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Aparna Kaul  
*Washington University School of Medicine in St. Louis*

Yi-Hsien Chen  
*Washington University School of Medicine in St. Louis*

Ryan J. Emnett  
*Washington University School of Medicine in St. Louis*

Sonika Dahiya  
*Washington University School of Medicine in St. Louis*

David H. Gutmann  
*Washington University School of Medicine in St. Louis*

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RESEARCH COMMUNICATION

Pediatric glioma-associated KIAA1549:BRAF expression regulates neurogliial cell growth in a cell type-specific and mTOR-dependent manner

Aparna Kaul,1,3 Yi-Hsien Chen,1,3 Ryan J. Emmett,1 Sonika Dahiya,2 and David H. Gutmann1,4

1Department of Neurology, 2Department of Pathology and Immunology, Washington University School of Medicine, St. Louis, Missouri 63108, USA

Tandem duplications involving the BRAF kinase gene have recently been identified as the most frequent genetic alteration in sporadic pediatric glioma, creating a novel fusion protein [f-BRAF] with increased BRAF activity. To define the role of f-BRAF in gliomagenesis, we demonstrate that f-BRAF regulates neuroglial cell, but not astrocyte, proliferation and is sufficient to induce glioma-like lesions in mice. Moreover, f-BRAF-driven NSC proliferation results from tuberin/Rheb-mediated mammalian target of rapamycin (mTOR) hyperactivation, leading to S6-kinase-dependent degradation of p27. Collectively, these results establish mTOR pathway activation as a key growth regulatory mechanism common to both sporadic and familial low-grade gliomas in children.

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In the pediatric population, the most common solid tumors originate in the brain, where they can be associated with significant morbidity. Among the histological subtypes, low-grade pilocytic astrocytomas [PAs] are the most frequently encountered brain tumors [Central Brain Tumor Registry of the United States 2012]. PAs arise either sporadically or in the context of the Neurofibromatosis type 1 [NF1] inherited cancer disposition syndrome. Tumors arising in children with NF1 typically develop along the optic pathway, following biallelic inactivation of the NF1 tumor suppressor gene in neuroglial cells. The NF1 protein [neurofibromin] is a negative regulator of the RAS proto-oncogene such that neurofibromin loss in neuroglial cells results in increased RAS-dependent mammalian target of rapamycin (mTOR) signaling (Lee et al. 2010).

In contrast, sporadic PAs do not harbor mutations in the NF1 gene [Kluwe et al. 2001] but rather are associated with alterations in the BRAF gene locus [Pfister et al. 2008]. High-resolution genomic arrays and fluorescent in situ hybridization (FISH) analysis have identified tandem duplications on chromosome 7q34 that create novel genes containing the kinase domain of BRAF fused with a fragment of the KIAA1549 gene. Subsequent studies have confirmed that the KIAA1549:BRAF fusion [f-BRAF] is found in 65%–75% of sporadic PAs [Jones et al. 2008], leading to elevated mitogen-activated protein kinase (MAPK) activation.

While it has been established that the presence of f-BRAF is a hallmark of sporadic PAs with diagnostic potential, its precise role in neurogliial cell growth and gliomagenesis is unresolved. Although f-BRAF can transform NIH3T3 cells [Jones et al. 2008], previous studies have demonstrated that BRAF does not increase astrocyte proliferation [Jacob et al. 2009], induces senescence of astrocytes [Jacob et al. 2011] and neural stem cells [NSCs] in vitro [Raabe et al. 2011], and does not result in gliomagenesis when ectopically expressed in mouse brains in vivo [Robinson et al. 2010].

In this study, we sought to define the role of this signature genetic alteration in neurogliial cell function and glioma formation. We demonstrate that f-BRAF regulates neurogliial cell growth in a cell type-specific manner via tuberous sclerosis complex (TSC)/Rheb activation of mTOR and is sufficient to induce glioma-like lesions in vivo.

Results and Discussion

The discovery of the signature KIAA1549:BRAF genetic alteration represents a major advance in our understanding of the molecular pathogenesis of sporadic PA. However, subsequent studies have raised important questions regarding the role of this potential driver mutation in neurogliial cell proliferation and PA tumorigenesis. Moreover, prior studies have examined the impact of wild-type or oncogenic BRAF [BRAFV600E] expression on astrocyte or astroglial progenitor function, rather than the signature PA-associated BRAF fusion protein. To determine whether f-BRAF expression is sufficient to confer a growth advantage to neuroglial progenitor cells, we expressed f-BRAF in cerebellar NSCs, since the majority of sporadic PAs arise in the cerebellum [Ohgaki and Kleihues 2005]. Primary NSC cultures generated from postnatal day 1 [P1] mouse cerebella expressed the Sox2 stem cell and Olig2 glial progenitor markers, but not glial fibrillary acidic protein [GFAP; astrocyte] [Supplemental Fig. S1A], and were capable of multilineage differentiation [Supplemental Fig. S1B]. Cerebellar NSCs were transduced with either empty pBABE-puro vector [pBABE] or f-BRAF. Since BRAF activates MAPK in a MEK-dependent manner, a constitutively active MEK mutant [MEK signalling]. caMEK] was included. Following caMEK or f-BRAF expression in cerebellar NSCs, there was increased MAPK activation [1.5-fold and twofold increase] of Thr202/Tyr204 phosphorylation, respectively [Fig. 1A] and increased NSC proliferation, as assessed by secondary neurosphere diameters [28% and 46% increases, respectively], direct cell counting [1.5-fold increase] and limiting dilution analysis [37 ± 7 pBABE-transduced vs. 2 ± 1 f-BRAF-transduced cells] [Supplemental Fig. S1C].

Oncogenic BRAF has been reported to induce activation of the mTOR pathway in melanoma, thyroid, and breast carcinomas [Bachhoe et al. 2010; Duong et al. 2012; Fantastico et al. 2012]. In addition, previous studies from our laboratory have demonstrated that the NF1 gene product neurofibromin regulates murine astrocyte, NSC, and glioma growth in an mTOR-dependent manner.

Keywords: pilocytic astrocytoma, astrocytes, neural stem cells

3These authors contributed equally to this work.

E-mail gutmann@neuro.wustl.edu

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mTOR inhibition attenuated the f-BRAF-induced increases in S6 activation [Fig. 1E] and proliferation [Fig. 1F,G], similar to that observed following PD901 treatment. Finally, whereas MEK inhibition blocked f-BRAF-induced mTOR activation, rapamycin had no effect on f-BRAF-induced MAPK activation [Supplemental Fig. S1G]. Collectively, these results demonstrate that f-BRAF regulates NSC proliferation by activating the mTOR pathway in a MEK-dependent manner.

Several studies have shown that ectopic expression of either RAF or BRAF alone is not sufficient to induce gliomas in mice [Lyustikman et al. 2008; Robinson et al. 2010; Gronych et al. 2011], suggesting that BRAF may not be a driver mutation. However, BRAF expression was targeted to progenitor cells in the cerebral hemispheres rather than the more typical locations [cerebellum, optic pathway, and brainstem] where f-BRAF-containing PAs arise in children. To establish a causative role for the signature BRAF alteration in gliomagenesis, we show that f-BRAF expression resulted in a fivefold increase in cerebellar NSC soft agar colony formation [Supplemental Fig. S2A]. Next, mCherry-expressing cerebellar NSCs infected with control [pBABE] or f-BRAF were injected into the cerebella of 3-wk-old wild-type mice and analyzed at 2.5 and 6 mo post-transplantation. At 2.5 mo, we observed threefold increases in the numbers of Ki-67+ and Iba1+ cells at the injection sites in mice transplanted with f-BRAF-expressing NSCs [n = 3] relative to control virus-infected NSCs [n = 3]. In addition, there was only a modest increase in cellularity and GFAP immunoreactivity and no nuclear atypia or cells with piloid morphologies [Supplemental Fig. S2B,C]. However, at 6 mo post-injection, mice transplanted with f-BRAF-expressing NSCs [n = 5] harbored clear areas of increased cellularity near the injection sites, consistent with glioma-like lesions, including abnormal cell clusters with pale nuclei [Fig. 2A, H&E, inset], increased GFAP+ cells with piloid morphologies and elongated hair-like cytoplasmic processes [Fig. 2A, inset], increased numbers of proliferating [Ki67+] cells [Fig. 2A,B], increased microglial [Iba1+] cells infiltration [Fig. 2A,B], and increased numbers of endoglin+ endothelial cells [data not shown] relative to pBABE-containing NSC-injected control mice [n = 4]. Whereas mCherry+ cells were identified at the injection sites from both pBABE- and f-BRAF-transduced NSC-transplanted mice [Fig. 2A], both NSC-derived astrocytes [GFAP and mCherry double-positive cells] [Supplemental Fig. S2E] and host-derived astrocytes [GFAP+ only] [Supplemental Fig. S2E] were detected in the f-BRAF-expressing lesions. Consistent with the in vitro results, there was also increased pMAPK and pS6 immunostaining in f-BRAF-expressing NSC-engrafted mice at both 2.5 and 6 mo of age [Fig. 2C; Supplemental Fig. S2D]. While no gross neurological deficits or changes in survival were observed, body weight was reduced by 28% in mice injected with f-BRAF-expressing NSCs.

The finding that f-BRAF expression in cerebellar NSCs generated glioma-like lesions in the cerebellum following engraftment likely reflects differences in the innate capabilities of these brain region-specific NSCs. In this regard, previous studies from our laboratory have revealed NSC regional specificity in response to f-BRAF expression and Nf1 gene loss. Whereas lateral ventricle NSCs exhibit marginal or no increase in NSC proliferation following Nf1 inactivation or f-BRAF expression, respectively, third ventricle and brainstem NSCs demonstrate increased proliferation and...
f-BRAF expression does not increase RSK phosphorylation [Thr573], excluding RSK-mediated TORC1 activation as the mechanism underlying f-BRAF growth regulation (Fig. 3A). Second, we observed a 2.6-fold increase in tuberin phosphorylation [Ser939] following f-BRAF expression in NSCs [Fig. 3A]. Similarly, there was a 2.9-fold and 1.6-fold increase in tuberin phosphorylation in NSCs after caMEK and BRAFV600 expression, respectively (Supplemental Fig. S3A,B). Moreover, treatment of f-BRAF-expressing NSCs with PD901 reduced the observed increases in tuberin and S6 phosphorylation [Fig. 3B], demonstrating that f-BRAF-induced tuberin phosphorylation was MEK-dependent.

Since prior reports on BRAF growth regulation in astrocytes have yielded conflicting results, we transduced primary GFAP+ but Sox2/Olig2-negative astrocytes from P1–P2 mouse cerebella (Supplemental Fig. S3C) with pBABE, BRAFV600 or f-BRAF. Consistent with the known effects of BRAF on MAPK activation, both BRAFV600 and f-BRAF expression increased MAPK phosphorylation [6.5-fold and 4.4-fold, respectively], but neither BRAF molecule increased astrocyte proliferation (Fig. 3C). The inability of BRAF to increase astrocyte proliferation was not the result of induced cellular senescence or programmed cell death (TUNEL labeling) (Supplemental Fig. S3D). Similarly, this failure to increase cell proliferation was also observed in another astrocyte population (forebrain) despite increased MAPK activation (Supplemental Fig. S3E). Moreover, the inability of BRAF to increase astrocyte proliferation was not dependent on mitogen (EGF, PDGF, or PACAP) availability (Supplemental Fig. S3F). Consistent with the finding that BRAF-induced MAPK activation is dependent on MEK activity (Supplemental Fig. S3G), caMEK expression also did not increase primary astrocyte proliferation (Supplemental Fig. S3H). Together, these results demonstrate that f-BRAF increases neural/glial cell proliferation in a cell type-specific manner unrelated to its ability to activate MEK/MAPK signaling. This observed cell type specificity underscores the critical cellular context in which cancer-associated driver mutations must occur in order to facilitate proliferation, transformation, and tumorigenesis. The differential response of NSCs and astrocytes to f-BRAF expression is consistent with previously reported roles for neuroglial progenitors in gliomagenesis (Taylor et al. 2005; Alcantara Llaguno et al. 2009; Liu et al. 2011). To elucidate the mechanism underlying this cell type-specific effect, we compared the status of mTOR pathway activation following f-BRAF expression in astrocytes and NSCs. While f-BRAF expression in NSCs resulted in an 8.6-fold increase in S6 phosphorylation, there was no change in S6 phosphorylation following f-BRAF expression in astrocytes (Fig. 3D). Furthermore, there was no change in tuberin phosphorylation following f-BRAF expression in astrocytes (Fig. 3E), indicating that MAPK, although activated by f-BRAF, was unable to phosphorylate and inactivate tuberin and thus could not activate mTOR in astrocytes.

We next sought to define the potential mechanism underlying differential tuberin phosphorylation in NSCs relative to astrocytes. Following hypotonic lysis fractionation, there was ~13-fold more tuberin in the membrane fraction of astrocytes compared with NSCs following normalization to total tuberin in each fraction [Fig. 3F]. These results support a model in which cell type-specific f-BRAF-mediated mTOR activation reflects the subcellular localization of tuberin. Polycystin-1, an integral membrane protein, suppresses mTOR activation by directly interacting with...
manner in NSCs. First, to confirm that TSC complex inactivation was responsible for f-BRAF-mediated mTOR activation, we expressed f-BRAF in wild-type or Tsc1<sup>−/−</sup> NSCs. Compared with their wild-type counterparts, empty vector-expressing Tsc1<sup>−/−</sup> NSCs exhibited a 2.5-fold increase in S6 phosphorylation as well as increased NSC proliferation (1.5-fold increase in cell number and 23% increase in neurosphere diameter). However, f-BRAF expression did not further increase S6 phosphorylation or proliferation in Tsc1<sup>−/−</sup> NSCs (Fig. 4A,B).

Second, ectopic Rheb expression in NSCs using a conditional Rheb-expressing mouse strain (Banerjee et al. 2011) resulted in a 2.1-fold increase in S6 activation [Supplemental Fig. S4A] and increased NSC proliferation (1.4-fold in cell number; 23% increase in neurosphere diameter) [Supplemental Fig. S4B]. Third, to determine whether f-BRAF regulation of mTOR required Rheb activation, Rheb expression was reduced by shRNA-mediated knockdown. Attenuated Rheb expression [70% reduction] using two different shRNA constructs in f-BRAF-expressed NSCs reduced S6 phosphorylation and proliferation to wild-type levels with no effect on wild-type NSCs [Fig. 4C,D; Supplemental Fig. S4C]. Together, these results establish TSC/Rheb-mediated mTOR activation as the mechanism underlying f-BRAF-mediated growth regulation of cerebellar NSCs.

Since mTOR can regulate cell growth in either an mTORC1-dependent [4E-BP1 and STAT3] or mTORC2-dependent [AKT] manner, we examined the activation state of each of these downstream signaling molecules. No changes in 4E-BP1 (Thr37/46), STAT3 (Ser727), or AKT (Ser473) were observed following f-BRAF expression in cerebellar NSCs [data not shown], mTOR can also regulate proliferation and cell cycle progression by increasing p27 phosphorylation and reducing total p27 expression (Hong et al. 2008; Dalvai et al. 2010). Following f-BRAF expression, there was increased p27 phosphorylation [Thr187] and decreased total p27 expression [Supplemental Fig. S4D]. Moreover, both MEK [PD901] and mTOR [rapamycin] inhibition reduced p27 phosphorylation and restored p27 protein expression to wild-type levels [Supplemental Fig. S4D], indicating that f-BRAF controls NSC proliferation via mTOR-dependent regulation of p27 levels.

To elucidate the mechanism underlying f-BRAF regulation of p27 expression in cerebellar NSCs, we examined the mTOR downstream target S6K. Human S6K1 [hS6K1] expression increased NSC proliferation as well as p27 phosphorylation and decreased p27 protein levels [Supplemental Fig. S4E,F]. In addition, S6K1 knockdown using two different shRNA constructs abrogated the f-BRAF-mediated increase in cell proliferation, S6 activation, and p27 phosphorylation and restored p27 expression to wild-type levels [Fig. 4E,F; Supplemental Fig. S4C]. To assess whether p27 phosphorylation required cyclin-dependent kinase

Figure 3. Cell type-specific effects of f-BRAF expression on NSC proliferation and tuberin phosphorylation. (A) Increased tuberin phosphorylation was observed in f-BRAF-expressing NSCs, with no change in RSK phosphorylation. (B) f-BRAF-induced tuberin and S6 phosphorylation was inhibited by PD901 treatment. (C) Increased MAPK phosphorylation was observed in BRAF<sup>+/+</sup> and f-BRAF-expressing astrocytes. f-BRAF transgene expression was verified by RT–PCR. Compared with the vector control, BRAF expression did not increase astrocyte proliferation. (D) Increased S6 phosphorylation was observed in f-BRAF-expressing NSCs but not astrocytes. (E) f-BRAF expression increased tuberin phosphorylation in NSCs but not astrocytes. α-Tubulin served as an internal loading control. (F) Increased tuberin membrane localization was observed in astrocytes compared with NSCs. Calnexin served as a marker for the membrane fraction. (C) Cytoplasm; [M] membrane; [Veh] vehicle. Error bars denote mean ± SD. [NS] Not significant.
mTOR pathway inhibitors for these common childhood cancers. It is worth noting that while both f-BRAF activation and NF1 loss lead to mTOR activation, the mechanism underlying mTOR regulation in each case is distinct. Whereas neurofibromin loss activates mTOR and leads to TORC2-dependent AKT activation, resulting in p27 phosphorylation and degradation [Lee et al. 2010], f-BRAF expression causes MEK-dependent tuberin inactivation and Rheb-directed TORC1/S6K-mediated p27 phosphorylation and degradation. These divergent mechanisms underscore the innate heterogeneity at the tissue (brain region), cellular (astrocyte/NSC), and molecular levels relevant to gliomagenesis.

Materials and methods

Mice

Tsc1^fl/fl^C0/C0 mice (Uhlmann et al. 2002) and conditional Rheb-expressing transgenic mice [Banerjee et al. 2011] were generated as previously described. All mice were maintained on a C57BL/6 background and used in accordance with an approved Animal Studies protocol at Washington University.

Human tumor samples

Tumor specimens were obtained from the Tissue Procurement Core Facility at Washington University under an approved Institutional Review Board protocol.

Primary astrocyte and NSC cultures

Cerebellar hemispheres were microdissected from the brains of C57BL/6 mouse pups to establish primary astrocyte and NSC cultures, and proliferation assays were performed as previously described (Dasgupta and Gutmann 2005; Lee et al. 2010; Banerjee et al. 2011). Wild-type and Tsc1^fl/fl^C0/C0 NSCs were generated from Tsc1^fl/fl^C0/C0 pups following infection with LacZ and Cre adenovirus, respectively. Retroviral and lentiviral transduction was performed (Lee et al. 2010; Banerjee et al. 2011). All in vitro experiments were performed at least three times using primary NSC and astrocyte cultures generated using pups from different litters and were independently transduced with the respective constructs.

Subcellular fractionation

Following hypotonic (10 mM HEPES at pH 7.9, 1.5 mM MgCl2, 10 mM KCl) lysis and disruption of cells with a 30-gauge syringe needle, crude nuclei were pelleted by centrifugation, and supernatants were subjected to ultracentrifugation at 100,000 g for 1 h at 4°C to generate cytosolic and membrane fractions. Equal percentages of each fraction were subjected to SDS-PAGE and immunoblot analysis.

Western blotting

Cell lysis, SDS-PAGE, and immunoblot analysis were performed as previously reported (Uhlmann et al. 2004).

Intracranial injections

Three-week-old wild-type C57BL6 mice were anesthetized by an intraperitoneal (i.p.) injection of 100 mg/kg ketamine and 6 mg/kg xylazine. NSCs (5 × 10^5) in 2 μL of PBS were injected into the cerebellum using 2 (Cdk2) [Montagnoli et al. 1999], f-BRAF-expressing NSCs were treated with the Cdk2 inhibitor purvalanol-A [PurA]. Following PurA treatment, f-BRAF-induced cerebellar NSC proliferation [Supplemental Fig. S4H] and p27 phosphorylation were restored to wild-type levels with no effect on mTOR activation [Fig. 4G]. Collectively, these results establish that f-BRAF regulation of NSC proliferation requires mTOR-mediated activation of S6K1 to suppress p27 levels in a Cdk2-dependent manner [Fig. 4H].

The finding that f-BRAF regulates NSC growth in an mTOR-dependent manner establishes a central growth control target for both sporadic [KIAA1549:BRAF] and familial [NF1-associated] pediatric low-grade glioma and provides compelling preclinical evidence for the use of...
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A hamster syringe was 3 mm below the dura mater using a stereotaxic apparatus. Mice were euthanized 2.5 and 6 mo later.

**Immunostaining**

Paraffin or frozen sections were processed (Dasgupta and Gutmann 2005) prior to staining with appropriate antibodies (Supplemental Table 2).

**Statistical analysis**

All in vitro experiments were analyzed using the Student’s t-test. Statistical significance was set at P < 0.05.

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**References**


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