.

Acknowledgments
We thank Rune Tøftgard for sufu⁻/⁻ cells, Pao-Tien Chuang for kif3a⁻/⁻ and kif3a⁺/+ cells, Tyler Hillman and Eunice Lee for advice on Gli3 constructs, Trina Schroer for Kif3a constructs, Maika Delfieu and Suzanne Pfeffer for advice on subcellular fractionation, and Nicholas Tilmans and Pehr Harbury for Phos-tag acrylamide. M.P.S is an Investigator of the Howard Hughes Medical Institute; R.R. is supported by a NCI Pathway to Independence award [K99/RO0 CA129174], a V Foundation Scholar, a SU2C Innovation Award (AACR), and the March of Dimes Basil O’Connor award, and E.W.H is supported by the PanCAN-AAAC fellowship, a pilot grant from the Stanford Digestive Disease Center, and the Amgen Hematology-OncoLgy Fellowship.

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