PTEN Loss Mitigates the Response of Medulloblastoma to Hedgehog Pathway Inhibition


Abstract

Medulloblastoma is a cancer of the cerebellum, for which there is currently no approved targeted therapy. Recent transcriptomics approaches have demonstrated that medulloblastoma is composed of molecularly distinct subgroups, one of which is characterized by activation of the Hedgehog pathway, which in mouse models is sufficient to drive medulloblastoma development. There is thus considerable interest in targeting the Hedgehog pathway for therapeutic benefit in medulloblastoma, particularly given the recent approval of the Hedgehog pathway inhibitor vismodegib for metastatic and locally advanced basal cell carcinoma. Like other molecularly targeted therapies, however, there have been reports of acquired resistance to vismodegib, driven by secondary Hedgehog pathway mutations and potentially by activation of the phosphatidylinositol 3-kinase (PI3K) pathway. Given that acquired resistance to vismodegib may occur as a result of inappropriate PI3K pathway activation, we asked if loss of the PI3K pathway regulator, phosphatase and tensin homologue (Pten), which has been reported to occur in patients within the Hedgehog subgroup, would constitute a mechanism of innate resistance to vismodegib in Hedgehog-driven medulloblastoma. We find that Hedgehog pathway inhibition successfully restrains growth of Pten-deficient medulloblastoma in this mouse model, but does not drive tumor regression, as it does in Pten-wild-type medulloblastoma. Combined inhibition of the Hedgehog and PI3K pathways may lead to superior antitumor activity in PTEN-deficient medulloblastoma in the clinic. Cancer Res; 73(23); 7034–42. ©2013 AACR.

Introduction

Medulloblastoma is the most common malignant pediatric brain tumor, and is the leading cause of cancer-related mortality in childhood. Current available therapy consists of surgery, radiation therapy of the brain and spinal cord, followed by chemotherapy. Unfortunately, this aggressive therapeutic strategy is associated with serious adverse effects, including postoperative mutism, neurocognitive deficits, endocrinopathies, and increased susceptibility to secondary malignancies (1).

Recent transcriptional profiling has demonstrated that medulloblastoma is composed of 4 molecularly distinct subgroups: the Wnt subgroup, Sonic Hedgehog subgroup, Group 3, and Group 4 (2). The identification of these subgroups provides a much needed opportunity for the use of molecularly targeted therapeutics in medulloblastoma, which have the potential to both increase efficacy and reduce side effects when compared with the current standard of care. The Hedgehog subgroup, which makes up approximately 25% of medulloblastoma cases (3), may be particularly amenable to a targeted therapeutic approach, given the recent U.S. Food and Drug Administration approval of the Hedgehog pathway inhibitor, vismodegib (previously known as GDC-0449), in metastatic and locally advanced basal cell carcinoma (BCC).

Hedgehog signaling is critical for embryonic development and also plays a limited role in adult homeostasis. In the off-state, the transmembrane receptor Patched (PTCH) suppresses the activity of the GPCR-like molecule Smoothened (SMO). The Hedgehog ligands (Sonic, Indian, or Desert Hedgehog) activate the pathway by binding to PTCH, which releases its inhibition over SMO. SMO in turn signals to the GLI family of transcription factors and thus induces a change in the transcriptional profile of the cell (4). Inappropriate activation of the pathway, most often caused by inactivating mutations in PTCH, or activating mutations in SMO, is associated with cancer, predominantly BCC and medulloblastoma (5–8).

Vismodegib binds to, and inhibits SMO, blocking downstream Hedgehog pathway activation

In early-stage clinical studies, a patient with medulloblastoma from the Hedgehog subgroup harboring widespread metastatic disease, exhibited rapid and dramatic tumor regression when treated with vismodegib (9). Unfortunately, the robust initial response was followed by relapse, reminiscent of the acquired resistance seen in the context of other targeted therapies, such as erlotinib (10). Sequence analysis of a tumor...
biopsy obtained after progression in this patient indentified an amino acid substitution at a conserved residue of SMO. The D473H substitution disrupts the ability of vismodegib to bind SMO, but does not alter the ability of SMO to activate the Hedgehog pathway (11). This observation triggered a series of investigations into potential alternative mechanisms of resistance against vismodegib and sonidegib, another Hedgehog pathway inhibitor currently under clinical development (12). A variety of resistance mechanisms were identified through the use of mouse models, including additional mutations in SMO, as well as downstream Hedgehog pathway alterations such as Gli2 amplification (11, 13, 14). An additional, and unexpected potential mechanism of acquired resistance to sonidegib was the upregulation of PI3K signaling (13).

The PI3K pathway is a well-established oncogenic pathway that regulates cell growth, proliferation, and survival by relaying growth factor signaling (15). Aberrant activation of the PI3K pathway occurs in multiple tumor types and is frequently driven by disruptions in the negative pathway regulator PTEN, but can also be driven by gain-of-function mutations in PIK3CA. A recent genomic analysis of medulloblastoma tumors revealed that of 13 Hedgehog subgroup patients profiled, 2 had loss-of-function mutations in PTEN, and another patient had an activating mutation in PIK3CA (16). Of 66 patients profiled from the other subgroups, none had loss of PTEN, and 2 had mutations in PIK3CA. Another sequencing study similarly found a number of PTEN mutations in medulloblastoma tumors, one of which co-occurred with a homozygous PTCH mutation (17). In addition to genomic alterations as a mechanism to hyperactivate the PI3K pathway, epigenetic inactivation of PTEN has been reported to occur at a high frequency in medulloblastoma samples (18). Given that inappropriate activation of PI3K signaling may represent a potential mechanism of acquired resistance to Hedgehog pathway inhibitors, we wanted to determine if preexisting PTEN mutations, which occur in Hedgehog subgroup patients, would alter the initial response to vismodegib in Hedgehog-driven medulloblastoma.

Materials and Methods

Mouse models

Math1CreER and PtenloxP mouse strains were both obtained from The Jackson Laboratory (stock numbers 007684 and 004597, respectively), and the PchloxP strain was a kind gift from R. Toftgard and S. Teglund (Karolinska Institutet, Stockholm, Sweden; ref. 19). All mice were housed and maintained according to California State legal and ethical practices. Cre-dependent recombination was induced by oral gavage of the formula 1:500 for immunofluorescence and 1:1000 for Western blotting; Millipore, #MAB377), rabbit anti-Ki67 (1:300; Thermo Scientific, #BM9106), rabbit anti-pAkt 5473 (1:500 for IHC and 1:1000 for Western blotting; Cell Signaling Technology, #4060), rabbit anti-pS6 (1:1000; Cell Signaling Technology, #4858), rabbit anti-PTEN (1:100 for IHC and 1:1000 for Western blotting; Cell Signaling Technology, #9188), and rabbit anti-cleaved caspase-3 (1:100 for IHC; Cell Signaling Technology, #9661). The DAKO Envision+ horseradish peroxidase (DAB) system was used to detect primary antibodies for IHC. Images were acquired using a Zeiss Axioskop2 plus microscope fitted with an AxioCam Hrc or a Leica DMH400B fluorescence microscope. Adobe Photoshop CS3 was used to process images, and Fiji was used to quantify cleaved caspase-3 staining.

Generation of medulloblastoma allografts and drug treatments

To enable an assessment of the sensitivity of these medulloblastoma models to inhibition of the Hedgehog and PI3K pathways, tumor growth was relocated subcutaneously via grafting. The cerebella of mice displaying symptoms associated with medulloblastoma were harvested and prepared for subcutaneous inoculation into the right lateral thorax of female CD1-nude (CRL) mice aged at least 6 weeks, to establish passage 1. Allografts were generated via inoculation of a single cell suspension in 100 μL Neuralbasal Medium (Invitrogen; PM model, derived from PtchloxP/loxP, Math1CreER mice) or small tumor fragments (PPM model, derived from PtchloxP/loxP, Math1CreER mice). Serial in vivo propagation of the PPM model was repeated to generate sufficient tumor-bearing animals for drug treatment. Tumors were measured with calipers, and tumor volumes calculated using the formula $V = 0.5 \times \text{length} \times \text{width}^2$, where length and width represent perpendicular tumor diameters. As tumors reached 100 mm³, tumor-bearing animals were separated into groups of similarly sized tumors and drug administration was initiated. Compounds were formulated in 0.5% methylcellulose/0.2% Tween 80 (MCT) and mice were administered either vehicle or drug once daily (qd) by oral gavage; vismodegib and GNE-317 treatments were separated by 4 hours. To generate samples for pharmacodynamic analysis (quantitative PCR and Western blotting), tumor-bearing mice were treated for 3 consecutive days, and tumors were harvested 4 hours after the final dose.

Statistical methods

A mixed modeling approach was used to analyze the repeat-measurement of tumor volumes from the same animals over time (20). This approach addresses both repeated measurements and modest dropouts before study end. Restricted cubic splines were used to fit a nonlinear profile to the time courses of log₂(tumor volume) in each group. Fitting was done via a linear mixed effects model, using the R package nlme, version 3.1.97 in R version 2.12.0 (R Development Core Team 2008; R Foundation for Statistical Computing).

Tumor growth inhibition (TGI) as a percentage of vehicle control (%TGI) was calculated as the percentage of the area under the fitted tumor volume–time curve (AUC) on the linear
scale for the respective treatment group per day in relation to the starting volume on Day 0 (baseline) and in relation to the vehicle. As such, a TGI value of 100% indicates tumor stasis; a TGI value of >2% but <100% indicates tumor growth delay; and a TGI value of >100% indicates tumor regression and would be associated with a negative AUC.

To determine uncertainty intervals (UI) for %TGI, the fitted curve and the fitted covariance matrix were used to generate a random sample as an approximation to the distribution of %TGI. The random sample is composed of 1,000 simulated realizations of the fitted mixed model, in which the %TGI is recalculated for each realization. Our reported UI is the value for which 95% of the time the recalculated values of %TGI will fall in this region given the fitted model. The 2.5 and 97.5 percentiles of the simulated distribution were used as the upper and lower UIs, respectively. All TGI values were calculated at day 13 of the experiment, to allow for direct comparison across the two models; TGI cannot be calculated beyond day 13 in the PPM model as control/vehicle-treated tumor-bearing animals were euthanized before the end of the study, because tumor volumes exceeded 2,000 mm³.

Results

Loss of PTEN accelerates the onset of morbidity in a mouse model of Hedgehog-driven medulloblastoma

An earlier study showed that deletion of Ptc in cerebellar granule neural precursor cells (CGNP), which was achieved by crossing Math1CreER mice to Ptenlox/lox mice, resulted in the development of medulloblastoma, with 100% penetrance (21). For our studies, we combined this model with the previously described Ptenlox/lox mouse allele to generate Pchlox/lox, Ptenlox/lox, Math1CreER compound mutants (22). Similar to the previous report, Pchlox/lox; Math1CreER (hereafter referred to as PM) mice (induced with tamoxifen at E14.5) display signs of illness during early adulthood (6–10 weeks), which include a domed head and abnormal gait. Strikingly, loss of Pten in Pchlox/lox; Ptenlox/lox; Math1CreER (referred to as PPM) mice dramatically accelerates disease, with animals as young as 3 weeks of age presenting with ataxia; the median survival is 9.3 weeks in PM versus 4.0 weeks in PPM mice. Pchlox/lox; Ptenwt/wt; Math1CreER (PMwt/PM) littermates have an intermediate survival, with a median of 7.4 weeks (Fig. 1A). Importantly, loss of Pten alone in this model is not sufficient to initiate observable disease, as Pchwt/wt; Ptenlox/lox; Math1CreER mice survive long term with no symptoms.

Analysis of brain samples from PM and PPM mice revealed very large tumors within the cerebellum, which disrupt the normal cerebellar architecture (Fig. 1B–D). Histologically, tumors from PM mice resemble classic medulloblastoma, which is the histological subtype that predominates among human patients from the Hedgehog subgroup; these are frequently described as "small round blue-cell" tumors (Fig. 1C). In contrast, tumors from PPM mice have a markedly different appearance, with a histological phenotype analogous to medulloblastoma with extensive nodularity (MBEN), which in humans, is a histological subtype thought to be restricted to Hedgehog subgroup patients (3).

(1) Tumors from PMwt/PM mice are histologically indistinguishable from PPM tumors, with an MBEN appearance (Supplementary Fig. S1). The cerebella of Pchwt/wt; Ptenlox/lox; Math1CreER mice lack tumors, however, we did detect large ectopic cells both external to, and within the molecular layer (Supplementary Fig. S2).
Activation of PI3K signaling drives medulloblastoma cells toward a more differentiated phenotype

Immunohistochemical analysis revealed additional differences between PM and PPM tumors. PM tumors are largely made up of undifferentiated cells, positive for Ki67 and negative for the neuronal marker NeuN (Fig. 2A, see also Supplementary Fig. S3 for phospho-histone H3 IHC). Somewhat counterintuitively, the more aggressive PPM tumors have a high content of differentiated cells, positive for NeuN and negative for Ki67, with Ki67+ cells occurring sporadically within the tumor mass. Strikingly, in medulloblastoma tumors that are either PtenloxP/loxP or PtenloxP/wt, in addition to scattered Ki67 positive cells, we also find regions of Ki67+/NeuN− cells that occur as “stripes” (Fig. 2B, and Supplementary Fig. S3 for pH3 IHC). These proliferative stripes seem to localize to perivascular regions (see Fig. 2C, inset), an observation that was confirmed by EdU/CD31 double staining, in tumors harvested 2 hours after administration of the thymine analog (Fig. 2D). PM tumors have a relatively high level of baseline apoptosis, as revealed by the presence of cleaved caspase-3 (CC3), which seemed to be markedly reduced in PPM tumors (Fig. 2E and F). We used image analysis to quantify this apparent difference, taking into account the observation that in any field of view there seem to be more cells in the PM model than in the PPM model, and found that indeed, apoptosis is significantly suppressed in the PPM model (Fig. 2G, see also Supplementary Fig. S4 for an illustration how the image analysis was conducted).
Loss of PTEN in Hedgehog-driven medulloblastoma alters the response of tumors to vismodegib

The early onset of tumors in the PM and PPM models, the very rapid onset of morbidity of the PPM model in particular, and the lack of normal cerebellar tissue in this model, which would be required to maintain cerebellar functionality after targeting the tumor, prevented us from performing a vismodegib intervention study in the autochthonous setting. Fortunately however, the value and relevance of allograft studies in the context of medulloblastoma have previously been well established (11, 13, 14). Therefore, to evaluate the response of PM and PPM tumors to vismodegib, we generated allograft models; tumors harvested from PM and PPM animals were passaged subcutaneously in nude mice. This allowed tracking of tumor volumes over time, in response to various doses of drug (see also Materials and Methods). Although the histological characteristics distinguishing primary PM and PPM tumors do not seem to be strictly maintained in the allograft setting, key features, such as PTEN status and pAKT levels (Fig. 3A and B), are maintained. Note the loss of PTEN in PPM tumor cells, but not in stromal cells, consistent with the restriction of cre-recombinase activity to Math1-expressing neural progenitors. As expected, loss of PTEN is associated with robust upregulation of pAKT. In addition, PPM allografts seem to retain a somewhat more differentiated phenotype when compared with PM allografts, with apparent increases in NeuN levels (Fig. 3C), although the differentiation phenotype is less dramatic in the allografts when compared with the primary tumor.

Oral gavage of mice with 3 mg/kg vismodegib qd has little effect on allograft growth, in either model, despite having a modest effect on Hedgehog pathway activity (Fig. 4A, B, and D). This finding, that ~50% Hedgehog pathway inhibition is not sufficient to drive a tumor response, is consistent with the recent demonstration that sustained and robust inhibition of the Hedgehog pathway (>80%) is required for a meaningful antitumor effect (23). In contrast, 30 mg/kg vismodegib qd is sufficient to cause a meaningful growth delay in both models, with a mean TGI of 90% in the PM model, and 70% in the PPM model (Fig. 4A–C).

Interestingly, the response to vismodegib seems to diverge between the models at higher doses of vismodegib. In the PM model, vismodegib dosed at 60 and 90 mg/kg qd results in rapid and robust tumor regression, with 149% and 159% mean TGI, respectively; tumors continued to regress beyond day 13, and were barely detectable at day 21, when the study ended (Fig. 4A and C). In contrast, PPM tumors had not regressed by day 13, on either 60 or 90 mg/kg vismodegib, with a mean TGI of less than 100% in both cases (87% and 90%); rather, these doses achieved tumor stasis by the end of the study, despite a comparable level of Hedgehog pathway inhibition (Fig. 4D).

Combined PI3K and Hedgehog pathway inhibition drives tumor regression in the PPM model

GNE-317 is a PI3K/mTOR pathway inhibitor that was specifically designed to cross the blood–brain barrier, with the treatment of PI3K pathway-driven glioblastoma as the primary objective (24). We made use of this previously described compound to ask if inhibition of the Hedgehog pathway in combination with inhibition of PI3K signaling, would improve on vismodegib as a single agent. GNE-317 when dosed at 30 mg/kg qd successfully attenuates PI3K signaling in the allograft setting, as measured by pS6 levels (Fig. 5A), and by pAKT levels (Supplementary Fig. 5), but does not alter levels of Hedgehog pathway activity (Fig. 4D). Similarly, 90 mg/kg vismodegib does not influence activation of the PI3K pathway in this setting (Supplementary Fig. 5). GNE-317, as a single agent, achieved modest inhibition of tumor growth in the PM model, and a more meaningful inhibition of growth in the PPM model (mean TGI 37% and 66%, respectively; Fig. 5B–D). In the PPM model, although vismodegib treatment alone did not drive regression at any
concentration tested, GNE-317 treatment, when combined with either 60 or 90 mg/kg vismodegib, resulted in tumor regression (Fig. 5B and D). At 60 mg/kg vismodegib plus GNE-317, mean tumor volume at the study start was 232 mm³, which regressed to 152 mm³ on day 13 and 100 mm³ by the study endpoint. At 90 mg/kg vismodegib plus GNE-317, mean tumor volume at the study start was 244 mm³, which regressed to 102 mm³ on day 13 and 80 mm³ by the study end. It is also worth noting that the regression driven by the combination of GNE-317 plus 90 mg/kg vismodegib is highly consistent across individual tumors/animals (Fig. 5D).

Discussion

Inherited mutations in PI3K signaling components are associated with human syndromes that include neurological abnormalities, such as Lhermitte–Duclos disease, indicating that this pathway is important in normal neural development and/or function (25). Indeed, 2 independent mouse studies described the use of GfapCre to delete Pten in the brain, and showed that this led to lethal neurological defects including seizures and ataxia, which were coupled to an enlargement of the cerebellum (25, 26). Histological analysis revealed the presence of ectopic, enlarged cells at the pial surface and within the molecular layer of the cerebellum, which was attributed to a migration defect in mutant cells. Histologically, this phenomenon is very similar to the phenotype seen in Pchwt/wt; Ptenloxp/loxp; Math1CreER mice, although the mice described here do not display any overt clinical symptoms, potentially because of incomplete deletion of PTEN driven by the Math1CreER (Supplementary Fig. S2). A more recent study demonstrated that postnatal deletion of PTEN in migrating neuroblasts in the rostral migratory stream resulted in ectopic positioning and altered morphology of neurons. The authors argue that the migration defect associated with PTEN loss was likely secondary to precocious differentiation, rather than a defect in the mechanics of directional migration (27). The highly differentiated nature of the tumors in PPM mice described here, as well as NeuN expression in ectopic cells in the cerebella of Pchwt/wt; Ptenloxp/loxp; Math1CreER mice, supports the notion that loss of PTEN may drive precocious/ premature differentiation in neurons, although the presence of PTEN-deficient neurons within the inner granule layer (IGL) argues against a migration defect of these cells. Perhaps most relevant, the RCAS/tv-a system, which allows postnatal gene transfer in a cell-type-specific manner, was used to generate...
medulloblastoma by targeting SHH to nestin-expressing neural stem cells, either in the presence or absence of PTEN (28). Intriguingly, PTEN-deficient tumors were described as having MBEN histology, with high levels of NeuN, very similar to the PPM model described here. Moreover, the perivascular niche of these tumors was described as being highly proliferative, "in fact the only proliferative region in the tumors," again, very similar to the PPM model described here. We propose that these proliferative cells in the perivascular niche are major contributors to tumor growth. A different study, using a constitutively active mutant of Smo, SmoA1, to induce medulloblastoma in Pten−/− mice similarly demonstrated that activation of PI3K signaling accelerated tumorigenesis while driving a switch from classic to MBEN histology, and concomitantly increased neuronal differentiation (29). Notably though, blocking apoptosis in a SmoA1 model of medulloblastoma, by deleting proapoptotic Bax resulted in a very similar phenotype: a paradoxical increase in differentiation coupled to acceleration of disease (30). Strikingly, SmoA1; Bax−/− tumors seem indistinguishable from the PPM tumors described here (see Fig. 5, Garcia et al.). The authors propose a model in which medulloblastoma cells face a cell fate choice between apoptosis and differentiation; those cells that are competent to undergo apoptosis will do so and will thus be lost from the tumor, resulting in tumor turnover. In contrast, cells incapable of launching an apoptotic program will adopt a terminally differentiated fate, leading to the accumulation of differentiated cells. The differentiated, nonapoptotic, and aggressive phenotype of the PPM model described here, together with the established role of PI3K signaling in promoting cell survival, is in line with this fate choice model.

Despite the profound changes that occur in PTEN-deficient tumors with respect to PTEN wild-type tumors, PPM allografts are responsive to vismodegib: inhibition of the Hedgehog pathway restrains tumor growth and results in stasis, suggesting that even in the context of PTEN loss, tumors remain highly dependent on Hedgehog pathway activity for growth. Truly resistant tumors, for example allografts that harbor the mouse
equivalent of the patient-derived SMO D473H mutation described above, continue to grow robustly in the presence of 75 mg/kg vismodegib (11). Importantly then, although hyperactivation of PI3K signaling prevents regression of tumors in response to Hedgehog pathway inhibition, it does not confer \textit{bona fide} resistance. Nevertheless, the distinction between stasis and regression is of critical importance, and raises a key question: how is regression driven by Hedgehog pathway inhibition in the PM model, and how is this altered by the loss of \textit{Pten}? Another open question relates to the durability of the drug response in these models; specifically how the durability is influenced by the lack of regression in vismodegib-treated \textit{Pten} mutant tumors. It is likely that in the absence of complete regression, discontinuation of drug treatment will lead to immediate reinitiation of tumor growth, as occurs in \textit{Ptc}^{-/-}; \textit{ps3}^{-/-} allograft tumors (11).

Our findings have significant implications for the clinical development of Hedgehog pathway inhibitors in medulloblastoma, which are currently ongoing (see clinicaltrials.gov, and refs. 31–33) for descriptions of Hedgehog pathway inhibitors currently under clinical development). In the case of BCC, for which vismodegib is now approved, the vast majority of tumors display alterations in the Hedgehog pathway, and there is no current requirement for the stratification of patients. However, the additional genomic complexity seen in patients with medulloblastoma means that it will be critical to preselect the \textasciitilde{}25\% of patients who are defined as the Hedgehog subgroup. Based on the data described here, we now argue that it will also be important to monitor PI3K pathway status during patient selection, particularly in cases where a positive clinical trial outcome is defined by regression, rather than stasis. The diagnostic strategy, which will enable the selection of patients who may respond to Hedgehog pathway inhibitors as a single agent, versus those who might benefit from a combined regime of a Hedgehog pathway inhibitor plus a brain penetrant PI3K inhibitor, will require careful consideration, given that PI3K pathway alterations in medulloblastoma have been reported not only at the genomic, but also at the epigenetic level (16, 18). It will also be critical to determine if and how other alterations that have been reported to occur in the Hedgehog subgroup, such as \textit{N-myc} amplification, will alter the response of Hedgehog-driven medulloblastoma to Hedgehog pathway inhibition.

Disclosure of Potential Conflicts of Interest
C. Metcalfe is employed as a postdoctoral fellow in Genentech Inc. A. Crow is employed as a senior research associate in Genentech Inc. F.V. Peale is employed as a senior pathologist in Genentech, Inc. F.V. Peale also has ownership interest (including patents) in Roche. F.J. de Sauvage has ownership interest (including patents) in Roche. No potential conflicts of interest were disclosed by the other authors.

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