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**Mitogen-Activated Protein Kinases and Hedgehog-GLI signaling in cancer:
a crosstalk providing therapeutic opportunities?**

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ABSTRACT

The Hedgehog-GLI (HH-GLI) signaling is of critical importance during embryonic development, where it regulates a number of cellular processes, including patterning, proliferation and differentiation. Its aberrant activation has been linked to several types of cancer. HH-GLI signaling is triggered by binding of ligands to the transmembrane receptor Patched and is subsequently mediated by transcriptional effectors belonging to the GLI family, whose function is fine tuned by a series of molecular interactions and modifications. Several HH-GLI inhibitors have been developed and are in clinical trials. Similarly, the Mitogen-Activated Protein Kinases (MAPK) are involved in a number of biological processes and play an important role in many diseases including cancer. Inhibiting molecules targeting MAPK signaling, especially those elicited by the MEK1/2-ERK1/2 pathway, have been developed and are moving into clinical trials. ERK1/2 may be activated as a consequence of aberrant activation of upstream signaling molecules or during development of drug resistance following treatment with kinase inhibitors such as those for PI3K or BRAF. Evidence of a crosstalk between HH-GLI and other oncogenic signaling pathways has been reported in many tumor types, as shown by recent reviews. Here we will focus on the interaction between HH-GLI and the final MAPK effectors ERK1/2, p38 and JNK in cancer in view of its possible implications for cancer therapy. Several reports highlight the existence of a consistent crosstalk between HH signaling and MAPK, especially with the MEK1/2-ERK1/2 pathway, and this fact should be taken into consideration for designing optimal treatment and prevent tumor relapse.

Keywords: Hedgehog, GLI, MAPK, ERK, Cancer, Signal Transduction, Signaling Integration, Targeted Therapy, Combination therapy

Abbreviations:

BCC, Basal Cell Carcinoma

BRAF-i, BRAF inhibitors

CCA, Cholangiocarcinoma

CSC, Cancer Stem Cell

EGF, Epidermal Growth Factor

EGFR, Epidermal Growth Factor Receptor

ERK, Extracellular Signal-Regulated Kinase

FGFb, basic Fibroblast Growth Factor

HCC, Hepatocellular Carcinoma

HH, Hedgehog

IGF1, Insulin-like Growth Factor 1

IGF1R, Insulin-like Growth Factor 1 Receptor

IHH, Indian Hedgehog

IRS1, Insulin Receptor Substrate 1

JNK, c-Jun N-terminal Kinase

MAPK, Mitogen-Activated Protein Kinase

MB, Medulloblastoma

MEK, MAPK/ERK Kinase

MMP9, Matrix Metalloproteinase-9

PDGF, Platelet-Derived Growth Factor

PDGFR, Platelet-Derived Growth Factor Receptor

PI3K, Phosphatidylinositol-3-Kinase

PTCH, Patched

RSK2, Ribosomal S6 Kinase 2

RTK, Receptor Tyrosine Kinase

SHH, Sonic Hedgehog

SMO, Smoothed

1. Classical activation of the MAPK pathway

Mitogen-activated protein kinases (MAPK) convert extracellular stimuli into biological functions including cell survival, proliferation, migration and apoptosis. Growth factors, cytokines, extracellular matrix, osmotic stress, reactive oxygen species as well as lipopolysaccharide may activate MAPK. These enzymes are serine-threonine kinases that include conventional (Extracellular Signal-Regulated Kinases ERK1 and ERK2, p38, c-Jun N-terminal kinases, JNK, and ERK5) and atypical (ERK4, ERK8, human orthologs of rat ERK3 and ERK7, respectively, and Nemo-like kinase, NLK) MAPK [1]. Besides being involved in a number of biological processes, MAPK play an important role in many diseases including inflammation and cancer [2-4]. The MAPK pathway consists of a MAP kinase kinase kinase (MAP3K), a MAP kinase kinase (MAP2K) and a MAPK. Stimulation of the pathway results in the eventual activation of the MAPK by dual phosphorylation of a threonine and a tyrosine residue (T-X-Y) located in the phosphorylation loop. This activation is induced by MAP2K (e.g. in case of classical MAPK, MEK1 and MEK2 for ERK1/2; MKK3 and MKK6 for p38, MKK4 and MKK7 for JNK, MKK2 and MKK3 for ERK5). Fine-tuning of MAPK activation, in strength and duration, depends on cellular context and biological processes [5,6] and is achieved by several mechanisms, including dephosphorylation by phosphatases such as dual specificity phosphatases (DUSP), kinase interaction motif protein tyrosine phosphatases (KIM-PTP) and serine/threonine protein phosphatases (e.g. PP2A). Another equally important role in MAPK regulation is that of MAPK scaffolds, such as Kinase Suppressor of Ras, KSR, that play a key role in modulating the strength and duration of MAPK activation [7].

MAPK have cytosolic as well as nuclear targets [1]. Following activation, ERK1/2 phosphorylates a large number of substrates [8]. Among ERK1/2 cytoplasmic substrates, there are death-associated protein kinase (DAPK), tuberous sclerosis complex 2 (TSC2), RSK and MNK. Nuclear targets include NF-AT, Elk-1, myocyte enhancer factor 2 (MEF2), c-Fos, c-Myc and STAT3. Proteins located at the level of cytoskeleton (neurofilaments and paxillin) or associated with membranes (CD120a, Syk and calnexin) are also target of ERK1/2. The transcription factor c-Jun is a well-described substrate of activated JNK. Additional transcription factors are phosphorylated by JNK, including p53, ATF-2, NF-ATc1, Elk-1, HSF-1, STAT3, c-Myc, and JunB [9]. Substrates of activated p38 proteins include cytoplasmic proteins such as

cPLA2, MNK1/2, MK2/3, HuR, Bax and Tau. Among nuclear targets of p38 isoforms there are ATF1/2/6, MEF2, Elk-1, GADD153, Ets1, p53 and MSK1/2 [10].

MAPK are involved in a large variety of solid and hematological neoplasms and, indeed, several components of the MAPK network have already been proposed as targets in cancer therapy, such as p38, JNK, ERK1/2, MEK1/2, RAF, RAS, DUSP1 and ERK5 [11,12]. Among them, alteration of the RAS-RAF-MEK1/2-ERK1/2 pathway has frequently been reported in human cancer as a result of abnormal activation of receptor tyrosine kinases or gain-of-function mutations in genes of the pathway itself [13]. Components of JNK and p38 pathways are rarely mutated in cancer compared to those of the ERK1/2 pathway. Nevertheless, alterations in JNK and p38 signaling are associated to cancer, although they may act either as oncogenes or tumor suppressors depending on the cellular context [14]. ERK5 is also involved in human cancers including those of the prostate, breast and liver [15,16].

2. The canonical Hedgehog signaling pathway

Initially discovered in *Drosophila*, the Hedgehog (HH) signaling is an evolutionarily conserved pathway that plays a crucial role in patterning, proliferation and differentiation during embryogenesis [17,18]. In the adult it is mostly active in stem/progenitor cells, where it regulates tissue homeostasis, repair and regeneration [19]. Canonical HH pathway activation is initiated by the binding of HH ligands, Sonic (SHH), Indian (IHH) and Desert Hedgehog (DHH), to the 12-pass transmembrane protein receptor Patched (PTCH), which reside in the primary cilium [20-22]. Upon HH binding, PTCH relieves its inhibition on the G-protein-coupled receptor-like Smoothed (SMO), which translocates into the tip of the cilium and triggers a cascade of events that promote the formation of activator forms of the GLI transcription factors (GLI-A). GLI2 and GLI3 translocate into the nucleus and induce transcription of HH pathway target genes, including GLI1 [23-25]. In absence of HH ligands, PTCH inhibits pathway activation by preventing SMO to enter the cilium. This results in phosphorylation and proteasome-mediated carboxyl cleavage of GLI2 and GLI3 to their repressor forms (GLI2/3-R) [26,27]. GLI1 is degraded by the proteasome and transcriptionally repressed, with consequent inhibition of the pathway. GLI1 acts as an activator, whereas GLI2 and GLI3 display both positive and negative transcriptional functions [26,28,29]. The GLI transcription factors activate the expression of a number of targets, including regulators of proliferation and differentiation (e.g. CyclinD1 and

D2, N-Myc, E2F1, PDGFR α , Igf2, FoxM1, FoxF1, Hes1, Igfbp3, Neogenin), survival (Bcl2), angiogenesis (Vegf, Cyr61), self-renewal (Bmi1, Nanog, Sox2), epithelial-mesenchymal transition (Snail1, Sip1, Elk1) and invasiveness (Osteopontin). The HH pathway target genes include GLI1, which further amplifies the initial HH signaling, and the HH pathway negative regulators PTCH1 and HHIP1, which restrain the HH signaling.

Abnormal activation of the HH-GLI pathway is implicated in a variety of tumors, including those of the skin, brain, lungs, prostate, breast, gastrointestinal tract and blood. Multiple mechanisms of HH pathway activation have been described in cancer [30]. Ligand-independent activation is caused by loss-of-function mutations in the negative regulators PTCH1 [31,32], SUFU [33,34] or REN [35], activating mutations in SMO [36], or gene amplifications of GLI1 and GLI2 [37,38], that results in constitutive HH pathway activation. This type of HH pathway activation occurs more often in basal cell carcinoma (BCC), medulloblastoma and rhabdomyosarcoma. Ligand-dependent autocrine activation of the HH pathway has been identified in several types of cancer, including lung, pancreas, gastrointestinal tract, prostate and colon cancer, glioma and melanoma [39-48]. In this case, tumor cells secrete and respond to HH ligands and show increased HH ligands expression apparently in absence of genetic aberrations of HH pathway components. In the ligand-dependent paracrine activation of HH pathway, a mode of action that resembles the physiological HH signaling during development, HH ligands secreted by cancer cells activate HH signaling in the surrounding stroma rather than in the tumor itself. The mechanisms by which the HH signaling and the tumor stroma interact during paracrine signaling are not completely understood. Evidence supporting this mechanism has revealed from studies in human tumor xenograft models of pancreatic and colorectal cancers [49]. Similarly, the reverse paracrine HH pathway activation, in which HH ligands are secreted by the tumor microenvironment and activate the pathway in tumor cells, has been described in an experimental model of glioma [50] and in hematological malignancies, such as B-cell lymphoma and mantle cell lymphoma [51,52].

The HH signaling has also been implicated in the regulation of cancer stem cells (CSC) by promoting their self-renewal [53]. Activated HH signaling has been identified in CSCs of many solid tumors, such as glioblastoma, breast, colon, pancreatic cancer, melanoma, and hematological malignancies, including CML and multiple myeloma, and has been shown to increase tumor-initiating populations and contribute to

self-renewal, growth and tumorigenicity. Similarly, these CSC-promoting effects can be abrogated by inhibiting SMO.

Evidence of crosstalk between HH-GLI and other oncogenic signaling pathways, such as PI3K/AKT/mTOR, Notch, TGF β , Wnt/ β catenin, has been reported in many types of cancer and extensively described by recent reviews [54-58]. Here we will focus on the interaction between HH-GLI and the final MAPK effectors ERK1/2, p38 and JNK in cancer cells. However, we also discuss findings obtained in normal cells where possible mechanisms of interaction relevant for cancer cells have been described.

Non-canonical HH signaling activation involving MAPK has also been described in normal cells and tissues. For instance, specification of oligodendrocyte progenitors by SHH is blocked by the SMO antagonist cyclopamine and PD173074, an inhibitor of FGFR [59]. During limb development induction of SHH by FGF is mediated by the ERK1/2 [60]. MAPK has been shown to modulate the expression of IHH in chondrocytic cells. MEK1/2 inhibitor UO126 decreases levels of *IHH* mRNA. Conversely, constitutively active MEK1 or MKK3 increase IHH levels, which are diminished by dominant-negative MEK1 [61]. To date, there is no evidence of crosstalk between HH-GLI pathway and non classical MAPK neither in normal nor in cancer cells.

3. Crosstalk between HH-GLI and ERK1/2 signaling

The first direct evidence of a crosstalk between HH and ERK1/2 signaling came from a study performed in normal NIH/3T3 cells. This report showed that activated MEK1 (S218E, S222E or Δ 32-51) stimulates expression and transcriptional activity of GLI proteins, with consequent induction *PTCH1* and *GLI1* target genes, showing for the first time that ERK1/2 act upstream of HH-GLI signaling. Consistently, co-expression of activated MEK1 and GLI1 or GLI2 induces a synergistic increase in GLI transcriptional activity, that is blocked by the MEK1/2 inhibitor PD98059 [62]. Interestingly, this study identified for the first time the N-terminus of GLI1 (amino acids 1-130) as a critical region for sensing the ERK1/2 pathway. Indeed, deletion of this region produces active GLI1 protein with greatly reduced response to activation by MEK1. Nevertheless, *in vitro* kinase assays showed that GLI1 is not directly phosphorylated by ERK1/2, suggesting that the N-terminal region of GLI1 is a target for another kinase downstream of ERK1/2 [62]. A

later report identified possible MAPK consensus site, including ERK2, within the N-terminus of GLI proteins [63].

In the following Section we summarize studies providing evidence of a crosstalk between HH and ERK1/2 in different types of cancer.

3.1. Skin cancers

3.1.1. Basal Cell Carcinoma

Activation of HH-GLI signaling, through genetic loss of PTCH1 or activation of SMO, occurs frequently in BCC, the most common human skin cancer [64]. Consistently, the downstream effector GLI1 is often upregulated in BCC [65]. A causal role of the activation of HH pathway in the pathogenesis of BCC has been largely demonstrated by several mouse models [66]. Consistent activation of the ERK1/2 pathway in BCC has not been reported, suggesting that activation of this pathway is not a driving event in this neoplasm. Nevertheless, ERK1/2 may be activated in BCC as a consequence of aberrant activation of upstream signaling (see below).

A crosstalk between EGFR-MEK1/2-ERK1/2 and HH-GLI signaling has been reported in keratinocytes and BCC (Figure 1). A global gene expression study in human keratinocytes with combined or single activation of EGFR and HH-GLI signaling revealed three classes of target genes: genes responding to HH only, genes responding to EGFR only, and genes responding to combined activation of both pathways [67]. Of note, the last class of genes (EGFR-HH cooperation genes) contains functional GLI binding sites in their promoters, suggesting that signaling integration occurs at the level of EGFR-HH target gene promoters. In this context, cooperation of EGFR with GLI1 and GLI2 depends on activation of MEK1/2-ERK1/2 signaling, but not on PI3K/AKT. In fact, treatment with EGFR inhibitor gefitinib and MEK1/2 inhibitor UO126 abolishes synergistic activation, whereas PI3K/AKT inhibitor LY294002 does not. Notably, MEK1/2-ERK1/2 signaling is involved in the stabilization of GLI1 and GLI2 proteins by the proteasome [67]. The same group showed that MEK1/2-ERK1/2-induced phosphorylation and activation of JUN/AP1 transcription factor is the critical event at the end of EGFR cascade, because it induces binding of activated JUN and GLI to common HH-EGFR target promoters, thereby cooperatively regulating target gene

expression and BCC transformation [68]. Of note, the beneficial effect of EGFR blockade in HH-driven BCC and pancreatic cancer models can be synergistically improved by combined targeting of both pathways [68,69]. Importantly, these studies highlight the central role of ERK1/2 in the integration of Receptor Tyrosine Kinase (RTK, see also above) and HH signaling in BCC.

HH pathway may be also upstream of MAPK and ERK1/2 activation (Figure 2). Indeed, GLI1 can lead to the induction of PDGFR α , thus resulting in the activation of the RAS-ERK1/2 pathway in BCC. Accordingly, inhibition of PDGFR or of downstream MEK1/2 decreases the proliferation of the murine BCC cell line ASZ001, that harbors constitutively active HH-GLI signaling. Similar results were obtained in HH-responsive mouse embryo fibroblasts C3H10T1/2, indicating that the signaling axis GLI1>PDGFR>ERK1/2 may be not restricted to BCC cells. The relevance of this mechanism *in vivo* is supported by a high level expression of PDGFR α in murine and human BCC [70].

The same group reported that IFN α , a local treatment option for BCC [71], prevents SMO agonist-mediated activation of ERK1/2 in BCC ASZ001 cells [72]. They also found that treatment with the MEK1/2 inhibitor UO126 induces FAS expression similarly to what happens following IFN α treatment. Interestingly, they showed that the crosstalk between IFN α and HH-GLI pathway might occur at the level of MEK1/2. Authors proposed that IFN α inhibits MEK1/2 and consequently ERK1/2 activation/phosphorylation, thus allowing the expression of Fas and the subsequent induction of apoptosis. An involvement of the MEK1/2-ERK1/2 pathway in HH-sustained survival has also been found in normal keratinocytes [73].

3.1.2. Melanoma

Melanoma is the most aggressive form of skin cancer, characterized by poor prognosis and high mortality. The most deregulated signaling pathway in melanoma is RAS/RAF/MEK1/2-ERK1/2. Indeed, the majority of melanoma show constitutively activated ERK1/2 due to the mutually exclusive activating mutations in BRAF and NRAS, which are present in 50% and 15-20% of cutaneous melanomas, respectively [74]. Either events lead to constitutive ERK1/2-MAPK pathway activation. BRAF inhibitors (BRAF-i) are effective in the treatment of BRAF mutant melanoma patients. However, treatment with BRAF-i is effective only for a limited time and complete clinical responses are rarely seen due to the onset of resistance. Although different

mechanisms of resistance have been described for BRAF-i, most of them lead to the reactivation of ERK1/2 or activation of the PI3K/AKT/mTOR pathway. Therefore, it is not surprising that simultaneous targeting of components of ERK1/2 and PI3K pathways can delay or overcome BRAF-i resistance [75].

Recent studies indicate that HH-GLI signaling is active in melanoma. Several components of the HH pathway are expressed in human melanoma samples [48] and high HH pathway activity is associated with decreased post-recurrence survival in metastatic melanoma patients [76]. Growth and proliferation of human melanoma cells *in vitro* and *in vivo* depends on active HH pathway. Indeed, treatment with SMO antagonists cyclopamine or sonidegib reduces proliferation of human melanoma cells and decreases human melanoma xenograft growth in nude mice [48,76,77]. Interestingly, BRAF mutant cell lines are more sensitive to sonidegib than BRAF wild type melanoma cells and combination of BRAF (vemurafenib) and Hedgehog (sonidegib) inhibitors leads to a modest but significant synergistic effect in inhibiting melanoma cell proliferation [76].

MEK1/2-ERK1/2 signaling has been shown to act upstream of HH and regulate the activity of the GLI transcription factors. For instance, oncogenic NRAS (NRAS^{Q61K}) and HRAS (HRAS^{V12G}) enhance GLI1 function, by increasing its transcriptional activity and nuclear localization. In particular, both HRAS or NRAS counteract GLI1 cytoplasmic retention by the negative regulator SUFU [48] (Figure 1). MEK1/2-ERK1/2 are likely to be the main effectors of RAS, because inhibition of MEK1/2 with UO126 reverses the effect of oncogenic RAS on GLI. A further confirmation of RAS-ERK1/2 acting upstream of HH, systemic cyclopamine treatment drastically reduces tumor growth in melanomas induced by oncogenic NRAS in a *Tyrosinase-NRAS^{Q61K};Ink4a^{-/-}* mouse model [48].

Growth factor receptor up-regulation, including that of PDGFR, is among the mechanisms underlying resistance to BRAF-i in melanoma cells [78]. Similarly to what previously observed for BCC (see above) [70], HH-GLI pathway activation induced by treatment with BRAF-i is responsible for PDGFR α up-regulation following vemurafenib treatment in human melanoma cells *in vitro*. Then PDGFR α expression through the activation of downstream ERK1/2 and PI3K determines vemurafenib resistance. Accordingly, PDGFR α or HH signaling inhibition decreases ERK1/2 phosphorylation and restores melanoma cells sensitivity to BRAF-i [79]. These findings suggest that monitoring patients for early PDGFR α up-regulation will facilitate the identification of those who may benefit from the treatment with BRAF-i in combination

with clinically approved PDGFR α or HH-GLI inhibitors and that the activation status of ERK1/2 and PI3K should be used as a read out of resistance.

3.2. *Gastrointestinal cancers*

3.2.1. *Esophageal cancer*

Previous reports have shown that HH-GLI signaling is active and required for *in vitro* and *in vivo* growth of esophageal cancer cells [42,80]. Indeed, frequent inactivating mutations in PTCH1, which lead to activation of the downstream HH pathway, have been described in esophageal squamous cell carcinomas [81]. Human esophageal cancer samples often express high levels of SHH and GLI1, while normal corresponding tissue expresses low amounts. Moreover, ERK1/2 phosphorylation/activation may be detected in samples where the HH-GLI signaling is active. Consistent with the possible activation of ERK1/2 by HH-GLI, SHH-induced ERK1/2 activation is inhibited by MEK1/2 inhibitor PD98059 and by cyclopamine in TE esophageal cancer cell lines. In these cells, GLI1 is expressed thus suggesting the potential activation of HH signaling at basal levels. Stimulation with SHH enhances TE cell proliferation, and this effect is blocked by pretreatment with cyclopamine and by PD98059, indicating that loss of ERK1/2 activity inhibits HH-induced proliferation of TE cells [82].

3.2.2. *Gastric cancer*

Although SMO and/or PTCH1 mutations are present at low frequency in different histological subtypes of gastric tumors [83], activation and requirement of HH signaling has been demonstrated for this cancer type [42,84]. On the other hand, there are no data on the percentage of cases in which the MEK1/2-ERK1/2 pathway is activated in gastric cancers. Nevertheless, the percentage is expected to be high since many RTK as well as RAS-RAF may be activated in this malignant neoplasm [85].

An interplay between HH-GLI and ERK1/2 has also been observed in gastric cancer cells. Indeed, KRAS-MEK1/2-ERK1/2 cascade increases GLI transcriptional activity and induces the expression of HH target genes in gastric cancer cells. In agreement with a previous study performed in NIH/3T3 fibroblasts [62], the deletion of the N-terminal domain of GLI1 reduces the response to MEK1 stimulation. However,

kinase assay experiments fail to show a direct phosphorylation of GLI1 by ERK1/2 [86]. On the other hand, SHH stimulates the proliferation of rat gastric mucosal cells through ERK1/2 activation by elevating intracellular calcium concentration [87]. In addition, GANT61 and cyclopamine treatment decreases proliferation, migration and ERK1/2 phosphorylation in MKN45 gastric cancer cells [88].

3.2.3. Pancreatic cancer

HH-GLI signaling is an early and late mediator of pancreatic cancer tumorigenesis, as suggested by experimental studies using human pancreatic cancer cells [40] and various mouse models (see below). On the other hand, since pancreatic adenocarcinoma is the human malignancy with the highest incidence of activating KRAS mutations (70–90%), high frequency of cases with constitutive activation of the MEK1/2-ERK1/2 pathway is expected [89]. KRAS can activate HH pathway via MEK1/2-ERK1/2 in pancreatic cancer cells. In fact, expression of KRASV12 in the immortalized human pancreatic ductal epithelial cell line HPDE-c7 increases GLI1 levels and transcriptional activity. Consistently, suppression of oncogenic KRAS by siRNA inhibits GLI1 expression and activity in pancreatic ductal adenocarcinoma (PDA) cell lines with activating KRAS mutations. KRAS-mediated HH activation is suppressed by pharmacological inhibition of MEK1/2 with UO126, which decreases GLI1 protein stability in PDA [90]. Therefore, the major effector of RAS in enhancing HH-GLI activity is likely to be the MEK1/2-ERK1/2 signaling module.

The interaction between RAS and GLI has been described also in various mouse models of PDA. Mice expressing endogenous levels of mutant KRAS (KRAS^{G12D}) and of mutant p53 (Trp53^{R172H}) in the pancreas show activation of HH pathway, suggesting the action of oncogenic RAS on the endogenous HH-GLI pathway during tumor development [91]. KRAS (KRAS^{G12D}) genetically cooperates with activated GLI2 to initiate PDA *in vivo* [92]. An additional mouse model of KRAS-induced PDA shows that SMO-independent GLI1 activation is required for survival of tumor cells and KRAS-mediated transformation [93]. KRAS also contributes to a shift from autocrine-to-paracrine signaling in PDA, by inducing SHH expression, thus leading to HH stimulation of adjacent cells, and by negatively modulating canonical HH signaling through its negative effector DYRK1B [94]. Although from these mouse models it is not possible to infer the effector of oncogenic RAS, MEK1/2-ERK1/2 are likely to be the main mediators.

The MEK1/2-ERK1/2 module might also play a role in mediating the paracrine interactions between CXCL12/CXCR4 and HH pathway (Figure 1). In fact, CXCL12 secreted by stromal cells binds to its receptor, CXCR4 on pancreatic cancer cells, initiating a downstream signaling that activates AKT and ERK1/2. This leads to accumulation of MEK1/2-ERK1/2-dependent nuclear NF- κ B, that directly binds to the SHH promoter inducing its expression in pancreatic cancer cells [95].

A number of studies reported that HH-GLI might as well act upstream of ERK1/2 in pancreatic cells. In pancreatic duct epithelial cells (PDEC) ectopic expression of SHH enhances proliferation and activates PI3K and ERK1/2. Consistent with a role for PI3K and ERK1/2 in SHH-induced PDEC proliferation, inhibition of PI3K with LY294002 or MEK1/2 signaling with PD98059 reduces the S-phase fraction while increasing the G1 fraction. The mechanism involved in the activation of ERK1/2 by SHH signaling was not clarified although an involvement of HER2 or EGFR was excluded. On the other hand, activated GLI1 does not stimulate ERK1/2 activation indicating that it is GLI-independent in PDEC cells [96]. The latter study indicates that activation of ERK1/2 by HH-GLI pathway may be involved in HH-GLI induced pancreatic tumorigenesis. Moreover, HH-GLI signaling enhances K-Ras-induced pancreatic tumorigenesis by reducing the dependence of tumor cells on the sustained activation of the MAPK and PI3K/AKT/mTOR signaling pathways. Indeed, simultaneous treatment with PD98059 and rapamycin failed to completely inhibit the growth of cells expressing KRAS and SHH, although KRAS and HH signaling determine an additive effect on cell proliferation [96].

3.2.4. Hepatocellular carcinoma

The HH-GLI signaling is involved in the development, invasion and metastasis of hepatocellular carcinoma (HCC) [97]. On the other hand, alteration in the ERK1/2 pathway is well documented in human HCC and phosphorylated ERK1/2 levels are significantly increased in at least 50% of HCC samples [98]. In HCC tissue samples there is a positive correlation between SHH expression and nuclear GLI1, while neither SHH nor nuclear GLI1 are found in normal liver tissue. Moreover, the amount of nuclear GLI1 positively correlates with tumor pathological grade, with the ability of the tumor to invade and metastasize, and with phosphorylated ERK1/2 and MMP9 expression [99]. Inhibition of HH-GLI pathway by KAAD-cyclopamine decreases invasion and migration of Bel-7402 HCC cells, the level of nuclear GLI1, MMP9 and p-ERK1/2.

Consistently, activation of HH-GLI pathway induces opposite effects. Furthermore, MEK1/2 inhibition with UO126 or PD98059 impairs invasion and metastasis formation of HCC cells. Therefore, HH-GLI promotes ERK1/2-dependent invasiveness by up-regulating MMP9. In this context, ERK1/2 does not seem to be an upstream regulator of the HH-GLI pathway, because UO126 and PD98059 have no effect on the GLI1 expression in HCC cells [99].

3.2.5. Cholangiocarcinoma

HH-GLI signaling is implicated in cholangiocarcinoma (CCA) and recently HH has been proposed as a potential target for treatment of human CCA [100]. Several pathways that activate ERK1/2 are involved in the pathogenesis and progression of CCA [101]. In CCA cells, HH-GLI and ERK1/2 pathways appear to be in parallel rather than in series, because combined inhibition of either pathways with cyclopamine and UO126 determines an additive anti-proliferative effect, particularly in cells with KRAS mutation, and induces caspase-dependent apoptosis in CCA cells [102].

3.2.6. Colon cancer

HH-GLI signaling is active in human colon cancer and is critical for tumor growth, recurrence, metastasis and stem cell survival and expansion [45]. In mice, *Apc* mutant epithelial cells secrete IHH to maintain an intestinal stromal phenotype that is required for adenoma development [103]. The ERK1/2 pathway is located downstream of many growth-factor receptors, including EGFR and of RAF/RAS, that are involved in the pathogenesis and progression of colon cancer [104]. A study reported that MEK1/2-ERK1/2 acts upstream of HH signaling in colon cancer cells. Indeed, inhibition of MEK1/2 with UO126 in human HT29 colon cancer cells decreases phosphorylated ERK1/2 and inhibits GLI transcriptional activity and GLI1 mRNA and protein levels [105].

3.3. Brain tumors

3.3.1. Medulloblastoma

Medulloblastoma (MB), a primitive neuroectodermal tumor of the cerebellum, is the most common malignant brain tumor in children [106]. High expression of the HH pathway occurs in approximately 25% of all MB (HH group). Activation of HH pathway in MB can occur through inactivating mutations in PTCH1 and SUFU, activating mutations in SMO, and GLI1 and GLI2 gene amplifications [33,38].

An interaction between EGFR and HH signaling occurs in the medulloblastoma cell line Daoy. EGF impairs the activation of the target GLI1 upon HH pathway activation with the SMO agonist SAG. Although EGF is able to activate ERK1/2 in these cells, MEK1/2-ERK1/2 activity is not required for inhibitory effect of EGF on GLI [107].

In murine cerebellar granule cell precursors (GCP) FGF-mediated inhibition of SHH-induced proliferation and GLI1 expression requires activation of ERK1/2. Using two different FGFR inhibitors, namely PD173074 and SU5402, it was shown that bFGF acts by means of FGFR to abrogate the effects of HH signaling. The bFGF-dependent inhibition on SHH proliferative effect depends on activation of ERK1/2 and JNK. Furthermore, bFGF inhibits the growth of medulloblastoma cells from *Ptch*^{+/-} mutant mice [108]. The involvement of ERK1/2 was not addressed, although it is likely to occur on the basis of results obtained in GCP.

In MB arising in *Ptch*^{+/-} mice, Chow and colleagues identified three tumor subtypes on the basis of microarray signatures. In the growth factor independent group, that contains cells capable to form spheres in culture in the absence of growth factors, high levels of phosphorylated ERK1/2 are found. No mechanism of HH-GLI ERK1/2 cross talk was identified, although this event could be explained by the occurrence of trisomy of chromosome 6. Indeed, murine chromosome 6 contains many oncogenes, including KRAS, BRAF and MET, that are activators of ERK1/2 [109].

In conclusion, although a consistent activation of the ERK1/2 pathway in MB has not been reported [110] and the evidence of a crosstalk between HH-GLI and MEK1/2-ERK1/2 is not clear, targeting MEK1/2-ERK1/2 with available molecules might be taken into consideration, especially in the HH group.

3.3.2. Glioblastoma

Glioma is the most frequent tumor of the central nervous system and can be classified into 4 grades, with glioblastoma multiforme being the most aggressive. *GLI1* was originally identified as a gene amplified in

malignant glioblastoma [37]. Several reports support an active role for HH signaling in glioma and glioma CSC [46,47]. On the other hand, ERK1/2 activation is likely to occur especially in gliomas driven by growth factor receptors, including EGFR, and/or activation of other pathways upstream of MEK1/2-ERK1/2 [111]. SHH mediates the activation of ERK1/2 signaling in radial glial cells during late neocortex development and in HeLa cells through EGFR transactivation [112] (Figure 2).

Insulin receptor substrate 1 (IRS1) is a GLI1 transcriptional target in glioma CSC cells. In these cells, GLI1 inhibition decreases basal phosphorylation of RAF1, MEK1 and ERK1/2 and that induced by IGF-1. Therefore, GLI1 inhibition antagonized IRS1-dependent ERK1/2 activity and desensitizes glioma CSC to IGF-I stimulation [113]. The existence of an interplay between HH-GLI and IGF-I signaling on the activation of ERK/2 has also been described in adult myogenic cells [114].

In another study, inhibition of the HH-GLI pathway by Sant-1 did not alter ERK1/2 phosphorylation in glioma/glioblastoma cell lines. Moreover, Sant-1 did not alter the phosphorylation of ERK1/2 induced by guggulsterone, a Ras/NF κ B inhibitor [115]. The authors suggest that the effects observed occur in the tumor bulk. Therefore, ERK1/2 seems to be downstream HH-GLI in CSC [113] but not in the bulk population [115].

3.4. Breast cancer

The HH signaling is required in breast cancer and breast cancer stem cells [116,117]. Consistently, transgenic mice conditionally expressing GLI1 in the mammary epithelium develop mammary tumors [118]. Deregulation of the MEK1/2-ERK1/2 pathway occurs frequently and plays a central role in the carcinogenesis and maintenance of breast cancers, especially in the basal-like subgroup [119].

A crosstalk between HH-GLI and ERK1/2 has been also described in breast cancer cells. Cyclopamine inhibits the proliferation of breast cancer cell lines, either estrogen dependent or independent, and decreases the expression of CCND1. This effect is partially prevented by UO126, indicating that HH pathway inhibition requires an active MEK1/2-ERK1/2 module to produce a decrease in proliferation [120]. Furthermore, SHH activates ERK1/2 in a SMO-independent manner in MCF10A normal mammary cells. Authors suggested an involvement of GRB2- or p85 β -recruited proteins in the activation of ERK/2 [121].

3.5. Urologic tumors

3.5.1. Renal carcinoma

ERK1/2 pathway is constitutively active and sustains tumor growth in clear cell renal carcinoma cells [122]. Similarly, HH signaling is active in tumors, as suggested by elevated expression of SMO and GLI transcription factors in tumors compared to corresponding normal tissues. In clear cell renal carcinoma cells, irrespectively of VHL status, inhibition of HH-GLI pathway with cyclopamine decreases AKT and ERK1/2 phosphorylation. No mechanism of interaction was proposed [123].

3.5.2. Prostate cancer

HH and MEK1/2-ERK1/2 pathways are both involved in prostate cancer [43,44,124]. EGF signaling has been shown to increase the invasive capability of ARCaP_E human prostate cancer cells via upregulation of pERK1/2 and of GLI1. Enhanced invasiveness is reversed by inhibition of GLI1 *in vitro* with GANT61. Authors hypothesized that the mediator of EGF and HH pathway crosstalk is ERK1/2 through an unknown mechanism [125].

3.6. Hematological malignancies

3.6.1. Leukemia

HH pathway components are commonly expressed across different acute T-cell leukemia (T-ALL) cell lines. In particular, GLI1 is activated by both canonical HH signaling (via SMO) and by non-canonical activation, through the PI3K/AKT and MEK1/2-ERK1/2 pathways. Consistent with a non-canonical activation of HH downstream of SMO, inhibition of SMO is less effective than targeting GLI in inducing cell death. The GLI inhibitor GANT58 reduces proliferation and induces cell death in T-ALL cells. Perifosine, a PI3K/AKT inhibitor, decreases GLI1 protein in part through AKT/GSK3b, and inhibition of MEK1/2 with PD98059 enhances this effect. Interestingly, combination of AKT inhibitor and GANT58 has a synergetic therapeutic role in the treatment of T-ALL. Combination of HH and MEK1/2 inhibition was not investigated, although of potential interest [126].

MEK1/2-ERK1/2 pathway may be aberrantly activated in chronic lymphocytic leukemia (CLL) [127]. SMO inhibition with cyclopamine, LDE-225 or IPI-926 decreases the number of CLL cells in culture and induces apoptosis in a subset of CLL samples. Responsiveness correlates with elevated GLI1 and PTCH1 transcript levels and the presence of trisomy 12 (interestingly, the gene locus for human DHH and GLI1 is present on chromosome 12), whereas no other karyotype correlates with responsiveness. All CLL with trisomy 12 display constitutive HH pathway activation driven by autocrine DHH ligand secretion, which could be blocked by anti-HH antibody 5E1. Moreover, PTCH1 activates ERK in a SMO-independent manner. In this case either ERK1/2 or ERK5 could be involved (see also Section 4) because antibodies for pERK in immunohistochemistry do not distinguish between pERK1/2 and pERK5. Consistently, ERK1/2 activation could be prevented by the 5E1 HH-blocking antibody but not by SMO inhibitors [128] (Figure 2). These results beg for a possible clinical development of HH ligand-blocking antibodies. Indeed, these therapeutic tools could effectively block canonical (SMO-dependent) and non-canonical (SMO-independent) HH signaling and might therefore be more effective than SMO inhibitors for the treatment of human CLL or other cancer types with ligand-dependent HH pathway activation.

HH-GLI components are expressed in the HL60 human acute myeloid leukemia cell line. In these cells, cyclopamine induces dose- and time-dependent apoptosis, cell cycle arrest and monocytic differentiation. Moreover cyclopamine determines an inhibition of AKT and ERK1/2, indicating that AKT and ERK1/2 are downstream to HH-GLI pathway. However, how GLI transcription factor activity sustains the activation of ERK1/2 in HL60 cells was not addressed [129].

Significant upregulation of PTCH1, Frizzled2, Lef1, CCND1, p21 and downregulation of HOXA10 and HOXB4 transcripts in CD34+ cells distinguish blast crisis from chronic phase CML. Ectopic SHH increases STAT phosphorylation (Y705) and activation in chronic phase CML primary blasts but not in those from blast crisis patients. On the other hand, no ERK1/2 or AKT activation/phosphorylation is detected. Moreover, cyclopamine, that is able to prevent SHH-induced STAT3 phosphorylation, is ineffective on constitutive ERK1/2 and AKT phosphorylation, indicating that HH-GLI does not sustain the activation of these two pathways in CML, at least for what concern the chronic phase [130].

3.6.2. Multiple myeloma

The HH signaling has been shown to maintain a tumor stem cell compartment in multiple myeloma (MM) [131]. More recently, it was shown that constitutively active MEK1 increases half-life of GLI2 and enhances its nuclear translocation, decreasing ubiquitination of GLI2 protein (Figure 1). RSK2, a protein kinase downstream of MEK1/2-ERK1/2 cascade, mimics the effect of MEK1 on GLI2 stabilization. MEK1 and RSK2 fail to augment the half-life of GLI2 lacking GSK3 β phosphorylation sites, suggesting that MEK1/2-RSK stabilizes GLI2 by controlling targeting GSK3 β -mediated phosphorylation and ubiquitination of GLI2. The significance of MEK1/2-RSK stabilization was demonstrated in experiments showing that activation of MEK1/2-RSK parallels higher GLI2 protein level in several MM cell lines compared to normal B cells. Inhibition of RSK function using SL0101 accelerates GLI2 degradation and reduces the expression of GLI2 target genes in MM cells. Interestingly, combined treatment with RSK inhibitor SL0101 and GLI inhibitor GANT58 leads to a synergistic decrease of apoptosis in MM cells [132].

4. Crosstalk between HH-GLI signaling and ERK5

To date no crosstalk has been reported between HH-GLI and ERK5 pathway. However, MEF2C, a well known target of ERK5 [133], has been shown to activate the expression of GLI2 by binding to its promoter during cardiomyogenesis *in vitro* [134]. Moreover, it is worth pointing out that the majority of experimental data presented in Section 3 have been performed with small molecule kinase inhibitors targeting the ERK1/2 pathway, and these molecules inhibit also MEK5-ERK5. Indeed, PD98059 and U0126, which were initially identified as MEK1/2-specific inhibitors, also affect the MEK5-ERK5 pathway [135-137]. Moreover, PD184352 (CI-1040), another MEK1/2 inhibitor, decreases the activity of MEK5-ERK5 pathway although at lesser extent [136].

5. Crosstalk between HH-GLI signaling and JNK

JNK are protein kinases that regulate many physiological processes, including inflammatory responses, morphogenesis, cell proliferation, differentiation, survival and death. It is increasingly apparent that persistent activation of JNK is also involved in cancer development and progression [138]. Few evidences of an interaction between JNK proteins and HH-GLI pathways have been identified. Below are listed the papers

that refer to a crosstalk between JNK and HH signaling in cancer cells or in normal contexts where possible mechanisms of interaction have been described.

Deregulation of HH signaling pathway in epidermal keratinocytes is a primary event leading to the formation of BCC (see above). Overexpression of SHH in HaCaT keratinocytes grown in organotypic cultures induces a basal cell phenotype and increases invasiveness. This behavior is linked to increased EGFR activation, JNK phosphorylation and MMP9 expression. However the effective role of JNK in these SHH-induced effects was not addressed [139]. On the other hand, bFGF can antagonize the effects of SHH in cerebellar GCP and mouse medulloblastoma cells. FGF-mediated inhibition of SHH-induced proliferation occurs in a JNK-dependent manner [108].

Treatment with lipotoxic agents determines JNK-dependent SHH expression, via AP-1, in human hepatocellular carcinoma HUH-7 cells silenced for caspase 9, but not in parental control cells. Moreover, caspase 9 deprived cells are more resistant to the lipotoxic effect of fatty acids. These results may suggest how in nonalcoholic steatohepatitis, a condition that might predispose to HCC, ballooned hepatocytes that express lower level of caspase 9 compared to neighboring normal cells may escape cell death [140].

Whisenant and colleagues identified a D-site, a MAPK-docking site, within residues 290-296 of GLI3 protein and found that phosphorylation of Ser343 by JNK1-3 was D-site-dependent. Computational analysis suggest that D-sites are present in GLI1 and GLI2 and that therefore JNK proteins may bind to and directly phosphorylate GLI proteins [63].

In another study, using chemoresistant cancer cell lines and their respective parental cells, namely human chronic myelogenous leukemia K562-K562/A02 cells and human epidermoid carcinoma KB-KB/VCR cells, it was shown that SMO may activate GLI through G α i, G $\beta\gamma$ -JNK signaling axis, thereby promoting the GLI-dependent acquired chemoresistance [141].

6. Crosstalk between HH-GLI signaling and p38

p38 kinases play a prominent role in regulating the production of pro-inflammatory cytokines. There are no data about a crosstalk between HH signaling and p38 in cancer. However, a series of studies suggest potential interactions in normal cells. For instance, a reciprocal crosstalk between p38 MAPK and HH signaling has been shown in primary astrocytes [142], the most abundant glial cells in the brain that protects

neurons against oxidative stress [143]. Indeed, p38 MAPK modulates the expression of downstream targets the HH signaling and, in turn, HH pathway induces phosphorylation of p38, but not that of JNK nor ERK1/2. Using RNAi and a constitutively-active mutant authors show that SHH-mediated p38 MAPK signaling and subsequent GLI1 gene transcription requires G-protein receptor kinase 2 [142].

Interestingly, p38 might also mediate the activation of the GLI by the G protein G_{13} in a SMO-independent manner. The α subunit of $G_{\alpha 13}$ promotes activation of GLI transcription factors in normal C3H10T1/2 and pancreatic cancer cell lines. Although the exact mechanism was not reported, authors proposed p38 as a possible mediator of this activation, because p38 inhibitor SB202190 impairs G_{13} -stimulated GLI transcriptional activity by 40–60%. Based on this model, SMO-independent activation of GLI is achieved through the 7-transmembrane receptors CCK_A , which couples with G_{13} . Therefore, activated G_{13} might promote activation of GLI through p38 [144].

7. Rationale for combining HH and ERK1/2 inhibitors

7.1. Inhibitors of the HH pathway

Three major modes of HH pathway inhibition have been exploited therapeutically: SMO inhibition, GLI inhibition and disruption of HH/PTCH interaction (Table 1). After cyclopamine (and its more effective derivative KAAD-cyclopamine), a naturally compound inhibitor of SMO [145,146], several more potent and specific SMO inhibitors have been developed. They include vismodegib, approved for the treatment of locally advanced or metastatic BCC, BMS-833923, saridegib (IPI-926), sonidegib/erismodegib (LDE-225), PF-04449913, LY2940680, LEQ506 and TAK-441 [147]. SMO inhibitors are particularly effective against MB and BCC harboring SMO or PTCH mutations. However, despite promising preclinical results, SMO inhibitors have yielded little clinical benefit in tumors not harboring mutations in components of the HH pathway. The poor clinical performance of SMO inhibitors beyond BCC and MB may be due, at least in part, to crosstalk between HH and other oncogenic signaling pathways (as reported above), that may significantly alter clinical response to HH pathway inhibition and limit efficacy.

The use of SMO inhibitors has been associated with the acquisition of resistance, mostly described in medulloblastoma, as a consequence of (*i*) mutations in human *SMO* (D473H) and the matching mutation in

mouse (D477G), observed during vismodegib treatment; (ii) amplification of downstream HH target genes, such as *GLI2* and *CyclinD1*, reported for both vismodegib and sonidegib; (iii) upregulation of other oncogenic signaling, such as PI3K/AKT pathway, observed during LDE-225 treatment; (iv) increased expression of adenosine triphosphate (ATP)-binding cassette transporter (ABC) such as P-glycoprotein, leading to increased drug efflux, observed during saridegib treatment [148-150]. Agents such as GANT58/GANT61 [151] and HPI 1-4 [152] act by blocking GLI processing, activation and/or transcriptional activity. Recently, other GLI inhibitors have been reported, including ATO (arsenic trioxide) [153], an already approved therapeutic for acute promyelocytic leukemia, the anti-pinworm pyrvinium [154] and glabrescione B, a small molecule that interferes with the binding of GLI to the DNA [155]. HH pathway can be blocked also by disrupting the interaction between HH proteins and PTCH, using anti-HH monoclonal antibody 5E1 [156] or the macrocyclic small-molecule robotnikinin [157], both exhibiting antitumor activity.

7.2. ERK1/2 inhibitors

Several RAF and MEK1/2 inhibitors have been developed and many are in clinical trials [158] (Table 1). On the other hand, efforts in the identification of ERK1- and ERK2-selective inhibitors have been scarce. This is partly due to the earlier assumption that MEK1/2 are the only known activators of ERK1/2 and therefore the ERK1/2 cascade might be efficiently blocked by MEK1/2 inhibitors. However, many evidences suggested to develop ERK1/2 inhibitors: i) the necessity of targeting components of the same pathway due to different possible outcomes in different molecular contexts (i.e. different types of cancer or different patients with the same type of cancer); ii) negative feedback loops elicited following treatment with inhibitors of RTK/RAS/MEK1/2-ERK1/2 cascade; iii) occurrence of ERK1/2 activation as a resistance mechanism to RAF and MEK1/2 inhibitors; iv) activation of ERK1/2 as a consequence of inhibition of PI3K [159,160]. More importantly, ERK1/2 activation induced by treatment with BRAF-i may lead to secondary malignancies as it is well known for squamous cell carcinoma and recently reported for secondary chronic lymphocytic leukemia [161,162]. The above mentioned reasons resulted, very recently, in the development of ERK1/2 inhibitors [3]. SCH772984 (Merck/Schering-Plough) is an ATP-competitive ERK1 and ERK2 inhibitor [163]. This molecule exerts its inhibiting activity by two mechanisms: inhibition of ERK1 and

ERK2 intrinsic kinase activity and prevention of phosphorylation of ERK1 and ERK2 by MEK1/2.

SCH772984 has been shown to work in tumor cell lines and mice models resistant to RAS-MEK inhibitors. Specifically, MK-8353 (formerly SCH900353; ClinicalTrials.gov Identifier: NCT01358331), a clinical grade analogue of SCH772984, is currently being tested in Phase 1 clinical trials. BVD-523 (Biomed Valley Discoveries) is employed in Phase 1 trials in patients with advanced malignancies and Phase 1/2 trials for patients with acute myelogenous leukemia or myelodysplastic syndromes. Another available ERK1/2 inhibitor is RG7842 (GDC0994; Genentech/Roche). Nevertheless, properties and clinical activities of the above mentioned ERK1/2 inhibitors are not publicly available yet.

7.3. Combination of HH and MEK1/2-ERK1/2 inhibitors

ERK1/2 and HH-GLI pathway are involved in several aspects of cancer, ranging from tumor initiation to promotion of invasiveness. In this review we extensively described several contexts in which the HH-GLI pathway and ERK1/2 interact in a diverse array of processes relevant for cancer, including cell proliferation, escape from apoptosis, cell migration, local invasiveness as well as metastasis formation. Several inhibitors targeting SMO and MEK1/2-ERK1/2 have been developed and are available. However, preclinical and clinical studies have revealed that the application of single-agent SMO or BRAF inhibitors might not be as broad as expected and, more importantly, is often associated to mechanisms of resistance. Tables 2 and 3 report examples of possible future directions for preclinical and clinical studies focusing on combination treatment of HH-i and MEK1/2-ERK1/2-i. Along this line, a recent report showed that combination of BRAF and HH inhibitors produces a modest but significant synergistic effect in inhibiting melanoma cell proliferation [76]. This suggests that a combined therapy targeting both HH signaling and BRAF or downstream molecules, i.e. MEK1/2-ERK1/2, might be beneficial in patients with mutated BRAF and activated HH signaling. This could apply also to other types of cancer, which depend on an active HH pathway and harbor mutations in BRAF or activation of downstream MEK1/2-ERK1/2. Moreover, treatment with SMO inhibitors might also partially prevent resistance to BRAF inhibitors. In fact, SMO inhibitor LDE-225 has been shown to restore and increase the sensitivity of melanoma cells to BRAF inhibitors [75]. Nevertheless, combination treatment targeting HH and MEK1/2-ERK1/2 should be taken into consideration

also in cases in which the two signaling pathways act in parallel, such as for cholangiocarcinoma or chronic myeloid leukemia [102,130].

In light of future clinical trials combining SMO and MEK1/2-ERK1/2 inhibitors, it will be equally important to develop sensitive biomarkers of activation of HH-GLI and MEK1/2-ERK1/2 pathways to identify the subset of cancers that will likely respond to such inhibitors and to monitor the efficacy of the therapy. In this respect, efforts should be made to develop specific and reliable antibodies to detect activated GLI1 and pERK1/2 in immunohistochemistry. Moreover, the detection of HH-induced activated RTK, such as PDGFR α [75], might be another possible biomarker to identify patients who might benefit from treatment with HH-GLI and MEK1/2-ERK1/2 inhibitors.

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Conflicts of interest

The authors declare that there are no conflicts of interest.

FIGURE LEGENDS

Figure 1. Modes of activation of HH signaling by the MAPK ERK1/2 pathway. Canonical activation of the HH signaling occurs through binding of HH ligands to PTCH receptor. Consequently, PTCH releases its inhibition on SMO. Activated SMO promotes an intracellular signaling cascade that leads to the translocation of activated forms of GLI (GLI^A) into the nucleus, where they induce transcription of target genes. MAPK ERK1/2 can activate HH signaling by: 1) enhancement of GLI activity by RAS-MEK1/2-ERK1/2 signaling, as shown in melanoma and pancreatic cancer cells [48,90]; 2) increase in GLI2 stability and activity by MEK1/2-ERK1/2-RSK2 signaling, as suggested in multiple myeloma [132]; 3) synergistic promotion of cooperative HH-EGFR target genes, as shown in keratinocytes and BCC [68]. In this case,

activation of EGF signaling induces RAS-RAS-MEK1/2-ERK1/2 signaling, leading to activation of GLI1 and/or JUN/AP1 transcription factors; 4) transcriptional activation of *SHH*. Here CXCL12 secreted by stromal cells binds to its receptor, CXCR4, on pancreatic cancer cells. This initiates a downstream signaling that activates AKT and ERK1/2, leading to accumulation of MEK1/2-ERK1/2-dependent nuclear NF- κ B, that directly binds *SHH* promoter inducing its expression [95]. Abbreviations: CXCL12, CXC ligand 12; CXCR4, CXC chemokine receptor type 4; EGF, Epidermal Growth Factor; EGFR, Epidermal Growth Factor Receptor; ERK, Extracellular Signal-Regulated Kinase; FGFb, basic Fibroblast Growth Factor; HH, Hedgehog; MEK, MAPK/ERK kinase 1; PDGF, Platelet-Derived Growth Factor; PDGFR, Platelet-Derived Growth Factor Receptor; RSK2, Ribosomal S6 kinase; PTCH, Patched; SMO, Smoothed; SHH, Sonic Hedgehog.

Figure 2. Modes of activation of the ERK1/2 pathway by HH signaling. Classical activation of ERK1/2 MAPK may occur in different manner. Here only activation induced by growth factor receptors via RAS/RAF/MEK1/2 is depicted being the most studied mechanism in reports involving HH-GLI-induced ERK1/2 activation. Arrows indicate activating pathways that are known (although not reported in the picture for simplicity). Broken lines indicate activating signaling whose intermediates are unknown. Red lines indicate identified GLI transcriptional targets (see below). The HH pathway may activate ERK1/2 by several mechanisms: 1) following SMO activation, in a GLI-independent manner, via unknown signaling events. These effects are blocked by cyclopamine [72,82]; 2) following GLI activation via unknown mechanisms; it is not known whether transcriptional activity of GLI is involved [88]; 3) following expression of GLI-dependent target genes that activate downstream ERK1/2, such as PDGFR and IRS1 [70,79,113]; 4) through PTCH in a SMO-independent manner [128]; 5) transactivation of EGFR by SHH has also been described [112]. Abbreviations: EGFR, Epidermal Growth Factor Receptor; ERK, Extracellular Signal-Regulated Kinase; GLI^A, GLI activator forms; IGF1, Insulin-like Growth Factor 1; IGF1R, Insulin-like Growth Factor 1 Receptor; IRS1, Insulin receptor substrate 1; HH, Hedgehog; SHH, Sonic Hedgehog; MEK, MAPK/ERK kinase; PDGF, Platelet-Derived Growth Factor; PDGFR, Platelet-Derived Growth Factor Receptor; PTCH, Patched; SMO, Smoothed; MMP9, Matrix metalloproteinase-9.

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REFERENCES

- [1] Cargnello M, Roux PP. Activation and function of the MAPKs and their substrates, the MAPK-activated protein kinases. *Microbiol Mol Biol Rev* 2011;75:50-83.
- [2] Roberts PJ, Der CJ. Targeting the Raf-MEK-ERK mitogen-activated protein kinase cascade for the treatment of cancer. *Oncogene* 2007;26:3291-310.
- [3] Samatar AA, Poulikakos PI. Targeting RAS-ERK signalling in cancer: promises and challenges. *Nat Rev Drug Discov* 2014;13:928-42.
- [4] Dhillon AS, Hagan S, Rath O, Kolch W. MAP kinase signalling pathways in cancer. *Oncogene* 2007;26:3279-90.
- [5] Marshall CJ. Specificity of receptor tyrosine kinase signaling: transient versus sustained extracellular signal-regulated kinase activation. *Cell* 1995;80:179-85.
- [6] Raman M, Chen W, Cobb MH. Differential regulation and properties of MAPKs. *Oncogene* 2007;26:3100-12.
- [7] Dhanasekaran DN, Kashef K, Lee CM, Xu H, Reddy EP. Scaffold proteins of MAP-kinase modules. *Oncogene* 2007;26:3185-202.
- [8] Yoon S, Seger R. The extracellular signal-regulated kinase: multiple substrates regulate diverse cellular functions. *Growth Factors* 2006;24:21-44.
- [9] Weston CR, Davis RJ. The JNK signal transduction pathway. *Curr Opin Genet Dev* 2002;12:14-21.
- [10] Cuadrado A, Nebreda AR. Mechanisms and functions of p38 MAPK signalling. *Biochem J* 2010;429:403-17.
- [11] Lei YY, Wang WJ, Mei JH, Wang CL. Mitogen-activated protein kinase signal transduction in solid tumors. *Asian Pac J Cancer Prev* 2014;15:8539-48.
- [12] Pritchard AL, Hayward NK. Molecular pathways: mitogen-activated protein kinase pathway mutations and drug resistance. *Clin Cancer Res* 2013;19:2301-9.
- [13] Burotto M, Chiou VL, Lee JM, Kohn EC. The MAPK pathway across different malignancies: a new perspective. *Cancer* 2014;120:3446-56.
- [14] Wagner EF, Nebreda AR. Signal integration by JNK and p38 MAPK pathways in cancer development. *Nat Rev Cancer* 2009;9:537-49

- [15] Lochhead PA, Gilley R, Cook SJ. ERK5 and its role in tumour development. *Biochem Soc Trans* 2012;40:251-6.
- [16] Rovida E, Di Maira G, Tusa I, Cannito S, Paternostro C, Navari N, et al. The mitogen-activated protein kinase ERK5 regulates the development and growth of hepatocellular carcinoma. *Gut* 2014;306761.
- [17] Nusslein-Volhard C, Wieschaus E. Mutations affecting segment number and polarity in *Drosophila*. *Nature* 1980;287:795-801.
- [18] Ingham PW, McMahon AP. Hedgehog signaling in animal development: paradigms and principles. *Genes Dev* 2002;15:3059-87.
- [19] Beachy PA, Karhadkar SS, Berman DM. Tissue repair and stem cell renewal in carcinogenesis. *Nature* 2004;432:324-31.
- [20] Rohatgi R, Milenkovic L, Scott MP. Patched1 regulates hedgehog signaling at the primary cilium. *Science* 2007;317:372-6.
- [21] Eggenschwiler JT, Anderson KV. Cilia and developmental signaling. *Annual Review of Cell and Developmental Biology* 2007;23:345-73.
- [22] Wong SY, Reiter JF. The primary cilium at the crossroads of mammalian hedgehog signaling. *Current Topics in Developmental Biology* 2008;85:225-60.
- [23] Rohatgi R, Scott MP. Patching the gaps in Hedgehog signalling. *Nature Cell Biology* 2007;9:1005-9.
- [24] Jiang J, Hui CC. Hedgehog signaling in development and cancer. *Developmental Cell* 2008;15:801-12.
- [25] Varjosalo M, Taipale J. Hedgehog: functions and mechanisms. *Genes & Development* 2008;22:2454-72.
- [26] Wang B, Fallon JF, Beachy PA. Hedgehog-regulated processing of Gli3 produces an anterior/posterior repressor gradient in the developing vertebrate limb. *Cell* 2000;100:423-34.
- [27] Pan Y, Bai CB, Joyner AL, Wang B. Sonic hedgehog signaling regulates Gli2 transcriptional activity by suppressing its processing and degradation. *Molecular and Cellular Biology* 2006;26:3365-77.
- [28] Dai P, Akimaru H, Tanaka Y, Maekawa T, Nakafuku M, Ishii S. Sonic Hedgehog-induced activation of the Gli1 promoter is mediated by GLI3. *J Biol Chem* 1999;274:8143-52.
- [29] Bai CB, Stephen D, Joyner AL. All mouse ventral spinal cord patterning by hedgehog is Gli dependent and involves an activator function of Gli3. *Developmental Cell* 2004;6:103-15.

- [30] Scales SJ, de Sauvage FJ. Mechanisms of Hedgehog pathway activation in cancer and implications for therapy. *Trends in Pharmacological Sciences* 2009;30:303-12.
- [31] Hahn H, Wicking C, Zaphiropoulos PG, Gailani MR, Shanley S, Chidambaram A, et al. Mutations of the human homolog of *Drosophila* patched in the nevoid basal cell carcinoma syndrome. *Cell* 1996;85:841-51.
- [32] Johnson RL, Rothman AL, Xie J, Goodrich LV, Bare JW, Bonifas JM, et al. Human homolog of patched, a candidate gene for the basal cell nevus syndrome. *Science* 1996;272:1668-71.
- [33] Taylor MD, Liu L, Raffel C, Hui CC, Mainprize TG, Zhang X, et al. Mutations in *SUFU* predispose to medulloblastoma. *Nature Genetics* 2002;31:306-10.
- [34] Sheng T, Li C, Zhang X, Chi S, He N, Chen K, et al. Activation of the hedgehog pathway in advanced prostate cancer. *Mol Cancer*. 2004;3:29.
- [35] Di Marcotullio L, Ferretti E, De Smaele E, Argenti B, Mincione C, Zazzeroni F, et al. *REN(KCTD11)* is a suppressor of Hedgehog signaling and is deleted in human medulloblastoma. *Proc Natl Acad Sci USA*. 2004;101:10833-8.
- [36] Xie J, Murone M, Luoh SM, Ryan A, Gu Q, Zhang C, et al. Activating Smoothed mutations in sporadic basal-cell carcinoma. *Nature* 1998;391:90-2.
- [37] Kinzler KW, Bigner SH, Bigner DD, Trent JM, Law ML, O'Brien SJ, et al. Identification of an amplified, highly expressed gene in a human glioma. *Science* 1987;236:70-3.
- [38] Northcott PA, Nakahara Y, Wu X, Feuk L, Ellison DW, Croul S, et al. Multiple recurrent genetic events converge on control of histone lysine methylation in medulloblastoma. *Nature Genetics* 2009;41:465-72.
- [39] Watkins DN, Berman DM, Burkholder SG, Wang B, Beachy PA, Baylin SB. Hedgehog signalling within airway epithelial progenitors and in small-cell lung cancer. *Nature* 2003;422:313-7.
- [40] Thayer SP, di Magliano MP, Heiser PW, Nielsen CM, Roberts DJ, Lauwers GY, et al. Hedgehog is an early and late mediator of pancreatic cancer tumorigenesis. *Nature* 2003;425:851-6.
- [41] Feldmann G, Dhara S, Fendrich V, Bedja D, Beaty R, Mullendore M, et al. Blockade of hedgehog signaling inhibits pancreatic cancer invasion and metastases: a new paradigm for combination therapy in solid cancers. *Cancer Res* 2007;67:2187-96.

- [42] Berman DM, Karhadkar SS, Maitra A, Montes De Oca R, Gerstenblith MR, Briggs K, et al. Widespread requirement for Hedgehog ligand stimulation in growth of digestive tract tumours. *Nature* 2003;425:846-51.
- [43] Karhadkar SS, Bova GS, Abdallah N, Dhara S, Gardner D, Maitra A, et al. Hedgehog signalling in prostate regeneration, neoplasia and metastasis. *Nature* 2004;431:707-12.
- [44] Sanchez P, Hernández AM, Stecca B, Kahler AJ, DeGueme AM, Barrett A, et al. Inhibition of prostate cancer proliferation by interference with SONIC HEDGEHOG-GLI1 signaling. *Proc Natl Acad Sci USA* 2004;101:12561-6.
- [45] Varnat F, Duquet A, Malerba M, Zbinden M, Mas C, Gervaz P, et al. Human colon cancer epithelial cells harbour active HEDGEHOG-GLI signalling that is essential for tumour growth, recurrence, metastasis and stem cell survival and expansion. *EMBO Mol Med* 2009;1:338-51.
- [46] Clement V, Sanchez P, de Tribolet N, Radovanovic I, Ruiz i Altaba A. HEDGEHOG-GLI1 signaling regulates human glioma growth, cancer stem cell self-renewal, and tumorigenicity. *Curr Biol* 2007;17:165-72.
- [47] Bar EE, Chaudhry A, Lin A, Fan X, Schreck K, Matsui W, et al. Cyclopamine-mediated hedgehog pathway inhibition depletes stem-like cancer cells in glioblastoma. *Stem Cells* 2007;25:2524-33.
- [48] Stecca B, Mas C, Clement V, Zbinden M, Correa R, Piguet V, et al. Melanomas require HEDGEHOG-GLI signaling regulated by interactions between GLI1 and the RAS-MEK/AKT pathways. *Proc Natl Acad Sci USA* 2007;104:5895-900.
- [49] Yauch RL, Gould SE, Scales SJ, Tang T, Tian H, Ahn CP, Marshall D, et al. A paracrine requirement for hedgehog signalling in cancer. *Nature* 2008;455:406-10.
- [50] Becher OJ, Hambardzumyan D, Fomchenko EI, Momota H, Mainwaring L, Bleau AM, et al. Gli activity correlates with tumor grade in platelet-derived growth factor-induced gliomas. *Cancer Res* 2008;68:2241-9.
- [51] Dierks C, Grbic J, Zirlik K, Beigi R, Englund NP, Guo GR, et al. Essential role of stromally induced hedgehog signaling in B-cell malignancies. *Nat Med* 2007;13:944-51.

- [52] Hegde GV, Munger CM, Emanuel K, Joshi AD, Greiner TC, Weisenburger DD, et al. Targeting of sonic hedgehog-GLI signaling: a potential strategy to improve therapy for mantle cell lymphoma. *Mol Cancer Ther* 2008;7:1450-60.
- [53] Takebe N, Miele L, Harris PJ, Jeong W, Bando H, Kahn M, et al. Targeting Notch, Hedgehog, and Wnt pathways in cancer stem cells: clinical update. *Nat Rev Clin Oncol* 2015;12:445-64.
- [54] Teglund S, Toftgård R. Hedgehog beyond medulloblastoma and basal cell carcinoma. *Biochim Biophys Acta*. 2010;1805:181-208.
- [55] Stecca B, Ruiz i Altaba A. Context-dependent regulation of the GLI code in cancer by HEDGEHOG and non-HEDGEHOG signals. *J Mol Cell Biol*. 2010;2:84-95.
- [56] Brechbiel J, Miller-Moslin K, Adjei AA. Crosstalk between hedgehog and other signaling pathways as a basis for combination therapies in cancer. *Cancer Treat Rev* 2014;40:750-9.
- [57] Aberger F, Ruiz i Altaba A. Context-dependent signal integration by the GLI code: the oncogenic load, pathways, modifiers and implications for cancer therapy. *Semin Cell Dev Biol*. 2014;33:93-104.
- [58] Pandolfi S, Stecca B. Cooperative integration between HEDGEHOG-GLI signalling and other oncogenic pathways: implications for cancer therapy. *Expert Rev Mol Med* 2015;17:e5.
- [59] Kessaris N, Jamen F, Rubin LL, Richardson WD. Cooperation between sonic hedgehog and fibroblast growth factor/MAPK signalling pathways in neocortical precursors. *Development* 2004;131:1289-98.
- [60] Bastida MF, Sheth R, Ros MA. A BMP-Shh negative-feedback loop restricts Shh expression during limb development. *Development* 2009;136:3779-89.
- [61] Lai LP, DaSilva KA, Mitchell J. Regulation of Indian hedgehog mRNA levels in chondrocytic cells by ERK1/2 and p38 mitogen-activated protein kinases. *J Cell Physiol* 2005;203:177-85.
- [62] Riobo NA, Haines GM, Emerson CP Jr. Protein kinase C- δ and mitogen-activated protein/extracellular signal-regulated kinase-1 control GLI activation in hedgehog signaling. *Cancer Res* 2006;66:839-45.
- [63] Whisenant TC, Ho DT, Benz RW, Rogers JS, Kaake RM, Gordon EA, et al. Computational prediction and experimental verification of new MAP kinase docking sites and substrates including Gli transcription factors. *PLoS Comput Biol* 2010;6:e1000908.
- [64] Otsuka A, Levesque MP, Dummer R, Kabashima K. Hedgehog signaling in basal cell carcinoma. *J Dermatol Sci* 2015;78:95-100.

- [65] Dahmane N, Lee J, Robins P, Heller P, Ruiz i Altaba A. Activation of the transcription factor Gli1 and the Sonic hedgehog signalling pathway in skin tumours. *Nature* 1997;389:876-81.
- [66] Kasper M, Jaks V, Hohl D, Toftgård R. Basal cell carcinoma - molecular biology and potential new therapies. *J Clin Invest* 2012;122:455-63.
- [67] Kasper M, Schnidar H, Neill GW, Hanneder M, Klingler S, Blaas L, et al. Selective modulation of Hedgehog/GLI target gene expression by epidermal growth factor signaling in human keratinocytes. *Mol Cell Biol* 2006;26:6283-98.
- [68] Schnidar H, Eberl M, Klingler S, Mangelberger D, Kasper M, Hauser-Kronberger C, et al. Epidermal growth factor receptor signaling synergizes with Hedgehog/GLI in oncogenic transformation via activation of the MEK/ERK/JUN pathway. *Cancer Res* 2009;69:1284-92.
- [69] Eberl M, Klingler S, Mangelberger D, Loipetzberger A, Damhofer H, Zoidl K, et al. Hedgehog-EGFR cooperation response genes determine the oncogenic phenotype of basal cell carcinoma and tumour-initiating pancreatic cancer cells. *EMBO Mol Med* 2012;4:218-33.
- [70] Xie J, Aszterbaum M, Zhang X, Bonifas JM, Zachary C, Epstein E, et al. A role of PDGFR in basal cell carcinoma proliferation. *Proc Natl Acad Sci USA* 2001; 98:9255-9.
- [71] Clark CM, Furniss M, Mackay-Wiggan JM. Basal cell carcinoma: an evidence-based treatment update. *Am J Clin Dermatol* 2014;15:197-216.
- [72] Li C, Chi S, He N, Zhang X, Guicherit O, Wagner R, et al. IFN α induces Fas expression and apoptosis in hedgehog pathway activated BCC cells through inhibiting Ras-Erk signaling. *Oncogene* 2004;23:1608-17.
- [73] Liu H, Jian Q, Xue K, Ma C, Xie F, Wang R, et al. The MEK/ERK signalling cascade is required for sonic hedgehog signalling pathway-mediated enhancement of proliferation and inhibition of apoptosis in normal keratinocytes. *Exp Dermatol* 2014;23:896-901.
- [74] Davies H, Bignell GR, Cox C, Stephens P, Edkins S, Clegg S, et al. Mutations of the BRAF gene in human cancer. *Nature* 2002;417:949-54.
- [75] Sabbatino F, Wang Y, Wang X, Ferrone S, Ferrone CR. Emerging BRAF inhibitors for melanoma. *Expert Opin Emerg Drugs* 2013;18:431-43.

- [76] O'Reilly KE, de Miera EV, Segura MF, Friedman E, Poliseno L, Han SW, et al. Hedgehog pathway blockade inhibits melanoma cell growth *in vitro* and *in vivo*. *Pharmaceuticals (Basel)*. 2013;6:1429-50.
- [77] Jalili A, Mertz KD, Romanov J, Wagner C, Kalthoff F, Stuetz A, et al. NVP-LDE225, a potent and selective SMOOTHENED antagonist reduces melanoma growth *in vitro* and *in vivo*. *PLoS One* 2013;8:e69064.
- [78] Nazarian R, Shi H, Wang Q, Kong X, Koya RC, Lee H, et al. Melanomas acquire resistance to B-RAF(V600E) inhibition by RTK or N-RAS upregulation. *Nature* 2010;468:973-7.
- [79] Sabbatino F, Wang Y, Wang X, Flaherty KT, Yu L, Pepin D, Scognamiglio G, et al. PDGFR α up-regulation mediated by sonic hedgehog pathway activation leads to BRAF inhibitor resistance in melanoma cells with BRAF mutation. *Oncotarget* 2014;5:1926-41.
- [80] Wang Y, Ding Q, Yen CJ, Xia W, Izzo JG, Lang JY et al. The crosstalk of mTOR/S6K1 and Hedgehog pathways. *Cancer Cell* 2012;21:374-87.
- [81] Zhang L, Zhou Y, Cheng C, Cui H, Cheng L, Kong P, et al. Genomic analyses reveal mutational signatures and frequently altered genes in esophageal squamous cell carcinoma. *Am J Hum Genet* 2015;96:597-611.
- [82] Wei L, Xu Z. Cross-signaling among phosphoinositide-3 kinase, mitogen-activated protein kinase and sonic hedgehog pathways exists in esophageal cancer. *Int J Cancer* 2011;129:275-84.
- [83] Wang XD, Inzunza H, Chang H, Qi Z, Hu B, Malone D, et al. Mutations in the hedgehog pathway genes SMO and PTCH1 in human gastric tumors. *PLoS One* 2013;8:e54415.
- [84] Yoo YA, Kang MH, Lee HJ, Kim BH, Park JK, Kim HK, et al. Sonic hedgehog pathway promotes metastasis and lymphangiogenesis via activation of Akt, EMT, and MMP-9 pathway in gastric cancer. *Cancer Res* 2011;71:7061-70.
- [85] Wadhwa R, Song S, Lee JS, Yao Y, Wei Q, Ajani JA. Gastric cancer-molecular and clinical dimensions. *Nat Rev Clin Oncol* 2013;10:643-55.
- [86] Seto M, Ohta M, Asaoka Y, Ikenoue T, Tada M, Miyabayashi K, et al. Regulation of the hedgehog signaling by the mitogen-activated protein kinase cascade in gastric cancer. *Mol Carcinog* 2009;48:703-12.

- [87] Osawa H, Ohnishi H, Takano K, Noguti T, Mashima H, Hoshino H, et al. Sonic hedgehog stimulates the proliferation of rat gastric mucosal cells through ERK activation by elevating intracellular calcium concentration. *Biochem Biophys Res Commun* 2006;344:680-7.
- [88] Yan R, Peng X, Yuan X, Huang D, Chen J, Lu Q, et al. Suppression of growth and migration by blocking the Hedgehog signaling pathway in gastric cancer cells. *Cell Oncol (Dordr)*. 2013;36:421-35.
- [89] Furukawa T. Impacts of activation of the mitogen-activated protein kinase pathway in pancreatic cancer. *Front Oncol* 2015;5:23.
- [90] Ji Z, Mei FC, Xie J, Cheng X. Oncogenic KRAS activates hedgehog signaling pathway in pancreatic cancer cells. *J Biol Chem* 2007;282:14048-55.
- [91] Hingorani SR, Wang L, Multani AS, Combs C, Deramautd TB, Hruban RH, et al. Trp53R172H and KrasG12D cooperate to promote chromosomal instability and widely metastatic pancreatic ductal adenocarcinoma in mice. *Cancer Cell* 2005;7:469-83.
- [92] Pasca di Magliano M, Sekine S, Ermilov A, Ferris J, Dlugosz AA, Hebrok M. Hedgehog/Ras interactions regulate early stages of pancreatic cancer. *Genes Dev* 2006;20:3161-73.
- [93] Nolan-Stevaux O, Lau J, Truitt ML, Chu GC, Hebrok M, Fernández-Zapico ME, et al. GLI1 is regulated through Smoothened-independent mechanisms in neoplastic pancreatic ducts and mediates PDAC cell survival and transformation. *Genes Dev* 2009;23:24-36.
- [94] Lauth M, Bergström A, Shimokawa T, Tostar U, Jin Q, Fendrich V, et al. DYRK1B-dependent autocrine-to-paracrine shift of Hedgehog signaling by mutant RAS. *Nat Struct Mol Biol* 2010;17:718-25.
- [95] Singh AP, Arora S, Bhardwaj A, Srivastava SK, Kadakia MP, Wang B, et al. CXCL12/CXCR4 protein signaling axis induces sonic hedgehog expression in pancreatic cancer cells via extracellular regulated kinase- and Akt kinase-mediated activation of nuclear factor κ B: implications for bidirectional tumor-stromal interactions. *J Biol Chem*. 2012;287:39115-24.
- [96] Morton JP, Mongeau ME, Klimstra DS, Morris JP, Lee YC, Kawaguchi Y, et al. Sonic hedgehog acts at multiple stages during pancreatic tumorigenesis. *Proc Natl Acad Sci USA* 2007;104:5103-8.
- [97] Zheng X, Zeng W, Gai X, Xu Q, Li C, Liang Z, et al. Role of the Hedgehog pathway in hepatocellular carcinoma (review). *Oncol Rep* 2013;30:2020-6.

- [98] Min L, He B, Hui L. Mitogen-activated protein kinases in hepatocellular carcinoma development. *Semin Cancer Biol* 2011;21:10-20.
- [99] Lu JT, Zhao WD, He W, Wei W. Hedgehog signaling pathway mediates invasion and metastasis of hepatocellular carcinoma via ERK pathway. *Acta Pharmacol Sin* 2012;33:691-700.
- [100] Riedlinger D, Bahra M, Boas-Knoop S, Lippert S, Bradtmöller M, Guse K, et al. Hedgehog pathway as a potential treatment target in human cholangiocarcinoma. *J Hepatobiliary Pancreat Sci* 2014;21:607-15.
- [101] Maemura K, Natsugoe S, Takao S. Molecular mechanism of cholangiocarcinoma carcinogenesis. *J Hepatobiliary Pancreat Sci* 2014;21:754-60.
- [102] Jinawath A, Akiyama Y, Sripa B, Yuasa Y. Dual blockade of the Hedgehog and ERK1/2 pathways coordinately decreases proliferation and survival of cholangiocarcinoma cells. *J Cancer Res Clin Oncol* 2007;133:271-8.
- [103] Büller NV, Rosekrans SL, Metcalfe C, Heijmans J, van Dop WA, Fessler E, et al. Stromal Indian hedgehog signaling is required for intestinal adenoma formation in mice. *Gastroenterology*. 2015;148:170-180.
- [104] Fang JY, Richardson BC. The MAPK signalling pathways and colorectal cancer. *Lancet Oncol* 2005;6:322-7.
- [105] Mazumdar T, DeVecchio J, Agyeman A, Shi T, Houghton JA. The GLI genes as the molecular switch in disrupting Hedgehog signaling in colon cancer. *Oncotarget*. 2011;2:638-45.
- [106] Polkinghorn WR, Tarbell NJ. Medulloblastoma: tumorigenesis, current clinical paradigm, and efforts to improve risk stratification. *Nat Clin Pract Oncol* 2007;4:295-304.
- [107] Götschel F, Berg D, Gruber W, Bender C, Eberl M, Friedel M, et al. Synergism between Hedgehog-GLI and EGFR signaling in Hedgehog-responsive human medulloblastoma cells induces downregulation of canonical Hedgehog-target genes and stabilized expression of GLI1. *PLoS One* 2013;8:e65403.
- [108] Fogarty MP, Emmenegger BA, Grasdeder LL, Oliver TG, Wechsler-Reya RJ. Fibroblast growth factor blocks Sonic hedgehog signaling in neuronal precursors and tumor cells. *Proc Natl Acad Sci USA* 2007;104:2973-8.

- [109] Chow KH, Shin DM, Jenkins MH, Miller EE, Shih DJ, Choi S, et al. Epigenetic states of cells of origin and tumor evolution drive tumor-initiating cell phenotype and tumor heterogeneity. *Cancer Res* 2014;74:4864-74.
- [110] Samkari A, White JC, Packer RJ. Medulloblastoma: Toward Biologically Based Management. *Semin Pediatr Neurol* 2015;22:6-13.
- [111] Thaker NG, Pollack IF. Molecularly targeted therapies for malignant glioma: rationale for combinatorial strategies. *Expert Rev Neurother* 2009;9:1815-36.
- [112] Reinchisi G, Parada M, Lois P, Oyanadel C, Shaughnessy R, Gonzalez A, et al. Sonic Hedgehog modulates EGFR dependent proliferation of neural stem cells during late mouse embryogenesis through EGFR transactivation. *Front Cell Neurosci* 2013;7:166.
- [113] Hsieh A, Ellsworth R, Hsieh D. Hedgehog/GLI1 regulates IGF dependent malignant behaviors in glioma stem cells. *J Cell Physiol* 2011;226:1118-27.
- [114] Madhala-Levy D, Williams VC, Hughes SM, Reshef R, Halevy O. Cooperation between Shh and IGF-I in promoting myogenic proliferation and differentiation via the MAPK/ERK and PI3K/Akt pathways requires Smo activity. *J Cell Physiol* 2012;227:1455-64.
- [115] Dixit D, Ghildiyal R, Anto NP, Ghosh S, Sharma V, Sen E. Guggulsterone sensitizes glioblastoma cells to Sonic hedgehog inhibitor SANT-1 induced apoptosis in a Ras/NFκB dependent manner. *Cancer Lett* 2013;336:347-58.
- [116] O'Toole SA, Swarbrick A, Sutherland RL. The Hedgehog signalling pathway as a therapeutic target in early breast cancer development. *Expert Opin Ther Targets* 2009;13:1095-103.
- [117] Liu S, Dontu G, Mantle ID, Patel S, Ahn NS, Jackson KW, et al. Hedgehog signaling and Bmi-1 regulate self-renewal of normal and malignant human mammary stem cells. *Cancer Res* 2006;66:6063-71.
- [118] Fiaschi M, Rozell B, Bergström A, Toftgård R. Development of mammary tumors by conditional expression of GLI1. *Cancer Res* 2009;69:4810-7.
- [119] Neuzillet C, Tijeras-Raballand A, de Mestier L, Cros J, Faivre S, Raymond E. MEK in cancer and cancer therapy. *Pharmacol Ther* 2014;141:160-71.

- [120] Che J, Zhang FZ, Zhao CQ, Hu XD, Fan SJ. Cyclopamine is a novel Hedgehog signaling inhibitor with significant anti-proliferative, anti-invasive and anti-estrogenic potency in human breast cancer cells. *Oncol Lett* 2013;5:1417-21.
- [121] Chang H, Li Q, Moraes RC, Lewis MT, Hamel PA. Activation of Erk by sonic hedgehog independent of canonical hedgehog signalling. *Int J Biochem Cell Biol* 2010;42:1462-71.
- [122] Huang D, Ding Y, Luo WM, Bender S, Qian CN, Kort E, et al. Inhibition of MAPK kinase signaling pathways suppressed renal cell carcinoma growth and angiogenesis *in vivo*. *Cancer Res* 2008;68:81-8.
- [123] Dormoy V, Danilin S, Lindner V, Thomas L, Rothhut S, Coquard C, et al. The sonic hedgehog signaling pathway is reactivated in human renal cell carcinoma and plays orchestral role in tumor growth. *Mol Cancer* 2009 8:123.
- [124] Georgi B, Korzeniewski N, Hadaschik B, Grüllich C, Roth W, Sülthmann H, et al. Evolving therapeutic concepts in prostate cancer based on genome-wide analyses (review). *Int J Oncol* 2014;45:1337-44.
- [125] Zhu G, Zhou J, Song W, Wu D, Dang Q, Zhang L, et al. Role of GLI-1 in epidermal growth factor-induced invasiveness of ARCaPE prostate cancer cells. *Oncol Rep* 2013;30:904-10.
- [126] Hou X, Chen X, Zhang P, Fan Y, Ma A, Pang T, et al. Inhibition of hedgehog signaling by GANT58 induces apoptosis and shows synergistic antitumor activity with AKT inhibitor in acute T cell leukemia cells. *Biochimie* 2014;101:50-9.
- [127] Wickremasinghe RG, Prentice AG, Steele AJ. Aberrantly activated anti-apoptotic signalling mechanisms in chronic lymphocytic leukaemia cells: clues to the identification of novel therapeutic targets. *Br J Haematol* 2011;153:545-56.
- [128] Decker S, Zirlik K, Djebatchie L, Hartmann D, Ihorst G, Schmitt-Graeff A, et al. Trisomy 12 and elevated GLI1 and PTCH1 transcript levels are biomarkers for Hedgehog-inhibitor responsiveness in CLL. *Blood* 2012;119:997-1007.
- [129] Bai LY, Weng JR, Lo WJ, Yeh SP, Wu CY, Wang CY, et al. Inhibition of hedgehog signaling induces monocytic differentiation of HL-60 cells. *Leuk Lymphoma* 2012;53:1196-202.
- [130] Sengupta A, Banerjee D, Chandra S, Banerji SK, Ghosh R, Roy R, et al. Dereglulation and cross talk among Sonic hedgehog, Wnt, Hox and Notch signaling in chronic myeloid leukemia progression. *Leukemia* 2007;21:949-55.

- [131] Peacock CD, Wang Q, Gesell GS, Corcoran-Schwartz IM, Jones E, Kim J, et al. Hedgehog signaling maintains a tumor stem cell compartment in multiple myeloma. *Proc Natl Acad Sci USA* 2007;104:4048-53.
- [132] Liu Z, Li T, Reinhold MI, Naski MC. MEK1-RSK2 contributes to Hedgehog signaling by stabilizing GLI2 transcription factor and inhibiting ubiquitination. *Oncogene* 2014;33:65-73.
- [133] Kato Y, Kravchenko VV, Tapping RI, Han J, Ulevitch RJ, Lee JD. BMK1/ERK5 regulates serum-induced early gene expression through transcription factor MEF2C. *EMBO J* 1997;16:7054-66.
- [134] Voronova A, Al Madhoun A, Fischer A, Shelton M, Karamboulas C, Skerjanc IS. Gli2 and MEF2C activate each other's expression and function synergistically during cardiomyogenesis *in vitro*. *Nucleic Acids Res* 2012;40:3329-47.
- [135] Kamakura S, Moriguchi T, Nishida E. Activation of the protein kinase ERK5/BMK1 by receptor tyrosine kinases. Identification and characterization of a signaling pathway to the nucleus. *J Biol Chem* 1999;274:26563-71.
- [136] Mody N, Leitch J, Armstrong C, Dixon J, Cohen P. Effects of MAP kinase cascade inhibitors on the MKK5/ERK5 pathway. *FEBS Lett* 2001;502:21-4.
- [137] Rovida E, Spinelli E, Sdelci S, Barbetti V, Morandi A, Giuntoli S, et al. ERK5/BMK1 is indispensable for optimal colony-stimulating factor 1 (CSF-1)-induced proliferation in macrophages in a Src-dependent fashion. *J Immunol* 2008;180:4166-72.
- [138] Bubici C, Papa S. JNK signalling in cancer: in need of new, smarter therapeutic targets. *Br J Pharmacol* 2014;171:24-37.
- [139] Bigelow RL, Jen EY, Delehedde M, Chari NS, McDonnell TJ. Sonic hedgehog induces epidermal growth factor dependent matrix infiltration in HaCaT keratinocytes. *J Invest Dermatol* 2005;124:457-65.
- [140] Kakisaka K, Cazanave SC, Werneburg NW, Razumilava N, Mertens JC, Bronk SF, et al. A hedgehog survival pathway in 'undead' lipotoxic hepatocytes. *J Hepatol* 2012;57:844-51.
- [141] Zhan X, Wang J, Liu Y, Peng Y, Tan W. GPCR-like signaling mediated by smoothened contributes to acquired chemoresistance through activating Gli. *Mol Cancer* 2014;13:4.

- [142] Atkinson PJ, Dellovade T, Albers D, Von Schack D, Saraf K, Needle E, et al. Sonic Hedgehog signaling in astrocytes is dependent on p38 mitogen-activated protein kinase and G-protein receptor kinase 2. *J Neurochem* 2009;108:1539-49.
- [143] Desagher S, Glowinski J, Premont J. Astrocytes protect neurons from hydrogen peroxide toxicity. *J Neurosci* 1996;16:2553-62.
- [144] Douglas AE, Heim JA, Shen F, Almada LL, Riobo NA, Fernández-Zapico ME, et al. The α subunit of the G protein G13 regulates activity of one or more Gli transcription factors independently of smoothened. *J Biol Chem* 2011;286:30714-22.
- [145] Incardona JP, Gaffield W, Kapur RP, Roelink H. The teratogenic Veratrum alkaloid cyclopamine inhibits sonic hedgehog signal transduction. *Development* 1998;125:3553-62.
- [146] Cooper MK, Porter JA, Young KE, Beachy PA. Teratogen-mediated inhibition of target tissue response to Shh signaling. *Science* 1998;280:1603-7.
- [147] Amakye D, Jagani Z, Dorsch, M. Unraveling the therapeutic potential of the Hedgehog pathway in cancer. *Nature Medicine* 2013;19:1410-22.
- [148] Yauch RL, Dijkgraaf GJ, Alicke B, Januario T, Ahn CP, Holcomb T, et al. Smoothened mutation confers resistance to a Hedgehog pathway inhibitor in medulloblastoma. *Science* 2009;326:572-4.
- [149] Buonamici S, Williams J, Morrissey M, Wang A, Guo R, Vattay A, et al. Interfering with resistance to smoothened antagonists by inhibition of the PI3K pathway in medulloblastoma. *Science Translational Medicine* 2010;2:51ra70.
- [150] Lee MJ, Hatton BA, Villavicencio EH, Khanna PC, Friedman SD, Ditzler S, et al. Hedgehog pathway inhibitor saridegib (IPI-926) increases lifespan in a mouse medulloblastoma model. *Proc Natl Acad Sci USA* 2012;109:7859-64.
- [151] Lauth M, Bergström A, Shimokawa T, Toftgård R. Inhibition of GLI-mediated transcription and tumor cell growth by small-molecule antagonists. *Proc Natl Acad Sci USA* 2007;104:8455-60.
- [152] Hyman JM, Firestone AJ, Heine VM, Zhao Y, Ocasio CA, Han K, et al. Small-molecule inhibitors reveal multiple strategies for Hedgehog pathway blockade. *Proc Natl Acad Sci USA* 2009;106:14132-7.

- [153] Kim J, Lee JJ, Kim J, Gardner D, Beachy PA. Arsenic antagonizes the Hedgehog pathway by preventing ciliary accumulation and reducing stability of the Gli2 transcriptional effector. *Proc Natl Acad Sci USA* 2010;107:13432-7.
- [154] Li B, Fei DL, Flaveny CA, Dahmane N, Baubet V, Wang Z, et al. Pyrvinium attenuates Hedgehog signaling downstream of smoothened. *Cancer Res* 2014;74:4811-21.
- [155] Infante P, Mori M, Alfonsi R, Ghirga F, Aiello F, Toscano S, et al. Gli1/DNA interaction is a druggable target for Hedgehog-dependent tumors. *EMBO J* 2015;34:200-17.
- [156] Ericson J, Morton S, Kawakami A, Roelink H, Jessell TM. Two critical periods of Sonic Hedgehog signaling required for the specification of motor neuron identity. *Cell* 1996;87:661-73.
- [157] Stanton BZ, Peng LF, Maloof N, Nakai K, Wang X, Duffner JL, et al. A small molecule that binds Hedgehog and blocks its signaling in human cells. *Nat Chem Biol* 2009;5:154-6.
- [158] Akinleye A, Furqan M, Mukhi N, Ravella P, Liu D. MEK and the inhibitors: from bench to bedside. *J Hematol Oncol* 2013;6:27.
- [159] Villanueva J, Vultur A, Lee JT, Somasundaram R, Fukunaga-Kalabis M, Cipolla AK, et al. Acquired resistance to BRAF inhibitors mediated by a RAF kinase switch in melanoma can be overcome by cotargeting MEK and IGF-1R/PI3K. *Cancer Cell* 2010;18:683-95.
- [160] Serra V, Scaltriti M, Prudkin L, Eichhorn PJ, Ibrahim YH, Chandarlapaty S, et al. PI3K inhibition results in enhanced HER signaling and acquired ERK dependency in HER2-overexpressing breast cancer. *Oncogene* 2011;30:2547-57.
- [161] Arnault JP, Wechsler J, Escudier B, Spatz A, Tomasic G, Sibaud V, et al. Keratoacanthomas and squamous cell carcinomas in patients receiving sorafenib. *J Clin Oncol* 2009;27:e59-61.
- [162] Yaktapour N, Meiss F, Mastroianni J, Zenz T, Andrlova H, Mathew NR, et al. BRAF inhibitor-associated ERK activation drives development of chronic lymphocytic leukemia. *J Clin Invest* 2014;124:5074-84.
- [163] Morris EJ, Jha S, Restaino CR, Dayananth P, Zhu H, Cooper A, et al. Discovery of a novel ERK inhibitor with activity in models of acquired resistance to BRAF and MEK inhibitors. *Cancer Discov* 2013;3:742-50.

- [164] Huang S, He J, Zhang X, Bian Y, Yang L, Xie G, et al. Activation of the hedgehog pathway in human hepatocellular carcinomas. *Carcinogenesis* 2006;27:1334-40.
- [165] Von Hoff DD, LoRusso PM, Rudin CM, Reddy JC, Yauch RL, Tibes R, et al. Inhibition of the Hedgehog pathway in advanced basal-cell carcinoma. *N Engl J Med* 2009;361:1164-72.
- [166] Pan S, Wu X, Jiang J, Gao W, Wan Y, Cheng D, et al. Discovery of NVP-LDE225, a Potent and Selective Smoothed Antagonist. *ACS Med Chem Lett* 2010;1:130-4.
- [167] Chen JK, Taipale J, Young KE, Maiti T, Beachy PA. Small molecule modulation of Smoothed activity. *Proc Natl Acad Sci USA* 2002;99:14071-6.
- [168] Sandhiya S, Melvin G, Kumar SS, Dkhar SA. The dawn of hedgehog inhibitors: Vismodegib. *J Pharmacol Pharmacother* 2013;4:4-7.
- [169] Jimeno A, Weiss GJ, Miller WH, Jr., Gettinger S, Eigl BJ, Chang AL, et al. Phase I study of the Hedgehog pathway inhibitor IPI-926 in adult patients with solid tumors. *Clin Cancer Res* 2013;19:2766-74.
- [170] Munchhof MJ, Li Q, Shavnya A, Borzillo GV, Boyden TL, Jones CS, et al. Discovery of PF-04449913, a Potent and Orally Bioavailable Inhibitor of Smoothed. *ACS Med Chem Lett* 2011;3:106-11.
- [171] Wang C, Wu H, Katritch V, Han GW, Huang XP, Liu W, et al. Structure of the human smoothed receptor bound to an antitumour agent. *Nature* 2013;497:338-43.
- [172] Ishii T, Shimizu Y, Nakashima K, Kondo S, Ogawa K, Sasaki S, et al. Inhibition mechanism exploration of investigational drug TAK-441 as inhibitor against vismodegib-resistant Smoothed mutant. *Eur J Pharmacol* 2014;723:305-13.
- [173] Sala E, Mologni L, Truffa S, Gaetano C, Bollag GE, Gambacorti-Passerini C. BRAF silencing by short hairpin RNA or chemical blockade by PLX4032 leads to different responses in melanoma and thyroid carcinoma cells. *Mol Cancer Res* 2008;6:751-9.
- [174] Dudley DT, Pang L, Decker SJ, Bridges AJ, Saltiel AR. A synthetic inhibitor of the mitogen-activated protein kinase cascade. *Proc Natl Acad Sci USA* 1995;92:7686-9.
- [175] Favata MF, Horiuchi KY, Manos EJ, Daulerio AJ, Stradley DA, Feeser WS, et al. Identification of a novel inhibitor of mitogen-activated protein kinase kinase. *J Biol Chem* 1998;273:18623-32.

- [176] Sebolt-Leopold JS, Dudley DT, Herrera R, Van Becelaere K, Wiland A, Gowan RC, et al. Blockade of the MAP kinase pathway suppresses growth of colon tumors in vivo. *Nat Med* 1999;5:810-6.
- [177] Smith JA, Poteet-Smith CE, Xu Y, Errington TM, Hecht SM, Lannigan DA. Identification of the first specific inhibitor of p90 ribosomal S6 kinase (RSK) reveals an unexpected role for RSK in cancer cell proliferation. *Cancer Res* 2005;65:1027-34.
- [178] Lee JC, Laydon JT, McDonnell PC, Gallagher TF, Kumar S, Green D, et al. A protein kinase involved in the regulation of inflammatory cytokine biosynthesis. *Nature* 1994;372:739-46.
- [179] Shishodia S, Aggarwal BB. Guggulsterone inhibits NF-kappaB and IkappaBalpha kinase activation, suppresses expression of anti-apoptotic gene products, and enhances apoptosis. *J Biol Chem* 2004;279:47148-58.
- [180] Mohammadi M, Froum S, Hamby JM, Schroeder MC, Panek RL, Lu GH, et al. Crystal structure of an angiogenesis inhibitor bound to the FGF receptor tyrosine kinase domain. *EMBO J* 1998;17:5896-904.
- [181] Mohammadi M, McMahon G, Sun L, Tang C, Hirth P, Yeh BK, et al. Structures of the tyrosine kinase domain of fibroblast growth factor receptor in complex with inhibitors. *Science* 1997;276:955-60.
- [182] Ciardiello F, Caputo R, Bianco R, Damiano V, Fontanini G, Cuccato S, et al. Inhibition of growth factor production and angiogenesis in human cancer cells by ZD1839 (Iressa), a selective epidermal growth factor receptor tyrosine kinase inhibitor. *Clin Cancer Res* 2001;7:1459-65.
- [183] Hilgard P, Klenner T, Stekar J, Nössner G, Kutscher B, Engel J. D-21266, a new heterocyclic alkylphospholipid with antitumour activity. *Eur J Cancer* 1997;33:442-6.
- [184] Kondapaka SB, Singh SS, Dasmahapatra GP, Sausville EA, Roy KK. Perifosine, a novel alkylphospholipid, inhibits protein kinase B activation. *Mol Cancer Ther* 2003;2:1093-103.
- [185] Vlahos CJ, Matter WF, Hui KY, Brown RF. A specific inhibitor of phosphatidylinositol 3-kinase, 2-(4-morpholinyl)-8-phenyl-4H-1-benzopyran-4-one (LY294002). *J Biol Chem* 1994;269:5241-8.
- [186] Vézina C, Kudelski A, Sehgal SN. Rapamycin (AY-22,989), a new antifungal antibiotic. I. Taxonomy of the producing streptomycete and isolation of the active principle. *J Antibiot (Tokyo)*. 1975;28:721-6.
- [187] Sabers CJ, Martin MM, Brunn GJ, Williams JM, Dumont FJ, Wiederrecht G, et al. Isolation of a protein target of the FKBP12-rapamycin complex in mammalian cells. *J Biol Chem* 1995;270:815-22.

Table 1. HH-GLI and MAPK inhibitors cited in the text.

Inhibitors	Alternative name	Pathway inhibited	Target	References
Robotnikinin		HH-GLI	SHH	[157]
5E1 HH-blocking Ab		HH-GLI	SHH	[156]
Cyclopamine		HH-GLI	SMO	[145,146]
KAAD-cyclopamine		HH-GLI	SMO	[164]
Vismodegib	GCD-0449	HH-GLI	SMO	[165]
Sonidegib	Erismodegib/LDE-225	HH-GLI	SMO	[166]
Sant1-4		HH-GLI	SMO	[167]
BMS-833923		HH-GLI	SMO	[168]
Saridegib	IPI-926	HH-GLI	SMO	[169]
PF-04449913		HH-GLI	SMO	[170]
LY2940680		HH-GLI	SMO	[171]
LEQ-506		HH-GLI	SMO	NCT01106508*
TAK-441		HH-GLI	SMO	[172]
GANT-58,61		HH-GLI	GLI	[151]
HPI1-4		HH-GLI	GLI	[152]
ATO		HH-GLI	GLI	[153]
Pyrvinium		HH-GLI	GLI	[154]
Glabrescione B		HH-GLI	GLI	[155]
Vemurafenib	PLX4032	ERK1/2	BRAF ^{V600E}	[173]
PD98059		ERK1/2/5	MEK1/2/5	[135,136,174]
UO126		ERK1/2/5	MEK1/2/5	[135,136,175]
PD184352	CI-1040	ERK1/2/5	MEK1/2/	[136,176]
SCH772984		ERK1/2	ERK1/2	[163]
MK-8353	SCH900353	ERK1/2	ERK1/2	NCT01358331*
BVD-523		ERK1/2	ERK1/2	NCT01781429*
RG7842	GDC0994	ERK1/2	ERK1/2	Robarge et al. 2014**
SL0101		ERK1/2/5	RSK	[177]
SB202190		p38	p38 α	[178]
Guggulsterone		several	NFkB	[179]
PD173074		several	FGFR1	[180]
SU5402		several	FGFR1, VEGFR2	[181]
Gefitinib	ZD1839	EGFR	EGFR	[182]
Perifosine	D21266	PI3K/AKT	AKT	[183,184]
LY294002		PI3K/AKT	PI3K	[185]
Rapamycin	Sirolimus	PI3K/AKT	mTOR	[186,187]

Abbreviations: ATO, Arsenic trioxide; EGFR, Epidermal Growth Factor Receptor; ERK, Extracellular Signal-Regulated Kinase; FGFR, Fibroblast Growth Factor Receptor; MEK, MAPK/ERK Kinase; mTOR, Mammalian Target of Rapamycin; NFkB, Nuclear Factor kappa B; PI3K, Phosphatidylinositol 3-Kinase; RSK, Ribosomal S6 Kinase; SHH, Sonic Hedgehog; SMO, Smoothened; VEGFR, Vascular Endothelial Growth Factor Receptor.

*ClinicalTrials.gov identifier number was added in absence of published references; **Robarge K, Schwarz J, Blake J, Burkard M, Chan J, Chen H, et al. Discovery of GDC-0994, a potent and selective ERK1/2 inhibitor in early clinical development. Proceedings of the 105th Annual Meeting of the American Association for Cancer Research; 2014 Apr 5-9; San Diego, CA. Philadelphia (PA): AACR; Cancer Res 2014;74:Abstract nr DDT02-03.

Table 2. Experimental *in vitro* and *in vivo* models in which the MEK1/2-ERK1/2 module acts upstream of HH-GLI signaling.

Mechanism of action	Tumor type	Biological effects/function	Therapeutic implications*	References
MEK1/2 > ERK1/2 > GLI2/1	Keratinocytes	Increased GLI transcriptional activity, protein stability (GLI2 more than GLI1)	EGFRi + HHi	[67]
EGFR > MEK1/2 >	Keratinocytes	EGFRi (gefitinib) and HHi (GANT61	MEK1/2-ERK1/2i +	[68]

ERK1/2 > JUN/AP1 > GLI	/BCC	or Cyc) synergistically reduce mouse BCC cell growth	HH-GLIi	
RAS > RAF > MEK1/2 > GLI (counteracting SUFU)	Melanoma	Increased GLI transcriptional activity and nuclear localization	MEK1/2-ERK1/2i + HH-GLIi	[48]
RAS > RAF > GLI	Melanoma	BRAF ^{V600E} inhibition decreases GLI1 expression		[77]
RAS > RAF > GLI	Melanoma	Combination of SMOi (sonidegib) and BRAFi (vemurafenib) synergistically decreases melanoma cell proliferation	MEK1/2-ERK1/2i + SMOi	[76]
KRAS ^{G12D} > GLI2	PDA mouse model	KRAS ^{G12D} cooperates with Gli2 in PDA initiation <i>in vivo</i>		[92]
KRAS > GLI1	PDA mouse model	GLI1 is required for KRAS-mediated transformation of PDAC cancer cells		[93]
KRAS > RAF > MEK1/2 > GLI1	PDA	UO126 decreases GLI1 protein stability and suppresses anchorage-independent growth	MEK1/2-ERK1/2i + HH-GLIi	[90]
KRAS > MEK1/2 > ERK1/2 > GLI	Gastric cancer	KRAS enhances GLI transcriptional activity	MEK1/2-ERK1/2i + HH-GLIi	[86]
RAS > RAF > ERK1/2 > GLI1	Colon cancer	Cell death and DNA damage; MEK1/2i (UO126) decreases GLI1 expression		[105]
EGF —I HH	Medulloblastoma (Daoy)	EGF down-regulates HH target genes (including GLI1) independently of MEK1/2 and PI3K		[107]
bFGF —I HH	Cerebellar GCP/ Medulloblastoma	bFGF promotes GCP differentiation and blocks <i>Ptch</i> ^{+/-} medulloblastoma cell proliferation		[108]
EGF > ERK1/2 > GLI1	Prostate cancer	EGF signaling increases invasion <i>in vitro</i> ; GLI inhibition (GANT61) can reverse the enhanced invasive effect induced by EGF	MEK1/2-ERK1/2i + HH-GLIi	[125]
MEK1/2 > ERK1/2 > GLI	Acute T-cell leukemia	MEK1/2 (PD98059) enhances down-regulation of GLI1 protein by AKT inhibition		[126]
MEK1 > RSK2 > GLI2 (via GSK3β inhibition)	Multiple myeloma	Combination of GLIi (GANT58) and RSKi (SL0101) synergistically increases apoptosis	MEK1/2-ERK1/2i + GLIi	[132]

Abbreviations: AP1, Activator protein 1; BCC, Basal Cell Carcinoma; Cyc, cyclopamine; EGF, Epidermal Growth Factor; EGFR, Epidermal Growth Factor Receptor; ERK, Extracellular Signal-Regulated Kinase; bFGF, basic Fibroblast Growth Factor; GCP, Granule cell precursors; GSK3β, Glycogen Synthase Kinase 3β; HH, Hedgehog; MEK, MAPK/ERK Kinase; PDA, Pancreatic Ductal Adenocarcinoma; PI3K, Phosphatidylinositol 3-Kinase; Ptch, Patched; RSK, Ribosomal S6 Kinase; SUFU, Suppressor of Fused; EGFRi, EGFR inhibitors; HHi, Hedgehog inhibitors; HH-GLIi, Hedgehog-GLI inhibitors; SMOi, Smoothed inhibitors; GLIi, GLI inhibitors; MEK1/2-ERK1/2i, MEK1/2 or ERK1/2 inhibitors. Symbols: >, activation; —I, inhibition. *Suggestions for possible future preclinical and clinical studies have been reported.

Table 3. Experimental *in vitro* and *in vivo* models in which the HH-GLI signaling has been shown to act upstream of ERK1/2.

Mechanism of action	Tumor type	Biological effects/functions/functions	Therapeutic implications
HH-GLI > PDGFRα > ERK1/2	BCC	Proliferation <i>in vitro</i>	pERK1/2 as a readout; MEK1/2i-ERK1/2i resistance
HH-SMO > MEK1/2-ERK1/2	BCC	Survival <i>in vitro</i> ; MEK1/2-ERK1/2 inhibition by IFNα determines apoptosis	IFNα+HH-GLIi to induce apoptosis
BRAFi > HH/GLI > PDGFRα >	Melanoma	RAFi chemoresistance, proliferation <i>in vitro</i>	BRAFi+PDGFRαi

ERK1/2				a read out of BRA
HH-SMO > MEK1/2-ERK1/2	Esophageal cancer	Cell proliferation <i>in vitro</i>		pERK1/2 as a read HH/GLi+MEK1/2
HH-GLI > ERK1/2	Gastric cancer	Human cell line <i>in vitro</i>		pERK1/2 status as inhibition
HH > ERK1/2 (EGFR-, HER2-, GLI-independent)	Pancreatic tissue/cancer	PDEC growth <i>in vitro</i> . HH reduces MEK1/2- ERK1/2-dependent tumor cell growth <i>in vitro</i>		HH-GLi and/or M tumorigenesis; K-
HH-GLI > ERK1/2 > MMP9	Hepatocellular carcinoma	Invasion <i>in vitro</i>		MEK1/2-ERK1/2i (aggressive/invasi
HH-GLI // ERK1/2	Cholangiocarcinoma	Human cholangiocarcinoma cell lines <i>in vitro</i>		MEK1/2-ERK1/2i
PTCHi > ERK1/2	Medulloblastoma	<i>In vitro</i> sphere formation**		Combined HH-GL (HH subgroup)
HH-GLI > IGF1-IRS1 > MEK1/2-ERK1/2	Glioma (CSC)	<i>In vitro</i> CSC proliferation, clonogenicity, invasion**; resistance to temozolomide		MEK1/2-ERK1/2i to overcome resist
HH-GLi no effect on ERK1/2	Glioma (bulk)	GS enhances the inhibitory effect of SANT-1 (HHi) on cell growth while activating ERK1/2		
	Breast cancer	ERK1/2 is required for inhibition of proliferation by <i>cyc in vitro</i>		
HH-GLI > ERK1/2	Clear cell renal carcinoma	Cyc decreases ERK1/2 phosphorylation		MEK1/2-ERK1/2i
HH > PTCH > ERK1/2 (SMO independent)	chronic lymphocytic leukemia	ERK1/2 is involved in HH-GLI-dependent growth in patient-derived cells		MEK1/2-ERK1/2i SMOi resistance
SMO > ERK1/2	Acute myeloid leukemia	Cyc inhibits cell growth, induces monocytic differentiation and ERK1/2 dephosphorylation**		
HH-GLI // ERK1/2	Chronic myeloid leukemia			MEK1/2-ERK1/2i

Abbreviations: BCC, Basal Cell Carcinoma; CSC, Cancer Stem Cells; Cyc, Cyclopamine; EGFR, Epidermal Growth Factor Receptor; ERK, Extracellular Signal-Regulated Kinase; EGFR, Epidermal Growth Factor Receptor; GS, Guggulsterone; HER2, Human Epidermal Growth Factor Receptor 2; HH, Hedgehog; IFN α , Interferon α ; IGF1, Insulin-like Growth Factor 1; IRS1; Insulin Receptor Substrate 1; MEK, MAPK/ERK Kinase; MMP9, Matrix Metalloproteinase-9; PDEC, Pancreatic Duct Epithelial Cells; PDGFR α , Platelet-Derived Growth Factor Receptor α ; PTCH, Patched; SMO, Smoothened; MEK1/2-ERK1/2i, MEK1/2 or ERK1/2 inhibitors; HH-GLi, HH-GLI inhibition or inhibitors; SMOi, Smoothened inhibitors; anti-HHAb, anti-Hedgehog blocking antibodies (see the text for details). Symbols: >, activate; //, parallel signaling. *Suggestions for further preclinical and clinical studies have been reported; **a direct dependence of this biological effect on ERK1/2 activity has not been addressed.