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

Scott M. Gianino
Washington University School of Medicine in St. Louis

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

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Neurofibromatosis-1 regulation of neural stem cell proliferation and multilineage differentiation operates through distinct RAS effector pathways

Yi-Hsien Chen, Scott M. Gianino, and David H. Gutmann

Department of Neurology, Washington University School of Medicine, St. Louis, Missouri 63110, USA

Neurofibromatosis type 1 (NF1) is a common neurodevelopmental disorder caused by impaired function of the neurofibromin RAS regulator. Using a combination of NF1 genetically engineered mice and pharmacological/genetic inhibition approaches, we report that neurofibromin differentially controls neural stem cell (NSC) proliferation and multilineage differentiation through the selective use of the PI3K/AKT and RAF/MEK pathways. While PI3K/AKT governs neurofibromin-regulated NSC proliferation, multilineage differentiation is MEK-dependent. Moreover, whereas MEK-regulated multilineage differentiation requires Smad3-induced Jagged-1 expression and Notch activation, MEK/Smad3-regulated Hes1 induction is only responsible for astrocyte and neuronal differentiation. Collectively, these findings establish distinct roles for the RAS effector pathways in regulating brain NSC function.

Supplemental material is available for this article.

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Results and Discussion

To determine which RAS downstream effectors were hyperactivated following NF1 inactivation, we focused on third ventricle zone (TVZ) NSCs [Lee et al. 2012]. NF1−/− and wild-type TVZ NSC cultures were generated from postnatal day 1 (P1) NF1lox/lox mice, and Nf1−/−/Nf1lox/lox pups following Cre or LacZ gene adenovirus infection, respectively. Following neurofibromin loss, increased ERK (3.5-fold, Thr202/Tyr204) and AKT (1.8-fold and threefold, Ser473 and Thr308) phosphorylation was observed (Fig. 1A). To identify which RAS effector pathway was responsible for neurofibromin regulation of NSC growth and multilineage differentiation, we used PI3K/AKT and MEK pharmacological inhibitors. While MK2206 treatment inhibited AKT activation [Fig. 1B] and reduced Nf1−/− NSC growth [Fig. 1C, direct cell counting], D [percentage of Ki67+ cells] to wild-type levels, it had no effect on ERK phosphorylation [Fig. 1B]. PD0325901 [PD901] treatment inhibited MEK activation but did not decrease Nf1−/− NSC proliferation [Fig. 1C] or AKT phosphorylation [Fig. 1B].

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Corresponding author: gutmann@neuro.wustl.edu

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Neurofibromin regulates NSC proliferation in a PI3K/AKT-dependent manner. (A) Nf1 loss in TVZ NSCs resulted in increased ERK and AKT activation (pERKT202/Y204, pAKTS473, and pAKTT308 phosphorylation) relative to wild-type controls. (B) Treatment with the MEK (5 nM PD0325901 [PD901]) or AKT inhibitor (50 nM MK2206) reduced ERK and AKT hyperactivation. Reduced NSC numbers (direct cell counting) (C) and percentage of Ki67+ cells (D) were observed only in Nf1−/− TVZ NSCs treated with MK2206. (E) NVP-BKM120 (BKM120) but not 5 mg/kg PD901 treatment decreased the percentage of Ki67+ cells in the TVZ of P18 Nf1−/− conditional knockout mice in vivo (n = 4 per group) to nearly wild-type levels (dotted line). ERK and AKT hyperactivation were decreased following PD901 and BKM120 treatment, respectively, relative to wild-type controls. n = 4 per group. (veh) Vehicle. Nuclei were counterstained with DAPI. Error bars denote the mean ± SD. Bar, 100 μm. [*] P < 0.05; [**] P < 0.01.

Figure 1. Neurofibromin regulates NSC proliferation in a PI3K/AKT-dependent manner. (A) Nf1 loss in TVZ NSCs resulted in increased ERK and AKT activation (pERKT202/Y204, pAKTS473, and pAKTT308 phosphorylation) relative to wild-type controls. (B) Treatment with the MEK (5 nM PD0325901 [PD901]) or AKT inhibitor (50 nM MK2206) reduced ERK and AKT hyperactivation. Reduced NSC numbers (direct cell counting) (C) and percentage of Ki67+ cells (D) were observed only in Nf1−/− TVZ NSCs treated with MK2206. (E) NVP-BKM120 (BKM120) but not 5 mg/kg PD901 treatment decreased the percentage of Ki67+ cells in the TVZ of P18 Nf1−/− conditional knockout mice in vivo (n = 4 per group) to nearly wild-type levels (dotted line). ERK and AKT hyperactivation were decreased following PD901 and BKM120 treatment, respectively, relative to wild-type controls. n = 4 per group. (veh) Vehicle. Nuclei were counterstained with DAPI. Error bars denote the mean ± SD. Bar, 100 μm. [*] P < 0.05; [**] P < 0.01.

To determine whether differential RAS pathway control of NSC proliferation was also observed in vivo, we used Nf1−/− conditional knockout mice to inactivate Nf1 gene expression in BLBP+ NSCs at embryonic day 9.5 [E9.5] [Hegedus et al. 2007]. At P0.5, increased ERK phosphorylation [Thr202/Tyr204], AKT phosphorylation [Ser473 and Thr308], and proliferating cell (percentage of Ki67+ cells) were observed in Nf1−/− conditional knockout relative to wild-type controls (Supplemental Fig. S1C,D). Following the treatment of pregnant females with either 5 mg/kg PD901 or 30 mg/kg BKM120 from E15 to E18, the percentage of proliferating Ki67+ cells within the TVZ was quantified at P0.5. ERK hyperactivation in the TVZ of Nf1−/−BLBP conditional knockout pups was reduced by PD901 treatment; however, there was no change in TVZ cell proliferation [Fig. 1E]. In contrast, BKM120 treatment inhibited AKT [Ser473 and Thr308 phosphorylation] hyperactivation and reduced TVZ cell proliferation [Fig. 1E]. Collectively, these data demonstrate that neurofibromin regulates NSC proliferation in a PI3K/AKT-dependent manner in vitro and in vivo, consistent with previous findings [Lee et al. 2010].

AKT maintenance of NSC growth has been reported in mice and flies [Lee et al. 2010, 2013; Amiri et al. 2012], however, the role of AKT in regulating NSC multilineage differentiation is less clear [Peltier et al. 2007]. Following in vitro differentiation, Nf1 loss in NSCs resulted in an increase in the percentage of GFAP+ and O4+ cells (3.4-fold and fourfold, respectively) and a decrease in Tuj1+ cells (2.5-fold) relative to wild-type cells [Fig. 2A]. While treatment with the AKT inhibitor [MK2206] had no effect on these Nf1−/− deficient NSC differentiation defects, MEK inhibition [PD901] restored Nf1−/− NSC astrocyte, oligodendrocyte [Olig2+ and O4+ cells], and neuron differentiation to near wild-type levels [Fig. 2A; Supplemental Fig. S2A]. Similar results were observed using other PI3K [BKM120] and MEK [UO126] inhibitors [Supplemental Fig. S2B].

To determine whether MEK activation was responsible for these multilineage defects in vivo, Nf1−/−BLBP conditional knockout pups were treated from P0.5 to P18 [astrocytes and oligodendrocytes] or from E15 to E18 [neurons and Olig2+ progenitors] with PD901 or BKM120. While Nf1−/− inactivation in BLBP+ neural progenitor cells led to increased numbers of GFAP+ astrocytes and APC+ oligodendrocytes at P18 [Supplemental Fig. S2C], decreased numbers of NeuN+ neurons and increased numbers of Olig2+ cells were observed at P0.5 [Supplemental Fig. S2E]. As observed...
NF1 controls neuroglial growth and differentiation

in vitro, MEK, but not PI3K/AKT, inhibition restored astrocyte [Fig. 2B,C] and oligodendrocyte numbers in Nf1−/−BLBP conditional knockout mice to wild-type levels at P18 (Supplemental Fig. S2D) as well as ameliorated the increase in Olig2+ cells and decrease in NeuN+ cells at P0.5 (Supplemental Fig. S2E). Together with the in vitro results, these data reveal that AKT and MEK independently regulate NSC proliferation and multilineage differentiation, respectively.

The observation that MEK is a central driver of gliogenesis is consistent with prior reports demonstrating that Mek1/2-deficient mice exhibit impaired glial cell specification (Li et al. 2012) and that neonatal MEK inhibition rescues the developmental defects in Nf1−/− brains by restoring normal neuron–glial specification (Wang et al. 2012). However, the mechanism responsible for neurofibromin/MEK-driven multilineage differentiation has not been elucidated. Two transcription factors, Erm and Ascl1, can regulate gliogenesis in response to elevated RAS/ERK signaling (Li et al. 2012; Breunig et al. 2015). While Nf1−/− NSCs exhibit increased Erm expression by quantitative RT–PCR (qRT–PCR) and Western blotting, this was not attenuated following MEK inhibition (PD9011) [Supplemental Fig. S3A,B]. In addition, no change in Ascl1 protein levels was observed after Nf1 loss, and nearly 100% of wild-type and Nf1−/− NSCs were Ascl1+ (Supplemental Fig. S3B,C). Since Erm and Ascl1 function can also be regulated by phosphorylation (Li et al. 2014), these proteins could still play a role in Nf1−/− NSC gliogenesis.

Based on increased Jagged-1 expression in Nf1−/− deficient mouse astrocytes (Banerjee et al. 2011) and numerous studies highlighting the critical role of Notch1 signaling in specifying neural cell fate during development (Lutolf et al. 2002, Stump et al. 2002), we examined Jagged1/Notch pathway activation. Following neurofibromin loss in NSCs, there was increased Jagged1 expression and Notch activation [Notch intracellular domain (NICD) expression] in vitro (Fig. 3A) and in vivo (Fig. 3B). However, in contrast to Nf1−/− deficient astrocytes (Banerjee et al. 2011), Jagged1 was not regulated by mTOR activation. While there was a 2.1-fold and 3.6-fold increase in S6 Ser240/244 and Akt Ser473 phosphorylation, respectively, mTOR inhibition (UO126) and PI3K (BKM120) inhibition was not regulated by mTOR activation. While there was an increase in Akt Ser473 phosphorylation, this was not attenuated following MEK inhibition (PD9011) [Supplemental Fig. S3A,B]. In addition, no change in Ascl1 protein levels was observed after Nf1 loss, and nearly 100% of wild-type and Nf1−/− NSCs were Ascl1+ [Supplemental Fig. S3B,C]. Since Erm and Ascl1 function can also be regulated by phosphorylation (Li et al. 2014), these proteins could still play a role in Nf1−/− NSC gliogenesis.

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The importance of Jagged1 to gliogenesis is further supported by studies using conditional Jagged1 deletion in cerebellar neuroepithelial cells (Weller et al. 2006) as well as reports demonstrating that Jagged1-mediated Notch pathway activation promotes astrogliogenesis in vivo (Hu et al. 2013) and inhibits neurogenesis in vitro (Wilhelmssson et al. 2012). The ability of activated Notch1 to dictate multilineage differentiation in neural progenitor cells typically involves the Hes1 and Hes5 transcription factors (Furukawa et al. 2000, Hojo et al. 2000). Following Nf1 loss in NSCs, there was increased Hes1 and Hes5 expression [Fig. 4A], which was reduced by PD901 treatment [Fig. 4B] in vitro. Moreover, ectopic expression of an activated MEK (caMEK), but not an activated AKT (myrAKT), molecule in NSCs increased Jagged1, NICD, Hes1, and Hes5 levels [Supplemental Fig. S4A]. Finally, MEK inhibition restored Hes1 and Hes5 expression to wild-type levels in the TVZ of Nf1−/−BLLP conditional knockout mice in vivo [Fig. 4C]. Together, these findings demonstrate that the Notch1 signaling pathway is activated following neurofibromin loss in a MEK-dependent manner.

Based on conflicting reports regarding Hes5 regulation of gliogenesis (Hojo et al. 2000, Wu et al. 2003) and the nearly exclusive expression of Hes1 within the TVZ, we chose to focus on Hes1. Using two independently generated Hes1 shRNA constructs to decrease Hes1 expression in NSCs [60% reduction], the increased astrocyte differentiation observed following neurofibromin loss was reduced to near wild-type levels [Fig. 4D]. Importantly, Hes1 reduction had no effect on Nf1−/− NSC growth (direct cell counting) [Fig. 4E] or proliferation (percentage of Ki67+ cells) [Fig. 4F]. Moreover, Hes1 knockdown ameliorated
the decrease in neuronal differentiation in Nf1-deficient NSCs but surprisingly had no effect on oligodendrocyte differentiation (percentage of O4+ cells) (Supplemental Fig. S4B). These findings demonstrate that neurofibromin regulation of astrocyte and neuronal differentiation is mediated by Hes1 in a reciprocally coordinated fashion, whereas other mechanisms underlie MEK-dependent oligodendrocyte differentiation. In this regard, Hes1 knockdown did not reduce the number of Olig2+ cells (Supplemental Fig. S4C). While RAF/MEK signaling is an important determinant of oligodendrocyte differentiation in mice [Galabova-Kovacs et al. 2008] and zebrafish [Shin et al. 2012], other neurofibromin-regulated MEK downstream pathways are likely responsible for governing oligodendrocyte differentiation.

To determine how neurofibromin controls Jagged1 expression, we examined Jagged1 mRNA expression using real-time qRT–PCR [Fig. 5A]. Jagged1 mRNA expression was regulated in Nf1−/− NSCs on the transcriptional level through MEK, since PD901 treatment restored Jagged1 mRNA to wild-type levels. Several potential regulators of Jagged1 expression have been identified, including β-catenin, YAP, and TGFβ/Smad3 [Chen et al. 2010; Zhang et al. 2010; Tschaharganeh et al. 2013]. While we observed no changes in β-catenin activation or YAP expression following neurofibromin loss, the increased Smad3 expression observed in Nf1-deficient NSCs was reduced to wild-type levels following PD901 treatment (Fig. 5B,C).

We next used genetic and pharmacologic approaches to reduce Smad3 function. Following Smad3 knockdown [using two different shRNA constructs], Jagged1, NICD, and...
Hes1 expression in Nf1<sup>−/−</sup> NSCs was restored to wild-type levels [Fig. 5D]. Similar to PD901 treatment, Smad3 knockdown of Nf1<sup>−/−</sup> NSCs restored astrocyte, oligodendrocyte, and neuronal differentiation to wild-type levels [Fig. 5E]. It should be noted that Smad3 knockdown did not change Hes5 expression [Fig. 5D], arguing against Hes5 as a mediator of neurofibromin-controlled multilineage differentiation. Similar results were observed in Nf1-deficient NSCs treated with the SIS3 Smad3 pharmacological inhibitor [Supplemental Fig. S5A,B; Jinnin et al. 2006]. Collectively, these results support a mechanism by which neurofibromin/MEK control of astrocyte and neuron differentiation operates in a Smad3/Jagged1/Hes1-dependent manner.

Neurofibromin regulation of Smad3 function could operate at the level of transcription, protein degradation, or phosphorylation (Massague et al. 2005). While neurofibromin loss results in increased Smad3 levels, subcellular fractionation revealed an enrichment of Smad3 in the nucleus of Nf1<sup>−/−</sup> NSCs (34%) relative to wild-type NSCs (8%) [Supplemental Fig. S5C]. However, the mechanism underlying this increase in Smad3 expression was not the result of increased Smad3 RNA levels [qRT–PCR] [Supplemental Fig. S5D] or degradation mediated by increased SCF/ROC1 and GSK3-β binding [Fukuchi et al. 2001; Guo et al. 2008]. Whereas Smad3 physically interacted with GSK3-β, but not with SCF/ROC1 [Supplemental Fig. S5E], neurofibromin loss or MEK inhibition [PD901 treatment] had no effect on Smad3 and GSK3-β binding, as assessed by immunoprecipitation. Finally, MEK-dependent Smad3 regulation was not dependent on TGFβ-induced phosphorylation, as Smad3-Ser423/425 phosphorylation was similar in wild-type and Nf1<sup>−/−</sup> NSCs [Supplemental Fig. S5F] and did not involve phosphorylation at the best-characterized ERK phosphorylation site [Ser208] [Supplemental Fig. S5F]. Future studies will be required to identify the mechanism responsible for neurofibromin regulation of Smad3 levels.

Taken together, our findings establish that neurofibromin control of NSC function involves the selective use of distinct RAS effector pathways. In this regard, RAS activation is critical for both neurofibromin-regulated NSC proliferation and multilineage differentiation such that inhibition using the nonselective RAS inhibitor [lovasatin] [Li et al. 2005] restored both Nf1-deficient NSC growth and multilineage differentiation to wild-type levels [Supplemental Fig. S5G–I]. However, whereas neurofibromin control of neuron and astrocyte differentiation requires Smad3 regulation of Hes1, the mechanism underlying Smad3-mediated oligodendrocyte differentiation likely involves other transcription factors. In this manner, Olig-1 and Olig-2 have been identified as essential factors for specifying oligodendrogligenesis [Lu et al. 2000; Takebayashi et al. 2002]. Consistent with recent findings demonstrating that Olig1 is not essential for oligodendrocyte development in mice [Paes de Faria et al. 2014], MEK inhibition [PD901] reduced the increased Olig2, but not Olig1, mRNA and protein expression in Nf1-deficient NSCs [Fig. 5F]. Moreover, the elevated Olig2 expression in Nf1-deficient NSCs was decreased following Smad3 genetic [Fig. 5G,H] or pharmacologic [Supplemental Fig. S5J] inhibition. These findings suggest a model in which neurofibromin control of NSC multilineage differentiation involves distinct transcriptional programs: Neuron and astrocyte differentiation requires MEK/Smad3-dependent Hes1 induction, whereas MEK/Smad3-dependent oligodendrocyte differentiation involves Olig2 function [Fig. 5I].

Coupled with observations that other RAS downstream pathways have cell type-specific functions [neurons vs. astrocytes] relevant to brain cell function [Hegedus et al. 2007; Anastasaki and Gutmann 2014], the observations reported here establish that differential use of distinct RAS effector signaling pathways can govern separable cellular functions even within the same cell type, further underscoring the importance of cellular context in interpreting the impact of genetic mutations on brain function.

Materials and methods

Mice

BLBP-Cre, Nf1<sup>fl/fl</sup>/wt transgenic mice were crossed with Nf1<sup>fl/fl</sup> mice to generate BLBP-Cre, Nf1<sup>fl/fl</sup> [conditional knockout] mice. Nf1<sup>fl/fl</sup> mice were used as wild-type controls. All strains were maintained on a C57BL/6 background and used in accordance with an approved animal studies protocol at Washington University.

Primary NSC analysis

TVZ NSCs were isolated from the TVZ of P1 Nf1<sup>fl/fl</sup> mouse pups and analyzed as previously described [Lee et al. 2010]. Retroviral and lentivirus [Supplemental Table 1] transduction was performed for overexpression and knockdown studies, respectively. All experiments were performed at least three times using primary NSCs generated from independent litters.

Western blotting

Western blotting was performed as previously reported [Lee et al. 2010] using primary antibodies [Supplemental Table 2] and was quantified by densitometry using a chemiluminescence imaging system [UVP]. Each experiment was performed at least three times, and representative blots are presented.

Immunostaining

Paraffin or frozen sections were processed [Dasgupta and Gutmann 2005] prior to staining with the appropriate antibodies. The percentage of Ki67<sup>+</sup> cells lining the TVZ was quantified as previously reported [Lee et al. 2012].

Pharmacologic inhibition studies

Neurospheres were trypsinized into single cells, and 5 × 10<sup>5</sup> cells per well were plated onto ultralow-binding 60-mm plates. Cells were treated with specific inhibitors for 4–5 d. PD901 (5 mg/kg/day; Selleck), BKM120 (30 mg/kg; Selleck), or matched vehicle (0.5% hydroxypropyl methycellulose) was added to each well except for the control group. Cells were incubated for 10 d before being fixed and stained with DAPI and antibodies against nestin and GFAP. Immunofluorescence was imaged with a Leica confocal microscope. Three independent experiments were performed, and similar results were obtained. Statistical analysis

Each experiment was performed with samples from at least three independent groups. Statistical significance was set at P < 0.05 using the Student’s t-test.

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