Novel Oncogenic PDGFRA Mutations in Pediatric High-Grade Gliomas

Barbara S. Paugh1, Xiaoyan Zhu1, Chunxu Qu2, Raelene Endersby7, Alexander K. Diaz1,6, Junyuan Zhang1, Dorine A. Bax8, Diana Carvalho8, Rui M. Reis3, Arzu Onar-Thomas3, Alberto Broniscer4, Cynthia Wetmore4, Jinghui Zhang2, Chris Jones8, David W. Ellison5, and Suzanne J. Baker1,6

Abstract

The outcome for children with high-grade gliomas (HGG) remains dismal, with a 2-year survival rate of only 10% to 30%. Diffuse intrinsic pontine glioma (DIPG) comprise a subset of HGG that arise in the brainstem almost exclusively in children. Genome-wide analyses of copy number imbalances previously showed that platelet-derived growth factor receptor α (PDGFRA) is the most frequent target of focal amplification in pediatric HGGs including DIPGs. To determine whether PDGFRA is also targeted by more subtle mutations missed by copy number analysis, we sequenced all PDGFRA coding exons from a cohort of pediatric HGGs. Somatic-activating mutations were identified in 14.4% (13 of 90) of nonbrainstem pediatric HGGs and 4.7% (2 of 43) of DIPGs, including missense mutations and in-frame deletions and insertions not previously described. Forty percent of tumors with mutation showed concurrent amplification, whereas 60% carried heterozygous mutations. Six different mutations impacting different domains all resulted in ligand-independent receptor activation that was blocked by small molecule inhibitors of PDGFR. Expression of mutants in p53-null primary mouse astrocytes conferred a proliferative advantage in vitro and generated HGGs in vivo with complete penetrance when implanted into brain. The gene expression signatures of these murine HGGs reflected the spectrum of human diffuse HGGs. PDGFRA intragenic deletion of exons 8 and 9 were previously shown in adult HGG, but were not detected in 83 nonbrainstem pediatric HGG and 57 DIPGs. Thus, a distinct spectrum of mutations confers constitutive receptor activation and oncogenic activity to PDGFRA in childhood HGG. Cancer Res; 73(20); 6219–29. ©2013 AACR.

Introduction

Pediatric high-grade gliomas (HGG) comprise 15% to 20% of all childhood tumors of the central nervous system (1). Despite aggressive therapy, prognosis for pediatric HGG remains very poor, with a 2-year survival rate of less than 20% (2). A subset of HGGs arise in the brainstem as diffuse intrinsic pontine glioma (DIPG), a disease that occurs almost exclusively in children and has a 2-year survival rate of less than 10% (3). Although the histopathologies of pediatric and adult HGGs can be similar, genome-wide studies have shown significant differences in the frequencies of specific copy number alterations as well as both similarities and differences in the gene expression signatures of HGGs in these two age groups (4–12). Somatic mutations in histone H3 occur in 78% of DIPGs and 36% of nonbrainstem pediatric glioblastomas, but occurred only rarely in young adults with glioblastoma and not in older patients with adult glioblastoma (11, 12). Thus, distinct molecular mechanisms drive gliomagenesis at different ages.

Platelet-derived growth factor receptor α (PDGFRA) is the most frequent target of focal amplification in pediatric HGGs arising within and outside the brainstem (4–7, 10), and somatic mutations of PDGFRA have been recently reported in pediatric HGGs (6, 12). In contrast, EGFR receptor (EGFR) is the predominant receptor tyrosine kinase (RTK) targeted by both amplification and mutation in adult glioblastoma (13, 14). Pediatric HGGs with genomic amplification of PDGFRA showed concomitant increases in PDGFRA mRNA by gene expression profiling. Furthermore, PDGFRA overexpression without genomic amplification is commonly found in pediatric HGGs, and amplification of the genes encoding PDGF ligands or overexpression with and without PDGFRA aberrations were also reported, suggesting both autocrine and paracrine signaling.

PDGF and its receptors are involved in many cellular processes such as migration, survival, and proliferation and they are critical during developmental processes (15). Ligand binding induces receptor dimerization and results in...
phosphorylation of the receptor at multiple tyrosine residues. Activated PDGF receptors (PDGFRs) transduce signals through multiple downstream pathways, including the PI3K/Akt, RAS/MAP kinase, Src kinase family, and PLC/PKC pathways, which have all been implicated in tumorigenesis (15, 16).

Abnormally activated PDGFRα signaling driven by viral expression of PDGFβ ligand is sufficient to induce glioma formation in vivo, indicating that activation of PDGFR pathways is potentially an early event in tumorigenesis (17–19). Furthermore, simultaneous overexpression of PDGFβ and loss of TP53 induced murine HGG with increased incidence and shorter latency, indicating cooperativity between these pathways (20, 21). However, these studies focused on autocrine and paracrine activation of PDGFR signaling pathways by PDGFβ ligand overexpression.

Here, we report that pediatric HGGs, including DIPGs, carry novel somatic-activating mutations of PDGFRA that are constitutively active, tumorigenic, and sensitive to small molecule inhibitors.

Materials and Methods

Clinical samples

Pediatric HGG samples were obtained from St. Jude Children’s Research Hospital (Memphis, TN) and the Royal Marsden Hospital (London, United Kingdom; Supplementary Table S2). Ethical Review Committee approval was obtained from each institution/consortium. Genomic DNA was extracted as previously described from snap-frozen (22) or formalin-fixed paraffin-embedded material (10).

Mutation analysis of PDGFRA

All coding exons of PDGFRA were sequenced by direct sequencing of PCR-amplified products from genomic DNA in the tumors listed in the Supplementary Table S2, including 39 cases of nonbrainstem pediatric HGGs and 43 cases of DIPGs, using primers listed in the Supplementary Table S4, or by exome sequencing for three DIPG samples. For an additional 51 cases of nonbrainstem pediatric HGG, DNA was extracted from formalin-fixed paraffin-embedded tissue and amplified and sequenced using primers published previously (9). Identified PDGFRA mutations were validated by independent PCR and matched normal samples were sequenced when available. Expression of mutated receptor was confirmed by reverse transcription (RT)-PCR and sequencing using primers listed in the Supplementary Table S4 for available cDNA samples. Eighty-three nonbrainstem pediatric HGG and 57 DIPG cases were screened for PDGFRA mutations; the previously reported 243 base-pair deletion in exons 8 and 9 as described previously (25). At passage one, p53-null astrocytes were transduced with retroviruses expressing wild-type PDGFRA, PDGFRA mutants or empty vector, and in vitro and tumorigenesis experiments were carried out before passage six. For proliferation assays, 5.5 × 10^5 cells per well were plated on 96-well plates in triplicate. Cells were grown in Dulbecco’s Modified Eagle Medium (DMEM)/F-12 supplemented with 10% FBS and 20 ng/mL mouse EGF (Millipore), but without exogenous addition of the PDGF ligand. Proliferation was measured using XTT (2,3-bis[2-methoxy-4-nitro-5-sulphophenyl]-2H-tetrazolium-5-carboxanilide inner salt) assay (Roche) at 24-hour intervals over a 4-day period, without replacing the growth medium. For inhibitor studies, cells were allowed to attach for 4 hours after seeding, then 225 nmol/L (100 ng/mL) crenolanib (AROG Pharmaceuticals), 50 nmol/L dasatinib (LC Laboratories), or vehicle (0.1% dimethyl sulfoxide, DMSO) were added to the cells in a single dose and growth was assayed by XTT as above. Data were normalized to the cell number measured at time zero of the experiment, which was acquired within the first 8 hours from cell seeding (4 hours for cell attachment and 4 hours for development of XTT). For cell-cycle analyses, 2 × 10^6 cells were seeded per 10 cm dish and the next day cells were treated with 225 nmol/L (100 ng/mL) crenolanib (AROG Pharmaceuticals), 50 nmol/L dasatinib (LC Laboratories), or vehicle (0.1% DMSO) for 24 hours. Following inhibitor treatment, cells in the supernatant from each dish were collected, pooled with trypsinized cells, and washed with PBS. Cells were fixed in 70% ethanol overnight at 4°C and then stained using Guava Cell Cycle Reagent (Millipore). Data were acquired on the Guava EasyCyte using CytoSoft software (Millipore).

Tumorigenesis studies

Mouse experiments were approved by the Institutional Animal Care and Use Committee and are in compliance with national and institutional guidelines. A total of 2 × 10^5 transduced astrocytes were implanted intracranially into athymic nude mice for tumorigenesis studies as previously described (25). On the manifestation of brain tumor symptoms, mice were anesthetized and perfused with PBS. GFP-labeled tumors were dissected using a fluorescent dissecting microscope. For each tumor, a portion was snap-frozen for protein analyses and RNA extraction, and the remainder was fixed in 4% paraformaldehyde in PBS at 4°C overnight, then processed, embedded in paraffin, and cut into 5 μm sections. Hematoxylin and eosin (H&E)-stained sections from all collected tumors were evaluated by a clinical neuropathologist (D.W. Ellison) and graded according to World Health Organization (WHO) criteria (26). Immunohistochemistry was conducted with microwave antigen retrieval in a citrate solution using the following primary antibodies from Cell Signaling Technology: PDGFRα (1:5241), phospho-Akt S473 (#9271), and phospho–E-BP1 Thr37/46 (#2855). Anti-rabbit biotinylated secondary antibodies were used in conjunction with horseradish peroxidase-conjugated streptavidin (Elite ABC; Vector Labs). Staining was developed with NovaRED substrate (Vector Labs) and the sections were counterstained with hematoxylin (Vector Labs).
Western blot analysis

Protein lysates were prepared in ice-cold radioimmunoprecipitation assay (RIPA) buffer (150 mmol/L NaCl; 50 mmol/L Tris–HCl, pH 8.0; 1% NP-40; 0.5% sodium deoxycholate and 0.1% SDS) supplemented with protease and phosphatase inhibitors (Roche). For in vitro experiments, cells were serum-starved in media containing 0.1% FBS for 16 hours and then treated with or without 50 ng/mL PDGF-AA for 30 minutes. For inhibitor experiments, serum-starved cells were pretreated with 225 mmol/L (100 ng/mL) crenolanib (AROG Pharmaceuticals) or 50 mmol/L dasatinib (LC Laboratories) for 3 hours and then stimulated with PDGF-AA for 30 minutes. To calculate the IC_{50} and IC_{90} concentrations for crenolanib serum-starved cells were pretreated with or without 50 ng/mL PDGF-AA for 30 minutes. Following treatment, cells were washed twice with ice-cold PBS then scraped and lysed in RIPA buffer. Snap-frozen tissues from brain tumor-bearing and control animals were lysed using a microcentrifuge tube pestle (Fisher Scientific). Twenty microgram of protein extract was separated by electrophoresis on NuPAGE 4% to 12% Bis-Tris gels run in NuPAGE MES SDS Running Buffer (Invitrogen). Antibodies for phospho-PDGFRα Tyr572/574 (ab5443), phospho-PDGFRα Tyr-742 (ab5452), and phospho-PDGFRα Tyr720 (ab65258) were from Abcam. Antibodies for phospho-PDGFRα Tyr754 (sc-12911), PDGF-α (sc-338), and α-tubulin (sc-23948) were from Santa Cruz Biotechnology. Antibodies for phospho-Akt S473 (#9271), phospho-Akt T308 (#9275), pan Akt (#4691), phospho-p44/42 mitogen-activated protein kinase (MAPK) Thr202/Tyr204 (#9101), p44/42 MAPK (#9102), phospho-MEK1/2 Ser217/221 (#9154), MEK1/2 (#9122), phospho-NDRG1 Thr346 (#3217), NDRG1 (#9408), phospho-PRAS40 Thr246 (#2997), PRAS40 (#2610), phospho-S6 ribosomal protein Ser235/236 (#2211), S6 ribosomal protein (#2217), phospho-SHP-2 Tyr542 (#3751), SHP-2 (#3752), phospho-Src family Tyr416 (#2101), phospho-Src family Tyr527 (#2105), Src family (#2109), phospho-Stat5 Tyr705 (#9145), Stat3 (#9139), phospho-4E-BP1 Thr37/46 (#9459), and 4E-BP1 (#9452) were from Cell Signaling Technology. Antibody for β-actin (A5441) was from Sigma. Horseradish peroxidase–conjugated secondary antibodies (NA934, NA931) were from GE Healthcare. Chemiluminescent signal was detected with ECL reagents (GE Healthcare) or SuperSignal West Dura (Thermo Scientific).

Gene expression microarray analysis

Total RNA was extracted from frozen tumor tissue dissected from mice with wild-type PDGFRA, PDGFRA mutants and from parental p53-null mouse primary astrocytes. In addition, RNA was isolated from high-grade astrocytomas generated by implantation of EGFRRvIII-expressing p53-null primary mouse astrocyte (PMa) as previously described (25). Gene expression profiles were generated using the Affymetrix Mouse Genome 430 Perfect Match Peg Arrays. Gene expression profiles were generated using the Affymetrix Mouse Genome 430 Perfect Match Peg Arrays in two batches. Three common samples run in both sets were used for batch correction with the program ComBat (27). Unsupervised hierarchical clustering (UHC) analysis was carried out with the merged data using the 1,000 most variable probe sets selected on the basis of median absolute deviation score. Single-sample gene set enrichment analysis (GSEA) was conducted as described previously (28, 29). For single-sample GSEA, signature gene sets defining human HGG expression subgroups (PN, proneural; Pro, proliferative; and Mes, mesenchymal) and murine cell-type–specific signatures (OPCs, oligodendrocyte progenitor cells; Oligo, oligodendrocyte; N, neurons; A, astrocytes; and CA, cultured astroglia) were taken from previously published work (30, 31). Data are deposited at www.ncbi.nlm.nih.gov/geo/, accession GSE46190.

Statistical analysis

There was no apparent association between histologic tumor-type and the presence of PDGFRA mutation in pediatric HGG as assessed by exact χ² test for independence (P = 0.2562). A Kruskal–Wallis test showed that the presence of PDGFRA mutations was not significantly associated with age at diagnosis (P = 0.068). Statistical significance of the associations of murine tumors driven by different PDGFRA mutations with histology, gene expression clusters, human HGGs gene expression signatures and neural cell-type–specific subgroups was assessed by exact χ² test for independence. Student two-tailed t test P values were calculated for cell-cycle analysis to assess response to crenolanib and dasatinib versus untreated controls.

Results

PDGFRA is frequently mutated in pediatric HGGs

Sequencing of all coding exons of PDGFRA in genomic DNA from 90 pediatric HGGs outside the brainstem and 43 DIPGs identified 15 cases with mutated PDGFRA (Fig. 1 and Supplementary Table S1). All mutations were confirmed by independent PCR reactions and were validated as somatic, found only in the tumor and not matching germline DNA when normal sample was available (Supplementary Table S1). Mutations were identified in the extracellular, transmembrane, and intracellular kinase domains and included missense mutations, in-frame insertions or deletions (Fig. 1). Analysis of cDNA showed that one of the somatic point mutations, N468S, generated a new splice site that removed 13 amino acids (E10del2; Supplementary Fig. S1A and Table S1). Sixty percent (9 of 15) of the new splice site that removed 13 amino acids (E10del2; Supplementary Fig. S1A and Table S1). Sixty percent (9 of 15) of the mutations in grade 4 glioblastomas, including two DIPGs (11 of 102; Supplementary Table S1 and S2). Both
mutations in the kinase domain, N659K and D842V were previously reported in gastrointestinal stromal tumors but not in gliomas (32, 33). The remaining mutations are all novel, including four different missense mutations (E229K, C235R, Y288C, and C290R), three in-frame insertions (C450ins, A491ins, and V544ins), and three in-frame deletions (E7del, E10del, and E10del2; Supplementary Table S1) not found in previous studies of a large collection of pediatric HGGs or adult HGGs (6, 12, 23, 34). Three of the identified mutations (E7del, E10del2, and N659K) were recurrent, each of them found in two different HGG cases.

We also evaluated whether activating PDGFRA mutations previously shown in adult HGG occur frequently in pediatric HGG. Forty percent of adult glioblastomas with PDGFRA amplification harbor an in-frame deletion of 243 base pairs in exons 8 and 9 of the extracellular portion of the receptor (PDGFRA exon 8,9) that renders the receptor constitutively active (23, 35). A gene fusion between PDGFRA and KDR (VEGFR2), which rendered the receptor constitutively active and tumorigenic in vivo, has been reported in one out of 215 cases of adult glioblastoma. We used RT-PCR to screen for these alterations that would have been missed by exonic sequencing. We found one case of KDR–PDGFRA in 83 nonbrainstem pediatric HGGs analyzed (Supplementary Fig. S1B). There were no examples of the PDGFRA exon 8,9 deletion in 83 nonbrainstem pediatric HGG and 57 DIPG screened by RT-PCR (Supplementary Fig. S1C).

Thus, a different spectrum of intragenic mutations target PDGFRA in HGGs from different age groups.

**PDGFRx Mutants are Constitutively Active**

To better understand the consequence of PDGFRx mutation in pediatric gliomagenesis, retroviral constructs expressing wild-type PDGFRx or six selected PDGFRx mutants that affect different regions of the receptor were generated for functional studies. p53-null PMA cultures were chosen as a relevant cellular background to assess PDGFRx function, because 70% of pediatric HGGs outside of the brainstem and 46% of DIPGs with amplified and/or mutated PDGFRA also have inactivating mutations of TP53 (Supplementary Table S2). All six mutants were constitutively active, inducing strong phosphorylation of PDGFRx at Tyr-572/574, Tyr-742, Tyr-720, and Tyr-754 when expressed in p53-null PMAs in the absence of serum. These phosphotyrosine sites have been shown to associate with activation of different downstream signaling pathways. Src family members bind to phosphorylated PDGFRx at Tyr-572/574, phospho-Src-Thr-742 promotes interaction with p85, the regulatory subunit of PI3K, and leads to PI3K pathway activation, whereas phosphorylated Tyr-720 and Tyr-754 recruit and activate SHP-2 (Src homology-2 domain-containing phosphatase), which regulates activation of Src family kinases and the MAPK pathway (16, 36–38). Different levels of receptor phosphorylation were observed depending on the specific mutation, with the E10del2 exhibiting the lowest receptor activation. All mutants were expressed to similar levels as shown by total PDGFRx (Fig. 2A, left). In contrast, overexpression of wild-type PDGFRx did not lead to receptor activation in the ligand-free condition. However, treatment of these cells with PDGF-AA, triggered wild-type PDGFRx phosphorylation to levels similar to or greater than the mutant receptors (Fig. 2A, right). Furthermore, phosphorylation of known downstream signaling targets of PDGFRx confirmed the constitutive activity of PDGFRx mutants. In the absence of ligand, elevated levels of phospho-Akt (Ser473 and Thr308) and higher phosphorylation levels of S6 ribosomal protein and PRAS40 were observed in comparison with wild-type PDGFRx-expressing cells, indicating ligand-independent activation of the PI3K pathway by the mutated receptor. Activation of MAPK signaling, detected by phosphorylation of p44/42 MAPK was not increased by mutant PDGFRx in the absence of ligand. Ligand stimulation further increased phosphorylation levels of PI3K pathway components but had only modest effect on the MAPK pathway activation (Fig. 2A and Supplementary Fig. S2). Expression of PDGFRx mutants as well as wild-type receptor added a significant proliferative advantage in comparison with empty vector control cells as determined by XTT assays (Fig. 2B).

**PDGFRx Signaling is Abrogated by Inhibitors**

To analyze whether wild-type and PDGFRx mutants have differential responses to small molecule inhibitors, two distinct
of three independent experiments is shown.

**Figure 2.** PDGFRα mutants are constitutively active and confer proliferative advantage. A, Western blot analysis of whole cell lysates from p53-null PMAs transduced with retroviruses expressing wild-type PDGFRα (WT), PDGFRα mutants, or empty vector. Cells were grown in serum-free conditions overnight and then with or without PDGF-AA for 30 minutes. PDGFRα signaling activation of downstream targets was monitored using indicated antibodies in the presence and absence of PDGF-AA. B, proliferation of p53-null PMAs transduced with retroviruses expressing wild-type, PDGFRα mutants, or empty vector was measured by XTT assay in triplicate. Error bars show SD. A representative figure of three independent experiments is shown.

compounds were selected. Dasatinib (BMS-354825) is a potent, multitytrosine kinase inhibitor that exerts broad antiproliferative activity by targeting PDGFRα, PDGFRβ, ABL, SRC family kinases, KIT, and several other tyrosine kinases (39, 40). In contrast, crenolanib (CP-868,596) is a relatively specific inhibitor of PDGFRβ that is more than 100-fold more selective for PDGFRs versus a variety of other kinases (e.g., KIT, VEGFR-2, TIE-2, FGFFR-2, EGFR, EBBB2, and SRC; refs. 41, 42). Both drugs have been shown to inhibit PDGFR kinase activity by competing with ATP. To compare wild-type and mutant PDGFRα signaling alterations in response to these inhibitors, cells were serum-starved overnight, then treated with crenolanib or dasatinib for 3 hours before adding PDGF-AA ligand. As previously reported, the D842V mutant was resistant to dasatinib treatment, however it was effectively inhibited by crenolanib (42). Both inhibitors significantly blocked activation of wild-type PDGFRα and all other mutants analyzed as shown by decreased phosphorylation of the receptor at Tyr-572/574, Tyr-742, Tyr-720, and Tyr-754 (Fig. 3A). Furthermore, downstream signaling activation was significantly diminished, including decreased phosphorylation of PI3K and MAPK pathway effectors (Fig. 3A and Supplementary Fig. S3A). D842V and V544ins were the only two mutants that induced a substantial increase in SHP2 phosphorylation (Supplementary Fig. S2) and the only two mutants for which crenolanib induced a substantial decrease in phospho-SHP2 (Supplementary Fig. S3A).

The effect of each inhibitor on cell proliferation was examined by XTT assay (Fig. 3B and Supplementary Fig. S3B), using a concentration greater than the IC90 determined to block receptor phosphorylation (Supplementary Fig. S4). Crenolanib selectively inhibited proliferation of PDGFRα-expressing cells, both wild-type and all analyzed mutants, whereas it did not affect proliferation of the empty vector control cells (Fig. 3B and Supplementary Fig. S3B). In contrast, dasatinib exerted broad antiproliferative effects and significantly inhibited empty vector control cells in addition to PDGFRα-expressing cells. Furthermore, concordant with the inability of dasatinib to block phosphorylation of the D842V mutant, cells expressing this mutant showed a diminished growth inhibitory response compared with other mutants (Fig. 3B). Crenolanib and dasatinib both exert cytostatic effects on PDGFRα-expressing p53-null PMAs, arresting cells in G0/G1 (Supplementary Fig. S5).

**Figure 3.** Crenolanib and dasatinib selectively inhibit proliferation of PDGFRα-expressing p53-null PMAs. A, proliferation of p53-null PMAs transduced with retroviruses expressing wild-type PDGFRα or PDGFRα mutants was measured by XTT assay (Fig. 3B and Supplementary Fig. S3B), using a concentration greater than the IC90 determined to block receptor phosphorylation (Supplementary Fig. S4). Crenolanib selectively inhibited proliferation of PDGFRα-expressing cells, both wild-type and all analyzed mutants, whereas it did not affect proliferation of the empty vector control cells (Fig. 3B and Supplementary Fig. S3B). In contrast, dasatinib exerted broad antiproliferative effects and significantly inhibited empty vector control cells in addition to PDGFRα-expressing cells. Furthermore, concordant with the inability of dasatinib to block phosphorylation of the D842V mutant, cells expressing this mutant showed a diminished growth inhibitory response compared with other mutants (Fig. 3B). Crenolanib and dasatinib both exert cytostatic effects on PDGFRα-expressing p53-null PMAs, arresting cells in G0/G1 (Supplementary Fig. S5).

However, neither inhibitor induced significant cell death, as assessed by annexin V staining and TUNEL (terminal deoxynucleotidyl transferase–mediated dUTP nick end labeling) assays (data not shown).

PDGFRα mutations are oncogenic in vivo and drive development of HGGs

To determine whether expression of wild-type PDGFRα or PDGFRα mutants renders p53-null PMAs tumorigenic, 2 million cells were implanted intracranially into the parietal lobe of 2-month-old athymic nude mice and monitored daily for signs of morbidity. Mice were euthanized and brain tumor tissue was analyzed as shown by decreased phosphorylation of the receptor at Tyr-572/574, Tyr-742, Tyr-720, and Tyr-754 (Fig. 3A).

The tumor-induced morbidity was detected between 23 and 72 days for all mutants except E7del-expressing tumors, which occurred at 103 to 119 days and the single tumor from wild-type PDGFRα, which occurred at 120 days after implantation (Fig. 4A). Standard histopathologic preparations from all tumors were evaluated (by D.W. Ellison) and classified according to WHO criteria (Fig. 4B and Supplementary Table S3). Overall, 63% (44 of 70) of tumors analyzed were grade 3 anaplastic astrocytoma, 26%
(18 of 70) were grade 3 anaplastic oligoastrocytoma, 16% (7 of 70) were grade 4 glioblastoma, and the single tumor that developed from cells expressing wild-type PDGFRα was the only low-grade tumor, a grade 2 oligoastrocytoma. Tumors expressing the D842V or V544ins mutation were significantly associated with anaplastic astrocytoma histology (P < 0.0001 and P = 0.0012, respectively) and tumors with E10del were significantly associated with anaplastic oligoastrocytoma histology (P = 0.002). The rest of the evaluated tumors expressing C540ins, E10del2, and E7del mutations were not significantly associated with a specific morphology (P > 0.2).

Immunohistochemical analysis for PDGFRα showed strong overexpression of the receptor throughout all tumors. PDGFRα-driven murine gliomas showed growth patterns similar to human HGGs including an easily visualized focal mass as well as diffuse infiltration into the normal brain parenchyma (Fig. 4C and Supplementary Fig. S6A). These tumors were immunopositive for p-4E-BP1 (Thr37/46) and p-Akt (Ser473), suggesting activated PDGFRα signaling (Fig. 4C). Furthermore, activation of PDGFRα in tumor tissues was confirmed by Western blot analysis, which showed high levels of phosphorylated receptor on Tyr-572/574, Tyr-742, Tyr-720, and Tyr-754 in all tumors examined but not in normal brain (Fig. 4D). Moreover, phosphorylation of PI3K pathway components, SHP2 and Src family kinases were strongly elevated compared with normal cortex. In contrast, levels of total STAT3 and phosphorylated STAT3 were similarly increased in all analyzed tumors compared with normal brain tissue, which may indicate cell type–specific differential expression of STAT3, not necessarily selective activation of STAT3 signaling in tumor. There was no significant difference in levels of MAPK pathway activation observed between tumor tissues and normal brain (Fig. 4D and Supplementary Fig. S6B).

**Gene expression signatures of PDGFRα-driven murine HGGs resemble human HGGs**

To evaluate the similarity of the molecular signatures of PDGFR-driven murine HGGs to human disease, gene expression profiles were analyzed for representative mutant and...
PDGFRA Mutations in Gliomagenesis

wild-type PDGFRα generated brain tumors. In addition, gene expression profiles of EGFRvIII-driven murine HGGs were assayed for comparison (25). UHC segregated the tumors into two distinct subgroups (Supplementary Fig. S7). Interestingly, PDGFRα and EGFRvIII-expressing tumors were distributed between both subgroups and there was no significant association of specific PDGFRA mutations or tumor histopathology with either of the identified subgroups. Furthermore, using single sample GSEA the gene expression profile of each murine tumor was compared with published signature gene sets for human HGG subgroups (proneural, proliferative, and mesenchymal) and murine cell type–specific signatures (oligodendrocyte progenitor cells, oligodendrocytes, neurons, astrocytes, and cultured astroglia; refs. 30, 31). We also compared the gene expression signatures of seven independent untransduced p53-null PMAs, which showed a significant similarity to the published expression signatures of astrocytes and cultured astroglia (31). Interestingly, transformation of p53-null PMAs by PDGFRα mutants resulted in gliomas with a range of expression signatures representing the three major expression subgroups observed in human HGGs (Fig. 5; ref. 30). Of note, 37.8% (14 of 37) of PDGFRα tumors showed proneural, 32.4% (12 of 37) proliferative, and 16.2% (6 of 37) mesenchymal subgroup expression signatures. There was no significant association of specific PDGFRA mutations with a particular expression subgroup described in pediatric and adult HGGs (4, 5, 30). Interestingly, tumors driven by E10del2 mutation were significantly associated with the oligodendrocyte progenitor cell–gene expression signature (P = 0.03); however, there was no significant association between specific mutation and expression signature of cell types.

Discussion

Aberrations of PDGFRA signaling via amplification and/or mutation of PDGFRA are frequent in pediatric HGGs. Here, targeted sequencing identified novel activating somatic mutations of PDGFRA in pediatric HGGs. Two recent studies...
reported PDGFRα mutations in pediatric HGGs, but the functional consequence on PDGFRα activation was not explored and none of the described mutations overlapped with our findings (6, 12). Interestingly, mutations were not represented by a single hotspot as observed in gastrointestinal stromal tumors. One of the identified mutations in this study, V544ins, a small duplication resulting in a 14 amino acid in-frame insertion, was found in the transmembrane domain, potentially facilitating oligomerization of the receptor via the transmembrane domain or disrupting the inhibitory conformation of the juxtamembrane region and consequently leading to ligand-independent receptor dimerization and activation as observed for PDGFRβ, c-Kit, and other RTKs (43–45).

In adult glioblastomas, the frequency of PDGFRα amplification and mutation is lower than in pediatric tumors and PDGFRα mutations comprise a distinct set of alterations compared with childhood disease (8, 9, 23, 34). Approximately 40% of amplified PDGFRα in adult glioblastomas is not wild-type, but contains recurrent genomic deletions of exons 8 and 9, resulting in an in-frame deletion in the extracellular domain and constitutive receptor activation. Several in-frame deletions occur in pediatric HGG; however, the recurrent alterations in adult glioblastoma were not found in pediatric tumors. Instead, mutations were not restricted to a single functional domain, but were distributed among different regions of the PDGFRα protein, including the kinase domain and extracellular regions involved in ligand binding and receptor–receptor interaction. The six PDGFRα mutants analyzed represented alterations in different functional domains, and all were constitutively active and tumorigenic. Thus, alternative genetic mechanisms are used to generate oncogenic mutations of PDGFRα in childhood and adult HGGs.

Numerous mouse glioma models have been generated by expression of exogenous PDGF, driving paracrine stimulation of cells expressing endogenous PDGF (17–19, 46–48). In this study, gliomas were driven by the PDGFRα mutations found in pediatric HGGs. Both wild-type and mutant PDGFRα conferred a proliferative advantage to p53-null PMAs; however, the wild-type showed minimal tumorigenic activity, resulting in only 1 of 19 mice developing a low-grade glioma, whereas all six of the mutants induced HGG formation with 100% penetrance. In contrast, a previous study showed that wild-type PDGFRα-transformed Ink4a/Arf-null PMAs to generate gliomas (49). The difference in the gliomagenic activity of wild-type PDGFRα may be explained in part by a higher propensity for transformation in the recipient cells, as the Ink4a/Arf-null PMAs formed tumors at lower frequency in the absence of PDGFRα, whereas the early passage p53-null PMAs in the present study did not form any tumors. In addition, Ink4a/Arf and p53 loss may differentially cooperate with PDGFRα overexpression to drive glioma (49). It is also possible that the levels of wild-type receptor expression in our model system were not sufficient to model the gene amplification that drives tumorigenesis in human tumors. However, the wild-type receptor was expressed at levels similar to the E7del, E10del, and Ink4a/Arf-null PMAs to generate gliomas (49). The difference in the gliomagenic activity of wild-type PDGFRα may be explained in part by a higher propensity for transformation in the recipient cells, as the Ink4a/Arf-null PMAs formed tumors at lower frequency in the absence of PDGFRα, whereas the early passage p53-null PMAs in the present study did not form any tumors. In addition, Ink4a/Arf and p53 loss may differentially cooperate with PDGFRα overexpression to drive glioma (49). It is also possible that the levels of wild-type receptor expression in our model system were not sufficient to model the gene amplification that drives tumorigenesis in human tumors. However, the wild-type receptor was expressed at levels similar to the E7del, E10del, and p53del mutations (Fig. 2), which were also amplified in human tumors.

The fact that all PDGFRα mutations showed ligand-independent phosphorylation, whereas wild-type receptor activation required ligand stimulation, suggests lack of sufficient ligand in the brain of implanted adult animals, or different selective advantage conferred by wild-type PDGFRα amplification versus mutation with or without amplification. Amplification of wild-type PDGFRα occurred more frequently in tumors within the brainstem (26%, 11 of 43 DIPG vs. 11%, 9 of 84 nonbrainstem HGG, P = 0.04), whereas PDGFRα sequence
mutations were more common in pediatric HGG arising outside the brainstem, although this was not statistically significant (14%, 13 of 90 nonbrainstem HGG vs. 5%, 2 of 43 DIPG, P = 0.14; refs. 4, 5). Moreover, all six samples with concomitant amplification and mutation of PDGFRα were from nonbrainstem tumors. Given the higher frequency of wild-type amplification in DIPGs, it is possible that wild-type PDGFRα requires a more specific or alternative cell of origin to drive transformation compared with the mutants, which may not be adequately recapitulated in our experimental system. These effects can vary among oncogenic mutations. For example EGFRvIII drives tumorigenesis equivalently from Ink4a/Arf-null cortical astrocytes or neural stem cells, whereas BRAF-null duplications show a differential growth response in cerebellar neural stem cells compared with astrocytes, and in neural stem cells from the cerebellum compared with those from neocortex (50, 51). Furthermore, comparison of DIPG and nonbrainstem pediatric HGG also revealed distinctive gene expression profiles, significant differences in the frequency of histone mutations and specific large-scale genomic imbalances as well as the absence of focal deletion of CDKN2A in DIPG, which is common in pediatric nonbrainstem HGG (4, 5, 11). This suggests that distinct tumor microenvironments within different locations of the brain may exert different selective pressures driving pediatric HGG, which could include differential susceptibility to PDGFRα mutation/amplification-driven tumorigenesis.

The tumors that arose from mutant PDGFRα-transformed PMAs showed a range of morphologies. Although the majority of murine HGGs were diagnosed as anaplastic astrocytomas or glioblastomas, a significant number of tumors showed a mixed glial (oligodendrocytic) phenotype. Because tumors were generated with virally transduced astrocytes, this suggests that in a subset of tumors, signaling activated by mutated PDGFRα triggered astrocyte dedifferentiation as described for tumors induced by PDGF ligands in transplantation in cultured astrocytes (18). Alternatively, rare progenitor cell populations in the starting populations may give rise to some of the tumors. In several different studies, viral introduction of PDGF into the brain induced gliomas that had a predominantly proneural signature, perhaps driven in part by the endogenous cells that expressed PDGF and responded to the exogenous ligand (18, 47, 52). In contrast, the tumors arising from transduced PMAs in this study displayed a range of gene expression signatures similar to the spectrum observed in human HGGs and with similarities to expression signatures of a range of different types of normal cells, despite the relatively uniform astrocytic gene expression signature in the parental PMAs. This may indicate significant plasticity in the neonatal PMAs, especially in the context of aberrant signaling driven by mutant PDGFRα.

Because PDGFRα signaling alterations are frequent in pediatric HGGs, including amplification and/or activating mutation of the receptor, understanding the therapeutic and phenotypic consequences of PDGFRα mutations is important to guide clinical intervention. The model system reported here showed that all mutants tested were constitutively active and capable of driving HGGs with complete penetrance and a range of gene expression signatures relevant to human tumors. This model varies from previous models driven by expression of exogenous ligand in that it recapitulates the autocrine signaling that the mutant receptor drives in tumor cells.

The consequence of oncogenic mutations to therapeutic inhibitors can have significant clinical ramifications. Some oncogenic mutations confer resistance to small molecule inhibitors. For example, PDGFRα D842V is a recurrent hotspot mutation in gastrointestinal stromal tumors that confers resistance to imatinib (32). In contrast, some oncogenic mutations cause enhanced sensitivity to small molecule inhibitors and are associated with significantly prolonged survival, such as BRAF mutations in melanoma, or EGFR mutations in small-cell lung cancer (53, 54). This is highly dependent on the specific mutation rather than the therapeutic target, as illustrated by the different spectrum of EGFR mutations in adult glioblastomas that are not sensitive to the same small molecule inhibitors that work well in lung cancer (55). All of the PDGFRα mutants tested here were inhibited by crenolanib and most were inhibited by dasatinib. While it is promising that these mutations do not confer resistance to available small molecule PDGFR inhibitors, these compounds induced a cytostatic, but not cytotoxic response. This strongly suggests that clinical use of PDGFR inhibitors as a single agent may not be sufficient to cause regression of pediatric HGG, but could be a useful addition to other therapeutic approaches.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

Authors’ Contributions
Conception and design: B.S. Paugh, D.A. Bax, C. Jones, S.J. Baker
Development of methodology: B.S. Paugh, X. Zhu, R. Endersby, D.A. Bax, D. Carvalho
Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): B.S. Paugh, X. Zhu, R. Endersby, A.K. Diaz, J. Zhang, D.A. Bax, D. Carvalho, A. Broniscer, C. Wetmore, C. Jones, S.J. Baker
Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): B.S. Paugh, X. Zhu, C. Qu, J. Zhang, D.A. Bax, D. Carvalho, A. Onar-Thomas, J. Zhang, C. Jones, D.W. Ellison, S.J. Baker
Writing, review, and/or revision of the manuscript: B.S. Paugh, X. Zhu, J. Zhang, R.M. Reis, A. Onar-Thomas, A. Broniscer, D.W. Ellison, S.J. Baker
Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): B.S. Paugh, X. Zhu, J. Zhang
Study supervision: B.S. Paugh, C. Wetmore, S.J. Baker

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Barbara S. Paugh, Xiaoyan Zhu, Chunxu Qu, et al.


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