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Repression of Smoothened by Patched-Dependent (Pro-)Vitamin D3 Secretion

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The developmentally important hedgehog (Hh) pathway is activated by binding of Hh to patched (Ptch1), releasing smoothened (Smo) and the downstream transcription factor glioma associated (Gli) from inhibition. The mechanism behind Ptch1-dependent Smo inhibition remains unresolved. We now show that by mixing Ptch1-transfected and Ptch1 small interfering RNA–transfected cells with Gli reporter cells, Ptch1 is capable of non–cell autonomous repression of Smo. The magnitude of this non–cell autonomous repression of Smo activity was comparable to the fusion of Ptch1-transfected cell lines and Gli reporter cell lines, suggesting that it is the predominant mode of action. CHOD-PAP analysis of medium conditioned by Ptch1-transfected cells showed an elevated 3β-hydroxysteroid content, which we hypothesized to mediate the Smo inhibition. Indeed, the inhibition of 3β-hydroxysteroid synthesis impaired Ptch1 action on Smo, whereas adding the 3β-hydroxysteroid (pro-)vitamin D3 to the medium effectively inhibited Gli activity. Vitamin D3 bound to Smo with high affinity in a cyclopamine-sensitive manner. Treating zebrafish embryos with vitamin D3 mimicked the smo–/– phenotype, confirming the inhibitory action in vivo. Hh activates its signalling cascade by inhibiting Ptch1-dependent secretion of the 3β-hydroxysteroid (pro-)vitamin D3. This action not only explains the seemingly contradictory cause of Smith-Lemli-Opitz syndrome (SLOS), but also establishes Hh as a unique morphogen, because binding of Hh on one cell is capable of activating Hh-dependent signalling cascades on other cells.

Introduction

Signal transduction of the morphogen hedgehog (Hh) is highly unusual, with many features unique to this signalling system, many of which are only partly understood [1]. For instance, Hh signalling is mediated by two membrane proteins: patched (Ptch1) and smoothened (Smo). The former is a 12-pass transmembrane protein [2,3] resembling the Niemann-Pick disease type C1 (NPC1) protein (which is involved in cholesterol trafficking and has a pump function); the latter is a seven-pass transmembrane protein that resembles a G protein–coupled receptor [4]. In the absence of the inhibitory receptor Ptch1 (or in the case of a specific mutation rendering Ptch1 dysfunctional), Smo is constitutively active and leads to the activation and nuclear translocation of its downstream transcription factor glioma associated (Gli). Under normal physiological circumstances, the activation of the signalling pathway is caused by binding of Hh to Ptch1, resulting in the internalisation of Ptch1 and, consequently, the alleviation of the inhibitory effect of Ptch1 on Smo [5,6]. The exact mechanism behind Ptch1 inhibition of Smo, however, remains unclear [7].

Similarities in the phenotypes of humans with inherited disorders of sterol biosynthesis (Figure 1A, lathosterolosis and Smith-Lemli-Opitz syndrome (SLOS)) and the phenotypes seen with mutations in the Hh signalling pathway have led to the suggestion that cholesterol-synthesizing enzymes may somehow be involved in Ptch1-dependent Smo inhibition [1]. Sterol content has been found to be crucial to a cell’s responsiveness to Hh, independent of proper Hh sterolation [8], suggesting that sterol—or more specifically cholesterol—levels are pivotal to a cell’s ability to respond to Hh, rather than to the accumulation of a specific inhibitory metabolite.

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Abbreviations:
- 7-DHC: 7-dehydrocholesterol
- BSA: bovine serum albumin
- CHOD-PAP: cholesterol oxidase peroxidase-amidopyrine
- CMV: cytomegalovirus
- DMEM: Dulbecco’s Modified Eagle Medium
- FCS: fetal calf serum
- FPLC: fast performance liquid chromatography
- Gli: glioma associated
- HDL: high-density lipoprotein
- Hh: hedgehog
- HMGC-CoA: 3-hydroxy-3-methylglutaryl coenzyme A
- hpf: hours post fertilisation
- Ihh: Indian hedgehog
- ISH: in situ hybridisation
- LDL: low-density lipoprotein
- MEF: mouse embryonic fibroblast
- mGli: mutant Gli binding site
- NPC1: Niemann-Pick disease type C1
- PBS: phosphate buffered saline
- Ptch1: patched
- RLU: relative light unit
- Shh: Sonic hedgehog
- siRNA: small interfering RNA
- SLOS: Smith-Lemli-Opitz syndrome
- Smo: smoothened
- VLDL: very-low-density lipoprotein

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activates its signalling cascade by inhibiting Ptch1-dependent secretion of the 3β-hydroxysteroid (pro-)vitamin D3. These data provide fundamental new insight into the molecular mechanisms by which Hh exerts its action in pathophysiology.

Results

A Model System for Measuring Ptch1-Dependent Smo Inhibition

An experimental system allowing the study of intercellular inhibitory actions of Ptch1 on Smo should fulfill four requirements: (1) cells must be capable of sustaining Ptch1 expression, (2) expressed Ptch1 must be functionally active, (3) the inhibition of Gli activity should be Smo-mediated, and (4) endogenous Hh should not be a contributing factor. To set up a model system for studying Ptch1-dependent inhibition, C3H/10T1/2 fibroblasts, which are cells extensively used for Hh research, were transfected with an 8× Gli-binding site luciferase construct [15] together with Ptch1, Smo, Smo and Ptch1, or Gli1.

Overexpression of Ptch1 drove cells into apoptosis (unpublished data, consistent with [16]), possibly a reflection of the function of Ptch1 as a so-called dependence receptor. To overcome this problem, we performed experiments in the presence of 20 μM caspase inhibitor zVADfmk. Under these conditions, transfection with a Ptch1 expression construct led to efficient overexpression of Ptch1 as detected by Western blot (Figure 2A). Transfection of Ptch1 effectively inhibited transactivation of the Gli reporter in the presence of overexpressed Smo (Figure 2B). The Ptch1-insensitive mutant SmoM2 [11,17] was not inhibited by Ptch1 cotransfection and showed a high basal Gli activity. Ptch1 transfection in the absence of Smo overexpression yielded no inhibition below control values, which has been described previously [18]. This finding suggests the presence of high basal Ptch1 levels and indicates the specificity of Ptch1 inhibition acting through Smo in our system. The inhibitory effect of the high basal Ptch1 levels could be overcome by the addition of 1 μg/ml recombinant N-terminal Sonic hedgehog (Shh) for 6 h, as can be seen from the high reporter activity upon stimulation (Figure 2B). Addition of 1 μg/ml 5E1 Shh-blocking antibody [19] could counteract the stimulation by Shh. Because Smo and Gli overexpression were capable of increasing trans-activation of the Gli reporter despite the presence of a caspase inhibitor, our experimental system is a valid readout for Smo-mediated Gli activity.

The requirement for Smo overexpression to respond to Ptch1 inhibition and the high responsiveness to exogenously added Shh suggest that endogenous Hh production is not a major factor in our setup, although others have shown mRNA for Indian hedgehog (Ihh) and Shh in C3H/10T1/2 cells [20,21]. To exclude Hh protein excretion by our C3H/10T1/2 cells as a contributing factor in our model system, we performed Western blot analysis on Shh-spiked medium and medium from fibroblast cell culture. The cells did not excrete Hh protein (Figure 2C). As can be seen, the detection limit was about 5 ng/ml, which was not reached in the (4× concentrated) medium, indicating that the Hh concentration in the medium was less than 1.25 ng/ml, a concentration too low to evade a response [22]. Reprobing the blot for Ihh did not yield a signal for the medium either.

Figure 1B depicts the proposed possible modes of Ptch1 action on Smo. Because Ptch1 and Smo do not unambiguously show physical association and because Ptch1 can inhibit Smo substoichiometrically, direct binding of Ptch1 to Smo as shown in Figures 1B, columns 1 and 2, seems an unlikely mechanism of inhibition [9]. Ptch1 shares high homology (for instance, a sterol-sensing domain) with NPC1, a protein involved in cholesterol trafficking [10], as well as with various (prokaryotic) pump proteins. Also, several small molecules with homology to cholesterol that act as Hh pathway antagonists have been identified [11–13]. Cyclopamine, a well-known antagonist of Smo, has been widely used for assessing the effects of Hh pathway inhibition in several model systems (for example, in [14]). Consequently, it has been anticipated that in the absence of Hh, Ptch1 translocates a small molecule resembling cholesterol across the membrane, acting as a Smo antagonist. This hypothesis is summarized in Figure 1B, column 3.

A consequence of the proposed “pump” model for Ptch1 is that the action of Ptch1 should be non-cell autonomous. We set out to test this prediction, and we established that Hh

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Figure 1. Cholesterol Synthesis and Possible Modes of Action of Ptch1

(A) Shown is a schematic representation of cholesterol synthesis. Boxed are lathosterol and 7-DHC, cholesterol precursors known to accumulate in lathosterolosis and SLOS patients, respectively. Mutations in or genetic loss of sterol C5-desaturase (Sc5d) cause stacking of lathosterol, whereas dysfunction of 7-DHC reductase (Dchr7) or the addition of its synthetic inhibitor AY-9944 causes accumulation of 7-DHC. The conversion of 7-DHC to vitamin D3 (cholecalciferol) is mediated by UV light. Statins, like pravastatin, inhibit HMG-CoA reductase, the enzyme that forms mevalonate.

(B) Shown are three possible models for the inhibitory action of the Hh receptor Ptch1 on Smo. (1) A cell-autonomous mode of action, in which direct binding of Ptch1 inhibits Smo. (2) An intracellular inhibitory action, mediated by direct binding of Ptch1 to Smo. (3) The model in which Ptch1 pumps a inhibitory small molecule that is capable of Smo-repression intercellularly (as well as intracellularly; not shown).
Ptch1 Can Inhibit Smo in a Non–Cell Autonomous Fashion

To assess the ability of Ptch1 to act upon Smo on another cell, we used a “mix-and-match” approach (as schematically shown in Figure 3A), in which two populations of cells are mixed. The donor population expresses Ptch1 at different levels (using an overexpression construct or small interfering RNA [siRNA]) that could act on reporter cells with a constitutively active Hh pathway (reporter cells: Smo receptor overexpressed and a Gli-luciferase reporter). We mixed reporter cells with vector, Ptch1, Ptch1 siRNA and scrambled control siRNA transfectants. Cell populations were detached by EDTA treatment, mixed, and replated. By using two fluorescent tracers for labelling the cell populations, the capability of this procedure to obtain a homogenous mixture could be assessed. Figure 3A shows that combining two cell populations yields evenly mixed cells with intimate cell-cell contacts (micrograph). When Gli reporter cells were mixed with Ptch1-overexpressing cells in these mix-and-match experiments, a significant reduction in Smo-mediated Gli activation could be seen compared with control. This inhibition could not be diminished by addition of 1 µg/ml 5E1 Hh-blocking antibody (Figure 3A), again demonstrating that endogenous Hh is not a contributing factor in our experimental setup. This is important, specifically because the presence of Hh in the medium would increase reporter activity. As Ptch1 scavenges Hh from the medium, medium of Ptch1-overexpressing cells would contain lower Hh levels than would control or Ptch1 siRNA-transfected cells. The reduction in reporter activity as consequence of scavenging would mask the action of a potential inhibitory molecule. The addition of 1 µg/ml recombinant Shh, which should inhibit Ptch1 present in these experiments, was able to abolish the inhibition conferred by Ptch1. Mixing reporter cells with Ptch1 siRNA-transfected cells increased Smo-dependent reporter activity (Figure 3A, blue bars), demonstrating that the inhibition is Ptch1 dependent and again suggests that C3H/10T1/2 cells have a significant basal level of Ptch1 activity. Showing opposite effects of Ptch1 siRNA versus DNA excludes any overexpression artefacts from responsibility for the observed non–cell autonomous effect. To exclude cell-specific artefacts, the procedures were also performed with MDA-MB-231 breast tumour cells, which had even higher levels of endogenous Ptch1 and Smo than the C3H/10T1/2 fibroblasts (Western blot, unpublished data). Indeed, using these cells yielded similar but more pronounced effects, as did the C3H/10T1/2 cells (Figure 3A, hatched bars).

To determine the maximal inhibition Ptch1 confers in a cell-autonomous fashion—that is, the extent to which Ptch1 can inhibit Smo on the same cell—we mixed and fused the two previously described cell populations. PEG1500 induced efficient cell fusion, which was evident from blended staining of PEG1500-treated cells and the multinucleated cells (procedure and micrographs shown in Figure 3B, left panel). Fusion of reporter cells with Ptch1-overexpressing cells again showed a reduction in Gli activation, similar to that observed in the mix-and-match experiments (Figure 3A). The reduction in reporter activity was of the same magnitude as that obtained in the mixing experiments. Therefore, we conclude that Ptch1 inhibition of Gli reporter activity in our system is mediated mainly intercellularly.

The specificity of the observed inhibitory action of Ptch1 acting through Smo was assessed by using the Ptch1-insensitive SmoM2 mutant, as previously shown in Figure 2B. As can be seen in Figure 3C, SmoM2-transfected reporter cells are no longer sensitive to mixing with Ptch1-over-
expressing donor cells, even when cotransfected with wild-type Smo. These findings led us to suggest the model for Ptch1 action as depicted in Figure 1B, column 3, and Figure 3D, in which Ptch1 on one cell is capable of specifically inhibiting Smo on another cell, to act non–cell autonomously.

Non–Cell Autonomous Ptch1-Dependent Smo Inhibition Is Carried Out by a Medium-Borne Factor

The intercellular Ptch1-mediated inhibition of Smo as identified in the mix-and-match experiments may be conferred by either an inhibitory molecule secreted or trans-
located by Ptch1 or by diffusion of a cytosolic mediator through tight junctions. The latter possibility is less likely, because it would result in a merged fluorophore signal in the mixed cell population, which was not observed (Figure 3A). Indeed, important support for the possibility that Ptch1 secretes a Smo inhibitory molecule into the medium was obtained from experiments in which medium conditioned on Ptch1-transfected cells was transferred to reporter cells in which Gli activity was assayed (procedure schematically shown in Figure 4A, left panel).

By using this experimental setup, we found that medium conditioned on Ptch1-transfected cells exerted a strong inhibitory effect on Gli activation as compared with medium conditioned on control-transfected cells (Figure 4A). This inhibition could not be blocked by the addition of 1 μg/ml Shh or 5E1 to the reporter cells. The inability of Shh to prevent Ptch1-conditioned, medium-dependent inhibition of Smo activity is expected, because the transferred medium does not contain donor cells expressing Ptch1 on which Shh should exert its action, and the presence of the medium-borne factor in the Ptch1-conditioned medium shortcuts the function of endogenous Ptch1 in the reporter cells. Using MDA-MB-231 cells in this setup, similar results were obtained (Figure 4A, hatched bars). As for the mix-and-match experiments, medium conditioned on Ptch1 siRNA-transfected cells increased Smo-dependent reporter activity in both cell lines. Medium conditioned on mouse embryonic fibroblasts (MEFs) from Ptch1 knockout mice [23] showed a distinct deficiency in their capacity to inhibit Smo compared with medium conditioned on wild-type (Ptch1+/+) MEFs (Figure 4, pink bars). This inhibitory effect could again not be conferred to reporter cells transfected with the Ptch1-insensitive SmoM2. The opposite effects, as observed with Ptch1 DNA transfection versus either Ptch1 siRNA transfection (blue bars) or genetic Ptch1-deficient MEFs, exclude transfection artefacts on the donor cells as the potential cause of the observed effects. Overall, these findings suggest that Ptch1 transfers a molecule to the medium that inhibits Smo activity. Medium conditioned on Ptch1-overexpressing MDA-MB-231 cells could inhibit Gli activity in C3H/10T1/2 cells and vice versa (unpublished data), suggesting that the inhibitory factor is not species-specific, at least not among mammals.

Using serum-free medium, we could confer no inhibitory action of Ptch1-conditioned medium on reporter cells (Figure 4A). Serum-free medium contains no lipoproteins, which implies an important role for lipoproteins in conveying the inhibitory signal from cell to cell. Alternatively, serum-free medium also lacks lipids, which could stress the necessity for lipids supplied in the medium for Hh responsiveness [8]. However, serum-free conditions for 8 h (the incubation time in our experiments) do not deplete a cell’s cholesterol metabolism, arguing in favour of a role for lipoproteins in communicating the inhibitory signal.

**Ptch1-Dependent Secretion of 3β-Hydroxysteroids**

The conditioned media were subjected to fast performance liquid chromatography (FPLC)-coupled cholesterol oxidase peroxidase-amidopyrine (CHOD-PAP) analysis, a technique that analyzes 3β-hydroxysteroid content. The Ptch1-conditioned medium was found to be enriched with 3β-hydroxysteroids relative to medium conditioned by control cells (Figure 4B and 4C; quantification of FPLC profiles as mM total 3β-hydroxysteroids). Judging from the retention profile, these 3β-hydroxysteroids were present on low-density lipoprotein (LDL) particles and, to a lesser extent, on very-low-density lipoprotein (VLDL). High-density lipoprotein (HDL) 3β-hydroxysteroid levels remained constant in all conditions. Medium incubated on cells transfected with siRNA for Ptch1 was virtually devoid of LDL-associated 3β-hydroxysteroids. This correlation between modified Ptch1 levels and the accumulation of 3β-hydroxysteroid molecules in the medium suggests that Ptch1 translocates or pumps these 3β-hydroxysteroids into the medium and thereby transfers the Smo inhibitory activity.

**3β-Hydroxysteroids Are Necessary for Ptch1-Dependent Smo Inhibition**

In the presence of pravastatin, a 3-hydroxy-3-methylglutaryl coenzyme A (HMG-CoA) reductase inhibitor that abrogates the biosynthesis of the 3β-hydroxysteroid precursor mevalonate (Figure 1A), LDL-associated 3β-hydroxysteroid (named LDL-C on axis) levels were substantially reduced (Figure 4C), and, correspondingly, reduced Gli inhibition was observed in Ptch1-overexpressing reporter cells as shown in Figure 4D. Conversely, the 3β-hydroxysteroid precursor mevalonate strongly increased LDL-associated 3β-hydroxysteroids and Ptch1-mediated inhibition of Gli transactivation. If the observed effects of steroid synthesis modifiers on Gli activation are Smo-specific, Hh responses mediated by Ptch1 (but not those by Smo) should remain unaffected. The endocytosis of Ptch1 is such a Smo-independent response to Hh [3,4]. By using [3H]-sucrose as a tracer [24], we observed no effect of 1 mM pravastatin on Hh-mediated endocytosis (Figure 4E), and thus the effects of steroid-synthesis inhibitors are Smo-specific. The above-mentioned reporter data, however, are not from medium transfer experiments, and the inhibition or stimulation of cholesterol synthesis and the concomitant effects on Gli activity do not unequivocally prove the contribution of sterol biosynthesis to the intracellular action of Ptch1.

**Using Dhcr7−/− and Sc5d−/− MEFs to Identify the Inhibitory Compound**

The paradoxical phenotype of SLOS patients, in which diminished Hh signalling is accompanied by an accumulation of the sterol 7-dehydrocholesterol (7-DHC; see Figure 1A), led us to hypothesize that 7-DHC might be a Smo inhibitor. To test this hypothesis, we used MEFs [8] from mice genetically deficient for 7-DHC reductase (Dhcr7−/−), because these cells stack 7-DHC. To confirm the specificity of 7-DHC as Smo inhibitor, we also used sterol C5-desaturase (Sc5d−/−) MEFs that stack the precursor of 7-DHC (lathosterol) and contain little or no 7-DHC. Indeed, as shown in Figure 5A, Dhcr7−/− MEFs had a significantly reduced Gli activity as compared with Sc5d−/− MEFs. In addition, the Smo-inhibitory potential of Dhcr7−/− MEF-conditioned medium was much higher than that of Sc5d−/− MEF-conditioned medium, as shown in the medium transfer experiment depicted in Figure 5A. In addition to stacking a specific metabolite, both MEFs are equally incapable of sterol synthesis. Our data therefore argue against reduced sterol levels as being responsible for the observed Smo inhibition. Overall, these data strongly suggest that 7-DHC or a Dhcr7-independent metabolite of 7-DHC have an inhibitory action on Smo.
To assess whether Ptch1 uses 7-DHC to inhibit Smo, we performed medium transfer experiments with Ptch1 (or Ptch1 siRNA)-transfected Dhcr7−/− and Sc5d−/− MEFs as donor cells. If Ptch1 would indeed pump 7-DHC, Ptch1 over-expression or knockdown in the Sc5d−/− MEFs should show no effect on Smo inhibition. As shown in Figure 5B, the Sc5d−/− MEFs were severely hampered in their ability to transfer Ptch1 action to the medium, because neither Ptch1 DNA nor siRNA transfectants differed from control transfectants in their ability to inhibit Smo on reporter cells. The Dhcr7−/− MEFs, however, were well capable of translating Ptch1 expression levels to differential inhibitory action on reporter cells. UVB treatment of Dhcr7−/− MEF-conditioned media, which catalyzes the reaction from 7-DHC to vitamin D3, increased the Ptch1 effect on reporter cells, raising the tantalising option that Ptch1 uses vitamin D3 to inhibit Smo.
Vitamin D3 Is Sufficient for Smo Inhibition

From the experiments described above, we hypothesized that the addition of synthetic 7-DHC or vitamin D3 would inhibit Gli activity in reporter cells as well. Indeed, as can be seen from Figure 6A, 7-DHC was capable of inhibiting Smo, but was not nearly as potent as its derivate, vitamin D3. This fits the observation that UV treatment enhanced the inhibitory potential of Ptch1-conditioned medium (Figure 5B). The addition of the 7-DHC reductase inhibitor AZ-9944 [25] successfully enhanced the effect of vitamin D3 treatment but was also capable of inhibiting Smo by itself, possibly by causing accumulation of endogenously synthesized 7-DHC or by acting as a 7-DHC mimetic. The magnitude of inhibition conveyed by either the transfer of Ptch1 transfectant-conditioned medium or Ptch1 cotransfection were both smaller than that of vitamin D3. In addition, inhibition conferred by vitamin D3 was stronger than that of 10 μM cyclopamine. The finding that AZ-9944 was not a necessity for inhibitory action excludes a role for sterol deprivation in this model (Figure 1A), because the exogenously added 7-DHC or vitamin D3 can be readily metabolized by these (wild-type) fibroblasts to produce downstream sterols.

Shown in Figure 6B is a dose-dependent response of reporter cells to vitamin D3 for 6 h. In agreement, the level of inhibitory N-terminal Gli3 protein increased accordingly, as quantified from Western blot. This digestion product of Gli3 originates from proteolysis in the SuFu/Fu complex present in Hh pathway inactive cells and is considered the repressor form [26]. To exclude cytotoxic artefacts of vitamin D3, we measured cell viability by MTT reduction. Only at very high (1 mM) concentrations of vitamin D3 could we observe a slight decrease in cell viability. Using SmoM2-transfected reporter cells, Gli reporter inhibition occurred only at 100 μM vitamin D3, and below that concentration, no inhibition could be observed. This is very similar to the impaired but not absent response of SmoM2 to cyclopamine [11].

To exclude Gli-independent effects of vitamin D3 from being responsible for the observed reporter inhibition, we used a panel of various luciferase reporter constructs. As can be seen in Figure 6C, interferon-stimulated response element (pISRE), TATA-like promoter (pTAL), nuclear factor–kappa B (pNF-kB), and mutant Gli binding site (mGli) luciferase reporter constructs were not significantly inhibited by the addition of 10 μM vitamin D3 for 6 h, whereas reporter activity of a TATA-like promoter–luciferase construct was increased. Thus, the inhibitory effect of vitamin D3 on Gli reporter activity appears to be a genuine effect of Smo-dependent signalling.

Figure 6D shows Gli reporter inhibition by vitamin D3 in the cell lines C3H/10T1/2 and MDA-MB-231 previously used in the mix-and-match and medium transfer experiments. Both showed a marked inhibition in reporter activity after treatment with 10 μM vitamin D3. Ptc1+/− MEFS also responded to vitamin D3. Because these cells have no Ptc1, any artefacts of vitamin D3 by interference with Ptc1 action rather than Smo activity can be excluded.

A consequence of our model in which vitamin D3 or a very similar molecule mediates Ptc1 action on Smo (Figure 6E) is that exogenously added vitamin D3 should overrule any effect of Hh on Ptc1. To confirm this, we stimulated stable Gli-luciferase transfectants (Shh-LIGHT II) overnight with 10 μM vitamin D3 and/or 200 ng/ml Shh. What is apparent from Figure 6F is that in the presence of vitamin D3 reporter activity could not be increased by the addition of Shh, confirming our hypothesis.

Scatchard Analysis Reveals Vitamin D3 Binding to Smo

To assess possible binding of vitamin D3 to Smo, we used a yeast strain (Pichia pastoris) transformed with Smo. The expression of Smo could be induced by the addition of methanol to the growth medium (kind gift of Dr. I. Mus-Veetan [27]). We chose this approach for two reasons: first, to our knowledge there is no vitamin D3 receptor in P. pastoris; second, baseline (or background) levels of Smo in noninduced P. pastoris are negligible.

First we confirmed the successful induction of Smo expression by Western blot using a Smo antibody as shown in Figure 7A. We then set out to perform a Scatchard analysis

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**Figure 5. Differentially Modulated Ptc1 Action in Dhcr7−/− and Sc5d−/− MEFS**

(A) Basal Gli reporter activity measured in MEFS either deficient for Sc5d or Dhcr7 shows that the stacking of 7-DHC (in the Dhcr7−/− MEFS) lowers Gli activity in the mutant cells compared with lathosterol stacking in the Sc5d−/− MEFS. Transfer of the conditioned media to reporter cells (indicated as “MEFS as medium donors”) shows that the inhibitory potential of the Dhcr7−/− MEFS is medium-borne. Media were incubated on donor MEFS for 16 h and transferred to reporter cells for 6 to 8 h. (n ≥ 4; * p < 0.05; ** p < 0.005).

(B) Medium transfer of Ptc1, Ptc1 siRNA, or control-transfected Sc5d−/− and Dhcr7−/− MEFS shows that cells stacking lathosterol but lacking 7-DHC (Sc5d−/− MEFS) are not able to translate different Ptc1 levels to an inhibitory action on reporter cells. The Dhcr7−/− cells were able to properly convey an inhibitory signal when transfected with Ptc1 or, inversely, show a diminished inhibitory potential upon Ptc1 siRNA transfection. UVB treatment of Ptc1 transfectant medium (2 h) amplified the inhibitory action. Media incubations and statistics are as in (A).

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with heterologous competition by cyclopamine. Cyclopamine is a ligand for Smo, and this enabled us to distinguish the observed competition from any background by non-specific binding or specific binding to a vitamin D3 receptor (although it is not known to exist in these cells). As can be seen from Figure 7B, [3H]-D3 was not capable of specific binding to non–methanol induced P. pastoris (BMGY), whereas after methanol induction (BMMY), specific binding of [3H]-D3 was observed that was subject to competition by cyclopamine [28]. Nevertheless, these results show that vitamin D3 has the potential to bind Smo at the same site.
as cyclopamine, indicating that vitamin D3 is indeed a physiological ligand for Smo.

**Vitamin D3 Treatment Mimics the smo<sup>−/−</sup> Phenotype in Zebrafish**

To test the action of vitamin D3 in a developmental in vivo model system, we continuously incubated zebrafish embryos starting between 32- and 64-cell stage in 1.2 mg/ml sonicated vitamin D3. We used sonication as described for 7-DHC [29], but did not use a stabilizing reagent. The vitamin D3 treatment phenocopied to a great extent the slow muscle omitted (smu) mutant phenotype [30], which has been identified as the zebrafish ortholog of smo [31,32].

One of the most striking features of the smo<sup>−/−</sup> phenotype is the U-shaped somites in contrast to the sharply defined chevron (V)-shaped somites of wild-type embryos. The vitamin D3-treated embryos showed these disrupted somites (as indicated by arrow 1 in Figure 8A) at the developmental stages shown. Of the treated animals, approximately 75% (n = 30 embryos in six individual experiments) showed this somite phenotype as well as the typical responses as listed below. Quantification of the somite angle was performed, measuring the angle between the dorsal and ventral portions of the individual somites while positioning the apex of the angle on the horizontal myoseptum (Figure 8B, top panel). In properly individual somites while positioning the apex of the angle on the U-shaped somites in contrast to the sharply defined somites was observed. Expression of Smoothened by Patched (ptc1) showed a marked reduction of transcript levels in the vitamin D3-treated animals. Because ptc1 is not only the primary receptor for the Hh pathway but also a transcriptional readout of Hh activity [32,37], the attenuated expression seen in the treated animals confirms that vitamin D3 specifically inhibits the Hh pathway. Another marker previously described to be indicative of Hh pathway activity is slow muscle fibre orientation and number in the somites. In smo<sup>−/−</sup> zebrafish, slow muscle fibres are fewer and malformed [30,31]. Shown in Figure 8 (panel marked F59) is the disturbed pattern and number of slow muscle fibres after vitamin D3 treatment, reminiscent of smo<sup>−/−</sup> zebrafish embryos. The use of the abovementioned molecular markers confirms that the effects of vitamin D3 on zebrafish embryo morphology are indeed due to reduced Hh pathway activity.

At later stages, we observed a subtle cardiac edema, and all treated embryos died after 5 d of vitamin D3 treatment, a feature again similar to the smo<sup>−/−</sup> phenotype (Figure 8C). Although we found the eyes to be relatively ventrally positioned throughout various developmental stages (Figure 8C), no absolute cyclopia was observed. However, cyclopia is not an unambiguous hallmark of the smo-deficient phenotype [31–33].

Because nearly all of the typical smo<sup>−/−</sup> phenotypic features were also prominently present in vitamin D3-treated zebrafish embryos and the molecular markers used all pointed to a defective Hh signalling, we conclude that the in vivo action of...
vitamin D3 on embryonic development is due to a specific inhibitory effect on Smo.

**Discussion**

In the present study, we investigated the molecular mode by which Ptch1 represses Smo activity. By mixing Ptch1-expressing cells with cells expressing Smo and a Gli reporter, we were able to show that Ptch1 is capable of non–cell autonomous repression of Smo. This non–cell autonomous repression is carried by the extracellular medium, because medium conditioned by Ptch1-transfected cells was capable of inhibiting Gli reporter activity as well. Conversely, medium conditioned by cells transfected with Ptch1 siRNA (so lacking endogenous Ptch1 expression) elevated Gli reporter activity significantly above medium that was conditioned by control cells, demonstrating that Ptch1 overexpression is not a prerequisite for observing this cell non-autonomous repression of Smo by Ptch1. Mixing Ptch1-overexpression cells with cells expressing Smo and Gli reporter produced inhibition of Gli reporter activity to approximately the same extent as fusing these cells, showing that this non–cell autonomous repression
repression of Smo by Ptc1 is of roughly similar potency compared to intracellular Smo repression by Ptc1. This result suggests that this intercellular repression constitutes an important physiological mechanism. In this context, it is important to note that Hh quenching was not a major contributing factor in our experimental system, because Hh-neutralising antibodies do not interfere with Ptc1-dependent intercellular repression of Smo and we were not able to detect Hh release by the cells.

Conditioning medium with Ptc1-transfected cells led to the appearance of a 3b-hydroxysteroid in this medium, suggesting that this compound is increasingly translocated into the medium as a consequence of elevated Ptc1 expression. These results are concordant with the observation that Smo antagonists bear structural similarities to steroids [12] and the high homology of Ptc1 to the NPC1 protein, which has cholesterol trafficking and pump functions [10], as well as to various prokaryotic pump proteins. These homologies gave rise to the suggestion that, in the absence of Hh, Ptc1 pumps a compound out of the cell that binds to and inhibits Smo, and the data from this study confirm this model. Transfection of Ptc1 siRNA abolished deposition of this 3b-hydroxysteroid into the medium when compared to control-transfected cells, showing that 3b-hydroxysteroid translocation is not an artefact of Ptc1 overexpression, but that endogenous Ptc1 expression levels are sufficient to sustain detectable 3b-hydroxysteroid translocation. This 3b-hydroxysteroid translocation seems important for the intercellular repression of Smo by Ptc1, because in the presence of 3b-hydroxysteroid synthesis inhibitors Ptc1 was no longer capable of repressing Smo, whereas artificial stimulation of 3b-hydroxysteroid biosynthesis by using mevalonate supplementation enhanced the inhibitory potential of Ptc1 on Smo.

The 3b-hydroxysteroid responsible for intercellular repression of Smo is most likely the (pro-)vitamin D3 (that is, either 7-DHC or its metabolite vitamin D3) or a highly similar molecule. Fibroblasts derived from animals genetically deficient for 3b-hydroxysteroid reductase (Figure 1A), leading to the accumulation of its substrate. This result suggests that this molecule mediates Hh inhibition. Treatment of patients with a cholesterol-rich diet, however, has been successful, and statin treatment does not seem to alleviate the symptoms, suggesting that the lack of cholesterol is the culprit [38,39]. Others have been able to counteract the effect of 7-DHC stacking in experimental settings by exogenously adding cholesterol [40], confirming that AY-9944 merely inhibits synthesis of cholesterol needed for proper Hh processing. Although these findings seem to preclude the stacking of a specific metabolite to be responsible for the SLOS phenotype, it has become clear that the clinical phenotype correlates best with the ratio of 7-DHC to cholesterol levels in patient plasma rather than the levels of cholesterol alone. Also, the treatment of infants with cholesterol is arguably too late an intervention, because most of the Hh patterning events are completed in utero. Our experiments show that even in the absence of AY-9944, addition of vitamin D3 strongly inhibits Hh signalling. This inhibition is stronger than Ptc1 cotransfection and Ptc1-transfectant conditioned medium, and we therefore conclude that the stacking of 7-DHC is responsible for the SLOS phenotype.

Very relevant to this manuscript and the abovementioned studies are the findings of Cooper et al., who found that reduced sterol levels impair a cell’s responsiveness to Hh [8]. By using fibroblasts from mice genetically deficient for the enzymes involved in lathosterolosis (Sc5d–/–) and SLOS (Dhcr7–/–) and by depleting lipids and sterols from the medium, they showed that sterol levels were crucial to a cell’s responsiveness to Hh. By analyzing the Hh protein in these cells under the various conditions, they could demonstrate proper Hh maturation, thereby excluding improper Hh sterolation as the cause of SLOS. They did not, however, hypothesize an inhibitory role for excess cholesterol precursors. We explain our hypothesis and findings in light of their results: by genetic and/or medium condition causes, steroid synthesis is seriously impaired in cells in their experiments. As a result, 7-DHC levels will drop, leaving Ptc1 devoid of substrate. Without substrate to pump or translocate, Ptc1 is “paralysed”, and addition of Hh will not exert an effect, explaining the reduced responsiveness. Hh responsiveness does not equal pathway activity, and the absence of Ptc1 substrate will diminish responsiveness but not pathway activity. Because both cell lines share the inability to properly synthesize cholesterol, and because we find a differential inhibitory potential on Smo, we conclude that steroid content alone cannot account for Ptc1-mediated Smo inhibition, and we suggest that the effects found by other groups take place elsewhere in the Hh signalling pathway. In our system, LDL seems to be a prerequisite for the diffusion of the inhibitory molecule, and, recently, a similar requirement has also been found for the distribution of Hh itself [41].

Although the present study clearly demonstrates that Ptc1 can inhibit Smo in an intercellular fashion, we have not addressed whether such intercellular action of Ptc1 on Smo is relevant for Hh action in vivo. Vitamin D3 is highly hydrophobic and is not expected to diffuse very far in the aqueous environment that surrounds cells. We observed that in the absence of LDL as a carrier for the hydrophobic Smo inhibitor, intercellular repression of Smo activity was
Interacellular action of Ptch1 will allow this molecule to exert its action as a tumour suppressor, on not only the Ptch1-expressing cell but also neighbouring cells that may have acquired inactivating mutations of Ptch1, making this mode of Ptch1-dependent Smo inhibition especially attractive with respect to tumour suppression. Thus, it will be interesting to investigate whether intercellular repression of Smo by Ptch1 actually contributes to tumour suppression in vivo. Experiments addressing this possibility are currently in progress.

Materials and Methods

Constructs/siRNA used. Mouse Ptch1 (a generous gift of Dr. M. P. Schمصر) was cloned into the pCDNA 3.1(+) vector (Invitrogen, Carlsbad, California, United States). Human Smo (referred to as Smo) cDNA (Image Consortium/RZPD, Berlin, Germany) was cloned into the pCDNA 3.1(+) vector. The Gli1 cDNA is in pCDNA 1(+) (a generous gift of Dr. A. Ruiz i Altaha). The Gli reporter 651-LucII was kindly provided by Dr. H. Sasaki, as was the mutant binding site variant (mGli). The NF-B, ISRE, and TAL luciferase constructs were from Clontech Laboratories (Mountain View, California, United States). The internal control cytomegalovirus (CMV) promoter-driven Renilla luciferase vector was from Promega (Madison, Wisconsin, United States). SmoM2 in pRf7 was obtained from Genentech (South San Francisco, California, United States). The Ptch1 (#63908) and scrambled control siRNA were from Ambion (Austin, Texas, United States).

Western blotting. Transfected cells were lysed in Laemmli buffer and brought onto SDS-PAGE gels. After electrophoresis, protein was transferred onto Immobilon-PVDF membranes (Millipore, Billerica, Massachusetts, United States). Membranes were blocked in 5% bovine serum albumin (BSA) (Sigma-Aldrich, St Louis, Missouri, United States) in TBS0.1% Tween-20 (TBS) for 1 h. Goat polyclonal α-Ptch1 antibody G-19, α-Smo C-17, α-Gli3 N-terminal N-19, α-Shh N-19, or α-Ihh I-19 (Santa Cruz Biotechnology, Santa Cruz, California, United States) were diluted to 1:500 in 3% BSA in TBS, and membranes were incubated overnight. Goat polyclonal α-β-actin I-19 (Santa Cruz Biotechnology) was diluted to 1:1000 in 3% BSA in TBS. After 1 h incubation in 1:1000 α-goat HRP-conjugated secondary antibody (DakoCytonoman, Glostrup, Denmark), blots were imaged using LumLiLight Plus enhanced chemiluminescence substrate (ECL) (Roche, Basel, Switzerland) on a GenGnome chemiluminescence imager (Syngene, Cambridge, United Kingdom).

Mix-and-match procedure. Mouse mesenchymal fibroblasts (3/1/112 from American Type Culture Collection CCL-226, Manassas, Virginia, United States) were grown in Dulbecco’s Modified Eagle Medium (DMEM) (Cambrex, East Rutherford, New Jersey, United States) containing 10% fetal calf serum (FCS) (Cambrex). Human MDA-MB-231 breast carcinoma cells (American Type Culture Collection HTB-26) were grown in L-15 Leibovitz medium (Cambrex) with 10% FCS. Cells were grown to approximately 70% and transfected with either Ptch1 or Smo and the Gli luciferase reporter in combination with a CMV-Renilla luciferase internal standard using Effectene (Qiagen, Hilden, Germany) according to routine procedures. Ptch1 and scrambled control siRNA were transfected using RNAiFect (Qiagen) following the supplied protocol. Transfected cells were treated with o-methylated 20 μM Z-VADfmk (Sigma-Aldrich) to neutralize the apoptotic effects of Ptch1. After 16 h, cells were washed three times with phosphate buffered saline (PBS), detached by 2 mM EDTA (Sigma-Aldrich) in PBS, resuspended in DMEM with 10% FCS, and pipetted three times through a 40-μm cell strainer (BD Biosciences, San Jose, California, United States) into a tube to allow a homogenous mixture. Equal volumes of reporter and donor cells were mixed thoroughly and subsequently transferred to 24-well plates. After 6 h (4 + 2 h for the fusion protocol), cells were lysed with passive lysis buffer as provided by Promega, and luciferase activity was assayed according to the Promega Dual-Glo Luciferase Assay System. The Dual-Glo (Promega) protocol on a Lumat Berthold LB 9501 Luminometer (Berthold Technologies, Bad Wildbad, Germany). Each firefly luciferase value was corrected for its cotransfected CMV-driven Renilla luciferase standard to correct for transfection efficiency or dilution effects. Recombinant N-terminal Shh was obtained from R&D Systems (Minneapolis, Minnesota, United States) and dissolved in PBS with 0.1% BSA. The 5E1 Shh-blocking antibody was from the Developmental Hybridoma Bank (Iowa City, Iowa, United States).

Fluorescent tracking of cells. Cells were grown to approximately 70% confluence in DMEM containing 10% FCS and washed with PBS.

undetectable. Hence, although Ptch1 exports (pro-)vitamin D3, it might act on Smo on the same cell (and thus function cell autonomously) or, depending on the cell’s surroundings, on Smo on adjacent cells (and thus function non–cell autonomously). Nevertheless, the expression of Ptch1 and Smo is often discordant, with Ptch1 expression being in the vicinity of Smo-expressing cells, without complete colocalisation [42,43]. We observed that in cardiac nerve branch ganglia, Smo and Ptch1 colocalise in the bronchial cartilage and epithelium, but not in the ganglion itself. In the ganglion, a pronounced staining for Ptch1 can be seen, whereas Smo staining is observed in only the adjacent cells. These findings are suggestive for intercellular signalling actually occurring in vivo (MF Bijlsma, unpublished data). In contrast with these findings are earlier reported experiments by Briscoe et al. [44] in which a Hh uninhibitable form of Ptch1 (Ptch1<sup>Δloop2</sup>) was evaluated with respect to its effects on Hh signalling in Drosophila melanogaster and Gallus gallus embryogenesis. The results obtained in this study suggest that the border of Hh-induced gene expression. Thus, it would appear that in these experimental systems, a Smo-inhibitory, vitamin D3–like ligand has not much capacity to diffuse over multiple cell layers. We therefore suggest that the action of Ptch1 can be cell autonomous or non–cell autonomous in various in vivo situations, perhaps dependent on the presence or absence of molecules that can carry the hydrophobic ligand over larger distances and subsequently present this molecule to Smo.

Recently it was demonstrated that Hh-bound Ptch1 could titrate the inhibitory action of the abovementioned Ptch1<sup>Δloop2</sup>. Furthermore, Hh-bound Ptch1 allowed Smo signalling to occur even in the presence of a Ptch1 form that is incapable of binding Hh [45]. This observation is inconsistent with a model in which Ptch1 serves to translocate a Smo-inhibitory molecule out of the cell, because in this model, Ptch1 action would depend on the amount of unliganded Ptch1, not the amount of liganded Ptch1. Casali and Struhl provide as a possible explanation for the titration effect that liganded and unliganded Ptch1 compete for access to Smo: Ptch1 acts as a multimer in which binding of Hh to any of the subunits blocks the action of the complex, or liganded and unliganded Ptch1 exert counteracting catalytic activities. Only the latter explanation seems consistent with the data presented in this study; the other explanation requires Ptch1 to function in a cell-autonomous fashion. Hence, it is possible that unliganded Ptch1 translocates a Smo inhibitor to extracellular medium, whereas Hh-bound Ptch1 would transport this inhibitor to the cytosol. Alternatively, Hh-bound Ptch1 is internalized, and it is possible that in this process it cointernalizes the Ptch1<sup>Δloop2</sup> protein, especially if both proteins would localize to the same plasma membrane compartment—for example, lipid rafts. Support for this notion might be deduced from the strong Hh-dependent endocytosis we observed in the present study, suggesting that endocytosis is indeed a major cellular response to Hh binding to Ptch1. But further studies are needed to address the exact mode by which wild-type Ptch1 impairs Ptch1<sup>Δloop2</sup> function.
to remove serum. CellTracker Green CMFDA or Orange CMTMR (Molecular Probes, Eugene, Oregon, United States) were diluted to 5 μM in serum-free DMEM and added to cells for 45 min, the medium was aspirated, and fresh medium containing 10% FCS was added. Cells were detached and mixed as described above. After 16 h, cells were fixed in 3.7% formaldehyde overnight or mixed as described above and subsequently fixed. For fluorescence microscopy, cells were washed with PBS/0.1% Triton X-100 (PBST) and incubated in 200 ng/ml DAPI (Roche) in PBST for 1 h. After microscopy, cells on cover slips were washed briefly in PBS, placed upside-down on another cover slip if imaged on a Leica TCS SP II confocal laser scanning microscope (Leica Microsystems, Wetlar, Germany), or placed on an object glass when imaged on a Zeiss Axioskop (Carl Zeiss, Oberkochen, Germany).

**Cell fusion.** After fluorescent labelling (1 h) or transfection (16 h), cells were washed with PBS, Prewarmed PEG 1500/HEPES (pH 7.4) 50% (Roche) was added to the cells for 90 s, after which the cells were washed three times with PBS. Fresh medium was added, and after 2 h, cells were either lysed with passive lysis buffer and assayed for luciferase activity or fixed for microscopy.

**Medium transfer experiments.** Donor and reporter cells were transfected for 16 h, after which the donor cells were washed extensively to wash out any remaining transfection complexes and supplied with fresh medium for 6 h. Medium was transferred to reporter medium for 3 h, after which cells were lysed and assayed for luciferase activity (according to manufacturer’s protocol). The mutant MEFs were grown in complete DMEM supplemented with 15% FCS and nonessential amino acids (Sigma).

**CHOD-PAP-coupled FPLC.** Steroid levels in the main lipoprotein classes (VLDL, LDL, and HDL) were determined using high-performance liquid chromatography. The system contained a PU-980 ternary pump with an LG-980–02 linear degasser, FP-920 fluorescence, and UV-975 UV/VIS detectors (Jasco, Tokyo, Japan). An extra ternary pump with an LG-980–02 linear degasser, FP-920 fluorescence, and UV-975 UV/VIS detectors (Jasco, Tokyo, Japan). An extra ternary pump with an LG-980–02 linear degasser, FP-920 fluorescence, and UV-975 UV/VIS detectors (Jasco, Tokyo, Japan). An extra ternary pump with an LG-980–02 linear degasser, FP-920 fluorescence, and UV-975 UV/VIS detectors (Jasco, Tokyo, Japan). An extra ternary pump with an LG-980–02 linear degasser, FP-920 fluorescence, and UV-975 UV/VIS detectors (Jasco, Tokyo, Japan).

**Supporting Information**

Accession Numbers

The Entrzy Protein (http://www.pubmedexpress.nih.gov/entrezy/query, feg/d=Protein) accession numbers for the genes and gene products discussed in this paper are Gil (BAAS5064), NPC1 (AABI3573), Pch1 (NP_0392983), and SAD (AAH48091).

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Author contributions. MFB, CAS, and MPP conceived and designed the experiments. MFB, CAS, DZ, SdW, FR, and MPP performed the experiments and analyzed the data. MFB, CAS, and MPP wrote the paper.

Competing interests. The authors have declared that no competing interests exist.

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