Heterozygosity for Pten Promotes Tumorigenesis in a Mouse Model of Medulloblastoma

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Abstract

Background: Recent publications have described an important role for cross talk between PI-3 kinase and sonic hedgehog signaling pathways in the pathogenesis of medulloblastoma.

Methodology/Principal Findings: We crossed mice with constitutive activation of SmoA1, with Pten deficient mice. Both constitutive and conditional Pten deficiency doubled the incidence of mice with symptoms of medulloblastoma and resulted in decreased survival. Analysis revealed a clear separation of gene signatures, with up-regulation of genes in the PI-3 kinase signaling pathway, including downstream activation of angiogenesis in SmoA1+/--; Pten +/- medulloblastomas. Western blotting and immunohistochemistry confirmed reduced or absent Pten, Akt activation, and increased angiogenesis in Pten deficient tumors. Down-regulated genes included genes in the sonic hedgehog pathway and tumor suppressor genes. SmoA1+/--; Pten +/- medulloblastomas appeared classic in histology with increased proliferation and diffuse staining for apoptosis. In contrast, Pten deficient tumors exhibited extensive nodularity with neuronal differentiation separated by focal areas of intense staining for proliferation and virtually absent apoptosis. Examination of human medulloblastomas revealed low to absent PTEN expression in over half of the tumors. Kaplan-Meier analysis confirmed worse overall survival in patients whose tumor exhibited low to absent PTEN expression.

Conclusions/Significance: This suggests that PTEN expression is a marker of favorable prognosis and mouse models with activation of PI-3 kinase pathways may be important for preclinical evaluation of promising agents for the treatment of medulloblastoma.

Introduction

Medulloblastoma is the most common malignant brain tumor of childhood. Multimodality treatment with surgery, radiation, and chemotherapy cures many patients, but often leaves survivors devastated with long-term toxicities that affect their neurocognitive and growth potential. Despite clinical advances, up to 30% of children with medulloblastoma experience tumor progression or recurrence, for which no curative therapy exists. The lack of more effective, less toxic therapies stems from our imperfect understanding of medulloblastoma tumor biology.

Currently, patients diagnosed with medulloblastoma are treated based upon disease stage, age at diagnosis, and extent of resection using a combination of surgery, chemotherapy, and ionizing radiation (IR) [1]. The importance of histology in tumor biology and treatment responsiveness has been controversial. The World Health Organization (WHO) currently recognizes at least 5 subtypes of medulloblastoma: classic, desmoplastic, extensive nodularity (MBEN), large-cell, and anaplastic [2]. While large-cell and anaplastic medulloblastomas tend to behave more aggressively and desmoplastic and MBEN tumors tend to be associated with a better prognosis for survival, medulloblastomas often contain cells of more than one histology [3,4]. In addition, factors such as age and disease stage have been associated with worse prognosis independent of histology and treatment protocols do not currently stratify patients based on tumor histology.

In an effort to improve treatment, tumors have also been classified based upon their cytogenetic and gene expression profiles [5,6]. Losses on chromosome 17q, the most common cytogenetic abnormality in human medulloblastoma, have been associated with classic or large-cell histology, while losses on 9q have been associated with desmoplastic tumors. Cytogenetic analyses have
also identified frequent allelic loss of chromosome 10q23.31, the locus of phosphatase and tensin homolog, PTEN, in human medulloblastomas [7]. PTEN dephosphorylates phosphatidylinositol-3,4,5-triphosphate (PIP3), and is a major inhibitor of signaling through the phosphatidylinositol 3-kinase (PI-3 kinase) pathway. Activation of PI-3 kinase signaling is a major driving force in progression of a majority of human neoplasms, including brain tumors [8]. Studies of human medulloblastoma have reported decreased expression of PTEN mRNA and protein, compared to normal cerebellum controls. In addition, the PTEN promoter has been found to be hypermethylated in 5 of 10 human cases of medulloblastoma. And, Immunohistochemistry (IHC) has detected increased staining for activated AKT in human medulloblastoma tissues, consistent with loss of upstream inhibition by PTEN [9]. We hypothesized that increased signaling through PI-3 kinase may influence medulloblastoma tumorigenesis in a mouse model.

We used the SmoA1 transgenic mouse model of medulloblastoma [10] to study the effect of Pten loss on medulloblastoma tumorigenesis. We found that heterozygosity for Pten, in the context of constitutive overexpression of SmoA1, altered tumor histology and accelerated medulloblastoma tumorigenesis in SmoA1 +/+; Pten +/− mice. Analysis by gene expression microarray revealed a clear separation of gene signatures, with downstream activation of angiogenesis and down-regulation of genes involved in cell cycle regulation in SmoA1+/−; Pten +/+− medulloblastomas. Western blotting and IHC confirmed PI-3 kinase pathway activation and increased angiogenesis in Pten deficient tumors. Compared to tumors from control mice, SmoA1+/−; Pten +/− tumors exhibited extensive nodularity with neuronal differentiation separated by focal areas of intense staining for proliferation and virtually absent apoptosis.

Examination of human medulloblastoma tissue microarrays revealed a significant association between PTEN loss and poor survival. PTEN expression was low to absent in over half of human medulloblastomas. The majority of those dead of disease had low to absent PTEN expression. Kaplan-Meier analysis confirmed worse overall survival in patients whose tumor exhibited low to absent PTEN protein expression, suggesting that PTEN expression is an important marker of prognosis in medulloblastoma.

Results

Heterozygosity for Pten promotes tumorigenesis in a mouse model of medulloblastoma

Approximately 50% of mice expressing one allele of SmoA1, SmoA1+/−, and 75% of mice expressing two alleles of SmoA1, SmoA1+/+, developed symptoms of medulloblastoma by 1 year of age (Figure 1A, Table S1). When SmoA1 mice were crossed with Pten +/− mice, 97.9% of the SmoA1+/−; Pten +/− offspring followed over the same time interval exhibited symptoms of medulloblastoma. All symptomatic animals were necropsied and found to have visible tumor in the posterior fossa and tumor histology consistent with medulloblastoma. SmoA1+/−; Pten +/− mice exhibited decreased survival compared to SmoA1+/−; Pten +/− or to SmoA1+/−; Pten +/+ mice (p<0.0001, Log-rank) (Figure 1B).

We confirmed this finding using mice that express the SmoA1 transgene, SmoA1+, and conditional, partial deletion of Pten, Pten (LoxP/−), in cells of neuronal lineage. In these triple transgene-positive mice, Cre was expressed under control of the Nestin gene promoter, Nestin-cre. We have not yet been able to generate mice that have complete deletion of Pten in Nestin-positive cells. However, we have evidence that conditional, partial knock-out of Pten, SmoA1+, Pten (LoxP/−); Nestin-cre+, accelerates medulloblastoma formation compared to controls, SmoA1+; Pten (LoxP/−); Nestin-cre− (Figure 1B). Mice with global Pten deficiency developed symptoms of medulloblastoma at a median age of 11.8±1.4 weeks and mice with conditional, partial knock-out of Pten developed symptoms at a median age of 13.2±1.7 weeks. In comparison, control SmoA1+; Pten +/+ and SmoA1+; Pten (LoxP/−); Nestin-cre− mice developed symptoms at median ages of 23.2±2.1 weeks, respectively (Figure 1C).

Loss of a single allele for Pten drives medulloblastoma histology to extensive nodularity

Mice that expressed the SmoA1 transgene and that were either wild-type (+/+ or deficient (+/−) in expression of Pten were prone to development of tumor in the developing mouse cerebellum. Tumor was not identified in other areas of the mouse brain. The cerebellar tumors in this study varied in histologic appearance by whether the animal was homozygous or heterozygous for Pten, with the histologies corresponding to patterns of human medulloblastoma. The tumors in the SmoA1+; Pten +/− mice showed a uniform pattern of “small round blue cells” arranged in sheets with molding of the tumor cell nuclei against each other and numerous mitoses and karyorhectic tumor nuclei, recapitulating the appearance of classic medulloblastomas in humans. In contrast, the tumors from SmoA1+; Pten +/− mice were biphasic, with areas that were histologically identical to the tumors from SmoA1+; Pten +/+ mice, but also with large nodular areas of increased neuronal differentiation. These nodular areas were less cellular and had round nuclei that were arranged in a streaming pattern over a background of neuronal fibrillarity, similar to the appearance of the nodules of medulloblastomas with extensive nodularity (MBEN) in humans. Only rare mitoses and karyorhectic nuclei could be identified in nodular areas (Table S2). This finding was confirmed in animals with conditional, partial knock-out of Pten, SmoA1+; Pten (LoxP/−); Nestin-cre+, which developed medulloblastomas with MBEN histology. Control SmoA1+; Pten (LoxP/−); Nestin-cre− animals developed medulloblastomas with classic histology (Data not shown).

SmoA1+; Pten +/− medulloblastomas exhibit increased signaling through PI-3 kinase pathways

SmoA1+; Pten +/+ mouse medulloblastomas exhibited diffuse expression of Pten in tumor cells. In contrast, Pten expression was virtually absent in medulloblastomas from SmoA1+; Pten +/− mice, except in the areas around blood vessels (Figure 2A, black arrow). As expected, there was much stronger staining for activated Akt, phosphorylated on serine 473, in medulloblastoma tumors from SmoA1+; Pten +/− mice (Figure 2A, white arrow). By western blotting, we confirmed reduced Pten expression and increased expression of activated Akt, phosphorylated on serine 473, in SmoA1+; Pten +/− medulloblastomas (Figure 2B). Total Akt expression was equivalent among SmoA1+; Pten +/+ and SmoA1+; Pten +/− tumors.

To confirm our findings from IHC and western blotting, we extracted RNA from SmoA1+; Pten +/+ and SmoA1+; Pten +/− medulloblastomas, and hybridized labeled RNA to mouse Illumina microarray BeadChips for analysis of differential gene expression. Unsupervised hierarchical clustering revealed 2,724 probes that were differentially regulated between the two tumor types, including 1,511 probes that were overexpressed and 1,213 probes that were underexpressed in tumors from SmoA1+; Pten +/− mice (Figure 2C, left panel).

To assess the effects of Pten deficiency on molecular pathways that promote tumorigenesis, we used the KEGG (Kyoto
Encyclopedia of Genes and Genomes) [11] and Gene Ontology [12] databases. SmoA1 +/− mice expressed 1.1-fold less Pten mRNA than SmoA1 +/+ tumors. This result failed to achieve statistical significance, likely due to the low mRNA levels in SmoA1 +/− tumors. However, mRNA transcripts for components of the PI-3 kinase enzyme complex, Pik3r3 and Pik3cb, and downstream targets of PI-3 kinase signaling, Mapk8 (Jnk) and Frap1 were up regulated 2.8, 1.9, 1.5, and 1.2-fold, respectively (Figure 2C, Table S3) in Pten deficient medullo- blastomas.

Pik3cb codes for the p110β catalytic subunit of PI-3 kinase and has been implicated as a driving force in PTEN-deficient tumors. Although activation of p110α (PI3KCA) is required to sustain the proliferation of established PIK3CA-mutant tumors, some PTEN-deficient tumors have been found to depend instead on signaling through p110β [14]. Frap1 in mice codes for

Figure 1. Compound SmoA1, Pten heterozygotic mice exhibit an increased incidence of medulloblastoma and reduced survival. SmoA1 +/- mice were crossed with Pten +/- mice and followed for symptoms. (A) Observed tumor incidence in Pten deficient versus control mice over the course of 1 year. (B) Kaplan-Meier survival analysis of SmoA1 +/-; Pten +/- (n = 43) and SmoA1 +/-; Pten (LoxP/LoxP); Nestin-cre +/− (n = 8) mice, compared to SmoA1 +/-; Pten +/- (n = 127) and SmoA1 +/-; Pten (LoxP/LoxP); Nestin-cre -/+ (n = 7) (p<0.0001, Log-rank) controls. (C) Mice with global Pten deficiency as well as those with conditional, partial knock-out of Pten developed symptoms earlier than controls (p<0.000001 and <0.005, respectively). doi:10.1371/journal.pone.0010849.g001
Figure 2. Pten deficiency activates PI-3 kinase signaling and drives medulloblastoma histology from classic to extensive nodularity. (A) SmoA1 +; Pten +/+ medulloblastomas demonstrated classic histology; SmoA1 +; Pten +/− tumors were extensively nodular in histology. Pten
deficient tumors exhibited focal regions of intense staining for activated Akt (white arrow) and virtually absent staining for Pten. Only regions around blood vessels (black arrow) stained positive for Pten in SmoA1 +/-; Pten +/- tumors. (B) Western blotting revealed decreased expression of Pten and increased activation of Akt in SmoA1 +/-; Pten +/- medulloblastomas (n = 3), compared to controls (n = 7). (C) Total RNA was extracted from SmoA1 +/-; Pten (+/+) (n = 4) and SmoA1 +/-; Pten +/- (n = 8) medulloblastomas and hybridized to Illumina mouse microarray chips. Expression of genes involved in PI-3 kinase signaling was up-regulated in Pten deficient tumors. Red pixels represent increased expression and green pixels represent decreased expression. Each column corresponds to mRNA extracted from an individual mouse medulloblastoma. The blue bar at the top of each heatmap indicates Pten +/- and the yellow bar indicates Pten +/- tumors.

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the mammalian target of rapamycin (mTOR), a known downstream target of PI-3 kinase. Development of prostate cancer in a mouse model with deletion of Pten specifically in prostate epithelium has been shown to require mTORC2, the mTOR complex 2 that contains the mTOR kinase and the Rictor regulatory protein [15].

**Pten +/- medulloblastomas down-regulate expression of targets of sonic hedgehog (Shh) signaling**

Of interest is our finding that expression of genes involved in development of the cerebellum and in medulloblastoma tumorigenesis was decreased in SmoA1 +/-; Pten +/- mouse tumors. Numerous studies have implicated Shh signaling in medulloblastoma pathogenesis, and modulation of this pathway has led to the vast majority of mouse models of medulloblastoma currently available. In addition, inactivating mutations of PTCH1 and SUFU and activating mutations of SMOH account, in total, for at least 20% of all cases of medulloblastoma in humans [1]. In spite of the fact that both Pten +/- and Pten +/- tumors expressed the SmoA1 transgene by tail DNA genotyping, the expression of multiple genes in the Shh-Smo signaling pathway was down regulated in Pten +/- medulloblastomas (Figure 3A). Notably, multiple probes for Gli2 and Smo were attenuated by 4.2, and 3.2-fold respectively (Table S3). Using real-time, RT-PCR we confirmed down-regulated expression of mRNA for downstream targets of Smo/Smoothened. Relative expression of Gli1, Gli2, N-myc, and cyclin-D1 was decreased 5.6, 7.6, 4.3, and 2.8-fold (p<0.05 for all transcripts), respectively in SmoA1 +/-; Pten +/- medulloblastomas (Figure 3B). IHC showed less intense staining for the Shh-signaling target Gli2 in nodules of SmoA1 +/-;Pten +/- medulloblastomas (Figure 3C). In comparison, the genes Wnt3 and Wnt7a, which were found to be up-regulated by gene expression microarray analysis, were validated as up-regulated by real-time, RT-PCR and western blotting in SmoA1 +/-; Pten +/- medulloblastomas (Figure S1). Since Gli2 is well-recognized as the main transcriptional effector of Shh signaling in granule neuron precursor cells that form the cerebellum [16], this suggests that loss of Pten may actually attenuate signaling through Shh signaling pathways.

**Pten deficiency promotes neuronal differentiation in mouse medulloblastomas**

Gene expression also revealed significant up-regulation of genes that promote neuronal differentiation and plasticity in SmoA1 +/-; Pten +/- medulloblastomas. mRNA transcripts for Bdnf (Brain-derived neurotrophic factor), NeuN (Neuronal homolog), Id4 (Inhibitor of DNA binding 4), and Neurod2 (Neurogenic differentiation 2) were up-regulated 5, 3.7, 2.7, and 2.2-fold in SmoA1 +/-; Pten +/- medulloblastomas (Figure S2A). Inactivation of Pten has been shown to promote Bdnf-mediated activation of Akt in cultures of rat primary neurons [17]. In addition, the transcription factor, Neurod2, is known to induce neuronal differentiation and promote survival of mature neurons [18]. To validate our findings from gene expression microarrays, we examined mouse medulloblastomas for markers of cell lineage using IHC. We observed intense staining for the marker of differentiated neurons, NeuN, in Pten deficient medulloblastomas and virtually no NeuN staining in SmoA1 +/-; Pten +/- tumors (Figure S2B). As a positive control, NeuN positive neurons were visualized in their expected location, in the internal granular layer (IGL) of the cerebellum, in both tumor types. Double-staining of tumor sections with an antibody against the proliferation marker PCNA and an anti-NeuN antibody revealed diffuse proliferation with scattered areas of staining for NeuN in SmoA1 +/-; Pten +/- medulloblastomas. Pten deficient tumors, in contrast, displayed larger islands of neuronal differentiation (Figure S2C, brown staining), surrounded by and distinct from PCNA positive (Figure S2C, red staining) areas of proliferation. Neither tumor type stained positive for the marker of astrocytic differentiation, GFAP (Figure S2D). Staining for synaptophysin, a marker of primitive neurons was weak in both tumor types, but appeared to overlap with staining for PCNA (Figure S2E). Thus, Pten deficiency appears to promote neuronal differentiation of medulloblastoma cells. The differentiated cells are juxtaposed with, but distinct from cells that are actively proliferating and that display features of immature neurons.

**SmoA1 +/-; Pten +/- medulloblastomas exhibit up-regulation of angiogenesis**

Downstream of signaling through PI-3 kinase, PTEN has been shown to play a key role in regulating angiogenesis in brain tumors [8]. Shh signaling has also been described as crucial for angiogenesis during embryonic development [19]. However, the role of angiogenesis in human medulloblastomas has not been explored extensively. We identified up-regulated expression of numerous genes in SmoA1 +/-; Pten +/- medulloblastomas that have been implicated in angiogenesis (Figure 4A). Notable genes include Vegf, Flt1, and Hbegf, which were up regulated 2.3, 2.1, and 1.0-fold, respectively in SmoA1 +/-; Pten +/- tumors (Table S3). Real-time, RT-PCR confirmed 2.4-fold increased median expression of Vegfa mRNA in medulloblastomas extracted from Pten deficient mice (n = 7), compared to controls (n = 4) (p = 0.005) (Figure 4B).

IHC of tumor tissue verified increased angiogenesis in SmoA1 +/-; Pten +/- medulloblastomas. Staining of OCT-embedded tumor tissue with an antibody against the endothelial antigen CD31, revealed increased staining for CD31-positive blood vessels in SmoA1 +/-; Pten +/- tumors (Figure 4C, small black arrow). We confirmed these findings by probing paraffin-embedded tissues for expression of the hematopoietic stem cell marker, CD34. Medulloblastomas from SmoA1 +/-; Pten +/- mice exhibited increased staining for CD34 and evidence of larger-bore blood vessels (Figure 4G, large black arrow).

**SmoA1 +/-; Pten +/- medulloblastomas exhibit increased proliferation and decreased apoptosis**

Gene expression also revealed significant down-regulation of genes that control progression through the cell cycle in SmoA1 +/-; Pten +/- medulloblastomas (Figure 5A). Expression of the key cell cycle regulators Tip53, Bica2, and Rb1 was down regulated 2.5,
1.9, and 1.8-fold, respectively (Table S3). Western blotting confirmed overall lower expression of Trp53 in SmoA1; Pten +/+; Pten +/− mouse medulloblastomas (Data not shown).

IHC analysis identified islands of intense staining for the proliferation marker PCNA, surrounded by relatively quiescent areas in Ptten deficient medulloblastomas. This pattern is similar to that seen in human medulloblastomas with extensive nodularity, where proliferation is limited to internodular tissue and is minimal within nodules of greater neuronal differentiation [20]. SmoA1; Pten +/+; Pten +/− tumors displayed diffuse staining for PCNA throughout each tumor section. In contrast, staining for cleaved caspase 3, a marker of apoptosis, revealed diffuse staining throughout SmoA1; Pten +/+ medulloblastomas, but virtually no expression in SmoA1; Pten +/− tumors (Figure 5B). This suggests that decreased apoptosis is an important cause for our finding of increased mortality in Pten deficient mouse medulloblastomas.

PTEN loss in human medulloblastoma is associated with a poor prognosis for survival

In order to validate our findings from mouse models, human TMAs were stained for expression of PTEN and were scored
independently by two pathologists on a scale of 0 (no staining) to 2 (intense staining). By IHC, PTEN expression was low to absent (score = 0) in 61% of medulloblastomas (n = 111) (Figure 6A, Table 1). For patients known to be alive (n = 27) or dead (n = 15) with PTEN expression data available, of those alive, only 18% had low to absent PTEN expression by IHC. In contrast, 73% of those dead of disease had low to absent PTEN expression by IHC. Medulloblastomas from patients who died with PTEN deficiency (score = 0) were of either classic (n = 9) or desmoplastic (n = 2) histology and none had metastasis initially at diagnosis. Patients who died with detectable PTEN expression (score = 1–2) had anaplastic histology (n = 1) or had metastases at diagnosis (n = 3).

Kaplan-Meier analysis confirmed worse overall survival in patients whose tumor exhibited low to absent PTEN protein expression compared to survival of patients with detectable expression of PTEN (p<0.0005) (Figure 6B), which suggests that loss of PTEN is an independent poor prognostic feature independent of tumor histology or disease stage.

Discussion

The ability to overcome mechanisms that promote apoptosis is essential for the development and progression of cancer. The PI-3 kinase signaling pathway provides such a mechanism by
transmitting a strong survival signal. In humans, one of the major inhibitors of signaling through the PI-3 kinase pathway is PTEN. One of the first mouse models to examine potential cross-talk between Shh and PI-3 kinase signaling in medulloblastoma employed the RCAS/tv-a retroviral system for exogenous gene expression in the mouse neonatal cerebellum. Rao et. al. was the first group to report that co-overexpression of Shh and either activated Akt or IGF2 significantly increased the incidence of medulloblastoma [21]. Another group demonstrated a high frequency of medulloblastomas in mice through co-overexpression of Shh and hepatocyte growth factor, HGF, the ligand for the transmembrane receptor c-Met. HGF overexpression activated PI-3 kinase signaling; and, compared to medulloblastomas generated by overexpression of Shh alone, exogenous Shh + HGF appeared to promote tumorigenesis by inhibiting apoptosis in granule neuron precursors of the developing cerebellum [22].

We found that Pten deficiency drove medulloblastoma tumors from classic to extensively nodular (MBEN) histology. MBEN tumors are characterized primarily by large nodules with a low proliferative index and neurocytic differentiation. MBEN tumors often contain smaller areas of proliferation, embedded in a dense network of reticulin fiber. Our finding of MBEN in Pten deficient tumors confirm those in prior reports in which tumors with extensive nodularity were generated through activation of PI-3 kinase signaling pathways. MBEN histology has been reported in medulloblastoma tumors generated when Pten was conditionally deleted in cells of neuronal lineage, using an RCAS/tv-a system [23]. Investigators have also generated a mouse model with MBEN by simultaneously overexpressing Shh and HGF [22]. Neither of these reports of mouse models with MBEN described an association of MBEN histology with decreased survival.
Our observation in mouse models is curious because it seems counter to the reported superior survival outcomes in children diagnosed with medulloblastoma with MBEN histology, compared to the survival of children with tumors of classic histology. In Gorlin syndrome, where patients have mutation of \textit{PATCHED1} and thus activation of signaling through Shh pathways and an increased incidence of medulloblastoma, medulloblastoma tumors are usually desmoplastic or MBEN in histology [4]. Patients with desmoplastic or MBEN tumor histologies have historically had a much better survival prognosis than patients with classic medulloblastoma [2]. A recent retrospective analysis reported a 5-year survival of 92% in patients with medulloblastoma with MBEN histology, 90% with desmoplastic histology, and 66% in patients with classic medulloblastoma. MBEN medulloblastomas were associated with a lower risk of metastasis at diagnosis and increased sensitivity to chemotherapy and IR [4]. In contrast, \textit{Shh}-driven tumors in mice may have some evidence of desmoplasia, but not true nodules, and overall look very classic in appearance [22,24]. Yet, we have found that MBEN mouse medulloblastomas have a survival that is inferior to \textit{Shh}-driven, classic mouse

**Figure 6. Loss of PTEN expression is an indicator of poor prognosis in patients with medulloblastoma.** (A) PTEN expression was scored from 0 to 2+ in human medulloblastoma (n = 111) tumors. (B) Kaplan-Meier analysis confirmed worse overall survival in patients whose tumor exhibited low to absent (score = 0) PTEN expression (n = 16), compared to survival of patients with detectable PTEN (n = 26) expression (score = 1–2) (Table 1) by IHC (p < 0.0005).

![PTEN expression in human medulloblastoma](image)

**Table 1.** Absent PTEN expression is associated with increased mortality.

|                     | <3 yo | 3–18 yo | ≥18yo | Unknown | TOTAL |
|---------------------|-------|---------|-------|---------|-------|
| **Classic Histology** |       |         |       |         |       |
| PTEN 0              | 1     | 4       | 7     | 10      | 22    | (73%) |
| PTEN 1–2            | -     | 6       | 2     | -       | 8     |
| **Anaplastic Histology** |       |         |       |         |       |
| PTEN 0              | 2     | 3       | 2     | 14      | 21    | (68%) |
| PTEN 1–2            | 2     | 6       | 1     | 1       | 10    |
| **Desmoplastic Histology** |       |         |       |         |       |
| PTEN 0              | 1     | 4       | 5     | 2       | 12    | (54%) |
| PTEN 1–2            | -     | 7       | 3     | -       | 10    |
| **All Tumors**      |       |         |       |         |       |
| PTEN 0              | 5     | 22      | 14    | 27      | 68    | (61%) |
| PTEN 1–2            | 4     | 30      | 7     | 2       | 43    |
| **TOTAL**           | 9     | 52      | 21    | 29      | 111   |
| **ALIVE**           |       |         |       |         |       |
| PTEN 0              | 1     | 4       | -     | -       | 5     | (18%) |
| PTEN 1–2            | 1     | 20      | 1     | -       | 22    |
| **DEAD**            |       |         |       |         |       |
| PTEN 0              | 3     | 5       | 3     | -       | 11    | (73%) |
| PTEN 1–2            | 1     | 3       | -     | -       | 4     |

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medulloblastomas. And, MBEN mouse medulloblastomas appeared to exhibit resistance to IR in one published report [23]. The significance of this disparity between tumor histology and survival in mouse models versus human medulloblastomas has yet to be addressed in the literature.

One mechanism that may explain the increased mortality of Pten deficient mice is increased angiogenesis. Persistent angiogenesis is one of the hallmarks that distinguish high-grade from low-grade brain tumors [23]. Our study found up-regulation of Vegf, Fli1, and Hbegf in Smo1 +/+; Pten +/−, medulloblastomas. Vascular endothelial growth factor A, Vegf, and the receptor for Vegf, Fli1(Vegfr1), are well described pro-angiogenic factors [26]. Hbegf, which codes for the heparin-binding EGF-like growth factor, has been established as a potent inducer of tumor growth and angiogenesis [27].

Tumor blood vessel density has also been identified as an independent prognostic factor in high-grade, malignant astrocytomas [28]. Early studies of human medulloblastomas identified increased microvascular density (MVD) in tumor tissue as compared to surrounding normal cerebellum [29]. However, there was high inter-tumor variability of MVD and MVD failed compared to surrounding normal cerebellum [29]. Our study found up-regulation of angiogenic factors including VEGF165, PDGF-A, and VEGF-B in 93% of human medulloblastomas [31]. We identified increased angiogenesis by IHC in Pten deficient medulloblastomas. This suggests that increased angiogenesis may be an important mechanism that negatively affects the survival of Pten deficient medulloblastomas.

Our study also identified down-regulation of cell cycle-related genes and significant reduction of apoptosis in Pten deficient medulloblastomas. Cell cycle genes Tjp53, Beca2, and Rb1 were down regulated in Pten +/− tumors. Loss of RB1 or other components of the RB1 pathway has been associated with decreased survival of patients with high-grade gliomas. This association was even stronger in combination with loss of wild-type PTEN [32]. Loss of Beca2 has previously been linked to medulloblastoma tumorigenesis, as concomitant loss of Tjp53 leads to rapid formation of medulloblastomas in Beca2/LoxP/LoxP; Nestin-cre mice [33]. p53 is a well characterized downstream target of PI-3 kinase signaling. And, PTEN functions as a key inhibitor of PI-3 kinase signaling through its physical interactions with p53 to control cell proliferation [34].

Our findings are in agreement with the findings of McCall et. al. who reported decreased apoptosis in mouse medulloblastomas derived from co-overexpression of sonic hedgehog and activated Akt in the developing mouse brain [35]. Similarly, Binning et al. report in increased staining for the proliferation marker, Ki67, and decreased staining for cleaved caspase-3 in Shh + HGF-driven mouse medulloblastomas. Given that Smo1+/−; Pten +/+ mice survive longer than Smo1+/−; Pten +/+; Pten +/+− mice, it appears that haploinsufficiency for Pten drives differentiation of cells in the cerebellum toward a neuronal phenotype with associated regions of reduced apoptosis.

Importantly, we found that over one-half of human medulloblastomas in our study exhibited decreased expression of PTEN. Absence of PTEN expression was associated with increased mortality and reduced survival of patients. Only one other study has reported down-regulation of PI-3 kinase signaling in human medulloblastomas [9]. Using a larger cohort of patients, we detected absent PTEN staining in 61% of human medulloblastomas. Unlike the previous study, we show a significant difference in survival between patients whose tumor stains positively and negatively for PTEN expression. This suggests that not only does Pten deficiency promote tumorigenesis in our mouse model; but, PTEN deficiency may be a marker of poor prognosis in patients, independent of tumor histology or disease stage.

We believe that our mouse model is particularly attractive for pre-clinical drug development because of the ease with which de novo medulloblastoma tumors develop in Pten deficient mice and because of the difference in tumor histology between the two mouse models. Other models of activated PI-3 kinase signaling require expertise with neuro-surgery. We were able to achieve similar results by crossing Smo1+/+ and Pten +/− mice, which are readily available. The Smo1+/−; Pten +/− mouse model may be useful for examining the effects of anti-angiogenic therapies in MBEN versus classic medulloblastomas. The recent availability of small molecule inhibitors of signaling through PI-3 kinase pathways [36], many of which are in early Phase I/II trials in adult malignancies, also gives us an opportunity to examine the efficacy of targeted agents in a mouse model that closely recapitulates classic and nodular medulloblastomas, before these agents are tested on children with medulloblastoma.

Materials and Methods

Animal Husbandry

Pten +/− mice were a gift from Ramon Parsons (Columbia University, New York, NY). N22;Smo1 (Smo1) transgenic mice were a gift from James Olson (University of Washington, Seattle, WA). Smo1+/+ founder genotypes were confirmed by fluorescent in situ hybridization (FISH) in the Olson laboratory. All offspring (n = 100) of Smo1×Smo1 matings have tested positive for the Smo1 transgene and are thus considered homozygous for Smo1, Smo1+/+.

Smo1+/+ mice were bred to Pten +/− mice to obtain Smo1 ++, Pten +/+ and Smo1 +−; Pten +/− F1 animals. All F1 offspring expressed the Smo1 transgene by tail PCR, and were considered to be hemizygous for the transgene, Smo1 +−. Pten LoxP/LoxP (gift from W. David Martin, Emory University) were crossed with Smo1+/+; Pten LoxP/LoxP offspring crossed with Nestin-cre + (Jackson Laboratories, Bar Harbor, ME) mice to obtain Smo1 +−; Pten LoxP/−; Nestin-cre + mice. Mice were observed for symptoms of medulloblastoma at least twice weekly for a period of 12 months. All mice were housed in an American Association of Laboratory Animal Care accredited facility and were maintained in accordance with NIH guidelines. This was approved by the Institutional Animal Care and Use Committee of Emory University (Protocol # 143-2009). Survival was analyzed using GraphPad Prism 4 (GraphPad Software, Inc., La Jolla, CA).

Mouse Necropsy and Tissue Handling

Mice were followed and sacrificed upon development of symptoms of medulloblastoma, which included head drooping, hunched posture, preferential turning to one side, lethargy, and/or weight loss, using CO2 inhalation. The cerebellar tumor was either snap-frozen in liquid nitrogen for RNA studies, snap-frozen in Optimal Cutting Temperature (OCT) cryoembedding media (Tissue-Tek, Sakura Finetek, Torrance, CA), or fixed in 4% paraformaldehyde for pathological examination. OCT blocks were cut into 10–20-μm sections and stained with antibody [37]. Tissue blocks were paraffin embedded, cut into 4-μm sections, and then stained with hematoxylin and eosin (H&E) [38]. All necropsied brains were classified by a pathologist as medulloblastoma.
**Western Blotting and Immunohistochemical Analysis of Mouse Medulloblastomas**

Proteins extracted from cells were electrophoretically separated on polyacrylamide denaturing gels, transferred onto nitrocellulose membranes, and immunoblotted with the designated antibodies as previously described [39]. Immunohistochemistry was performed according to manufacturer’s recommendations. Antibodies used included Pten (Cell Signaling), phospho-Akt (Ser473) (Cell Signaling), pS3 (DO-1) (Santa Cruz), Wnt-3 (Santa Cruz), Wnt-7 (Santa Cruz), β-actin (Sigma), NeuN (Millipore), GFAP (Abcam), Synaptophysin (Abcam), CD31 (BD Pharminagen), CD34 (BD Pharminagen), PCNA (Cell Signaling), and Cleaved Caspase 3 (Asp175) (Cell Signaling). Secondary antibodies were applied according to manufacturer’s recommendations (Vector Laboratories). Double stains were processed according to manufacturer’s recommendations using the Rat and Mouse Double Stain Kit (Biocare Medical, Concord, CA). Stained slides were visualized with a Nikon Eclipse E400 microscope (Nikon Instruments Inc., Melville, NY). Images were captured with a SPOT Flex Shifting Pixel Color Mosaic (FX1520) digital camera, and were analyzed using the SPOT basic software package (Diagnostic Instruments Inc., Sterling Heights, MI). Images were processed for publication using Adobe Photoshop Elements 5.0 (Adobe Systems, San Jose, CA).

**Analysis of Mouse Gene Expression Microarrays**

Total RNA was extracted using RNeasy (Qiagen, Germantown, MD). RNA integrity was assessed using an Agilent 2100 Bioanalyzer. All samples demonstrated RNA integrity (RIN) of 7.7 or greater. RNA was labeled using TotalPrep RNA (Ambion), and hybridized to Illumina MouseWG-6 v2 BeadChips for analysis of 45,261 transcripts covering 30,774 genes. Data was interpreted using BeadStudio and quantile normalized to adjust for sample-to-sample variation. Differential analysis was conducted on a subset of 21,649 probes that were detected in at least one sample (detection p-value < 0.01). Significance Analysis of Microarray (SAM) software [40] was used to determine differential expression with a false discovery rate (FDR) <1% and a minimum fold-change of 2 unless otherwise stated. Heatmaps were generated in R [41] using the heatmap.2 package. Probe expression data was Z-score normalized and hierarchical clustering was calculated on a Euclidean distance dissimilarity metric with an average clustering Z-score normalized and hierarchical clustering was calculated on a fold-change of 2 unless otherwise stated. Heatmaps were generated using Adobe Photoshop Elements 5.0 (Adobe Systems, San Jose, CA).

**Supporting Information**

**Figure S1** SmoA1 +; Pten +/− mouse medulloblastomas up-regulate expression of Wnt3 and Wnt7a. Analysis of gene expression in mouse medulloblastomas revealed higher expression of the Sonic Hedgehog pathway genes Wnt3 and Wnt7a in tumors from SmoA1 +; Pten +/− (white bars) versus from SmoA1 +; Pten +/+ (back bars) mice. (A) Using real-time, RT-PCR we confirmed up-regulated expression of mRNA for downstream targets of the Sonic Hedgehog signaling pathway, Wnt3 and Wnt7a. Relative expression of Wnt3 and Wnt7a was increased 5.9 and 6.3-fold (p<0.05 for all transcripts), respectively in SmoA1 +; Pten +/− (n = 7) medulloblastomas. Error bars, standard error of the mean. (B) This increased RNA expression correlated with a significant increase in expression of Wnt-3 and Wnt-7 protein by western blotting in SmoA1 +; Pten +/− (n = 4), compared to SmoA1 +; Pten +/+ (n = 3) mouse medulloblastomas. Found at: doi:10.1371/journal.pone.0010849.s001 (8.44 MB TIF)

**Figure S2** SmoA1 +; Pten +/− mouse medulloblastomas express markers of neuronal differentiation. (A) Analysis of gene expression in mouse medulloblastomas revealed higher expression of genes involved in neuronal differentiation, such as Bdnf, NeuN, Id1, and Neurod2 in tumors from SmoA1 +; Pten +/− (n = 5) versus from SmoA1 +; Pten +/+ (n = 4) mouse medulloblastomas. Red pixels in the heatmap visualization represent increased expression and green pixels represent decreased expression of mRNA transcripts for the listed gene probes. (B) Immunohistochemical analysis of paraffin-embedded sections of the two tumor types confirmed significant expression of the marker of neuronal differentiation, NeuN, in
SmoAI +; Pen +/- tumors (n = 5), and no expression of NeuN in tumors from SmoAI +; Pen +/- mice (n = 5), except in the expected location in the internal granule layer (IGL). (C) Double-staining of tumor sections revealed diffuse proliferation with scattered areas of staining for NeuN in SmoAI +; Pen +/- medulloblastomas. Pen deficient tumors displayed larger islands of neuronal differentiation, surrounded by and distinct from PCNA positive, areas of proliferation. (D) Neither tumor type stained positive for the marker of astrocytic differentiation, GFAP. (E) Staining for synaptophysin, a marker of primitive neurons was weak in both tumor types, but appeared to overlap with staining for PCNA.

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Author Contributions
Conceived and designed the experiments: RCC DLD. Performed the experiments: RCC MCB OB DH. Analyzed the data: RCC BGB MS MCB DB. Contributed reagents/materials/analysis tools: RCC GOGB OB DH TJM DLD. Wrote the paper: RCC.

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Author Contributions
Conceived and designed the experiments: RCC DLD. Performed the experiments: RCC MCB OB DH. Analyzed the data: RCC BGB MS MCB DB. Contributed reagents/materials/analysis tools: RCC GOGB OB DH TJM DLD. Wrote the paper: RCC.

Table S1 Survival of Pen +/- versus Pen +/+ mice.
Found at: doi:10.1371/journal.pone.0010849.s002 (10.16 MB TIF)

Table S2 Comparison of medulloblastomas from Pen wild-type versus deficient mice.
Found at: doi:10.1371/journal.pone.0010849.s003 (0.03 MB DOC)

Table S3 Differentially expressed genes in SmoAI +; Pen +/- mouse medulloblastomas.
Found at: doi:10.1371/journal.pone.0010849.s005 (0.10 MB DOC)
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