DNA methylation controls the timing of astrogliogenesis through regulation of JAK-STAT signaling

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Summary
DNA methylation is a major epigenetic factor that has been postulated to regulate cell lineage differentiation. We report here that conditional gene deletion of the maintenance DNA methyltransferase I (Dnmt1) in neural progenitor cells (NPCs) results in DNA hypomethylation and precocious astroglial differentiation. The developmentally regulated demethylation of astrocyte marker genes as well as genes encoding the crucial components of the gliogenic JAK-STAT pathway is accelerated in Dnmt1–/– NPCs. Through a chromatin remodeling process, demethylation of genes in the JAK-STAT pathway leads to an enhanced activation of STATs, which in turn triggers astrocyte differentiation. Our study suggests that during the neurogenic period, DNA methylation inhibits not only astroglial marker genes but also genes that are essential for JAK-STAT signaling. Thus, demethylation of these two groups of genes and subsequent elevation of STAT activity are key mechanisms that control the timing and magnitude of astroglial differentiation.

Key words: Dnmt1, CpG methylation, Neural differentiation, STAT1, Chromatin remodeling, MeCP2, Histone modification, Mouse

Introduction
CpG DNA methylation is one of the major epigenetic factors that influences gene expression in mammals (Jaenisch and Bird, 2003). DNA methylation is essential for embryogenesis as mice deficient in DNA methylation die at early to mid-gestation stages directly following gastrulation (Li et al., 1992; Okano et al., 1999). In addition to regulating development, DNA methylation has been implicated in tumorigenesis as changes of CpG methylation are frequently observed in cancer cells (Jones and Baylin, 2002). Moreover, alterations in DNA methylation and mutations of methyl-CpG binding protein 2 (MeCP2) have been linked to several mental retardation disorders such as Rett, ICF (immunodeficiency, centromere instability, facial anomaly), Fragile X and ATR-X syndromes, indicating that the central nervous system (CNS) is particularly sensitive to epigenetic abnormalities (Robertson and Wolffe, 2000). Thus, DNA methylation most probably plays crucial roles in the development and/or function of the CNS (Fan et al., 2001; Feng et al., 2005).

The mammalian CNS is established through a temporally and spatially well-organized sequence of events during development. Starting as a single layer of multipotent neural progenitor cells (NPCs), the developing CNS sequentially produces neurons, astrocytes, and oligodendrocytes at specific stages during development (Bayer, 1991; Qian et al., 2000; Sauvageot and Stiles, 2002). The sequential differentiation of neurons and glia from NPCs is not simply due to the sequential appearance of neuronal and glial inducing cues, because early CNS progenitors are not capable of immediately differentiating into glia, even when presented with strong glial-inducing factors (Sauvageot and Stiles, 2002; Takizawa et al., 2001). Therefore, during development, NPCs gradually acquire competence for gliogenesis. It is intriguing that when cells become gliogenic, they simultaneously lose their neurogenic potential, suggesting the existence of a neurogenic to gliogenic switch mechanism during CNS development.

Both cell intrinsic factors and extracellular cues have been postulated to influence the neuro- to gliogenic switch. For example, the presence of neurogenic factors such as the proneural basic helix-loop-helix (bHLH) genes has been shown to actively suppress the gliogenic state of NPCs during the period of neurogenesis (Nieto et al., 2001; Sun et al., 2001), contributing to the late onset of gliogenesis. In
addition, the transient rise of basic fibroblast growth factors (bFGFs) in the ventricular zone of the mouse cortex around embryonic day 14.5 (E14.5) may serve as a potential modulatory factor mediating the transition from neurogenesis to gliogenesis. Low levels of bFGF have been shown to increase neuronal differentiation, while high levels of bFGF expand the glial progenitor pool (Dono et al., 1998; Qian et al., 1997). In addition, bFGF regulates the expression of the epithelial growth factor receptor (EGFR), which is correlated with the appearance of astrogligenic progenitors (Lilien and Raphael, 2000). The expression of EGFR in neural progenitors could also be influenced by other factors, such as bone morphogenetic proteins (BMPs), WNT proteins and sonic hedgehog (SHH) in vitro (Viti et al., 2003b). As oligodendrocytes are generated from the ventral part of the forebrain, gliogenesis in the developing cortex is primarily confined to astrocyte differentiation. Although it remains to be determined whether the aforementioned glia-inducing factors are either necessary or sufficient to act in vivo to regulate the neuro- to gliogenic switch, most of these factors have been shown to influence the essential astrogligenic JAK-STAT pathway (Nakashima et al., 1999b; Song and Ghosh, 2004; Sun et al., 2001; He et al., 2005).

The JAK-STAT pathway, which is activated by cytokine leukemia inhibitory factor (LIF) through the heterodimeric receptor LIFRβ and gp130 can effectively induce astroglial differentiation (Bonnì et al., 1997; Rajan and McKay, 1998). BMPs also use STATs to activate the expression of astrocyte marker genes via the association between STATs and the transactivating complex composed of the BMP-activated signaling factors Smad1 and P300/CBP (Nakashima et al., 1999b). Gene knockouts of LIF (Bugga et al., 1998), LIFRβ (Koblar et al., 1998), gp130 (Nakashima et al., 1999a) or STAT3 (He et al., 2005) all result in impaired astrocyte differentiation in vivo, further indicating that JAK-STAT signaling contributes to astrogligenesis in the developing CNS.

Although LIF is a potent astrogligenic differentiation factor, it cannot immediately trigger astrogligenesis in early cortical NPCs. The lack of an astrogligenic response to LIF in early cortical NPCs has been primarily attributed to methylation of the coregligenic period and becomes robustly elevated during the neurogenic NPCs. Global DNA hypomethylation in the developing CNS leads to precocious astrogligenesis. However, hypomethylation-induced precocious astrogligenesis is not simply due to demethylation of the STAT binding element within the GFAP promoter (Takizawa et al., 2001), but primarily due to the elevation of overall JAK-STAT signaling activity. Our findings suggest that DNA methylation regulates the timing and magnitude of astrogligenesis through both modulation of JAK-STAT activity and its direct inhibition of glial marker genes via inactive chromatin remodeling.

Materials and methods

Transgenic mice, CNS precursor cell cultures, and immunocytochemistry

The generation of nestin-cre; Dnmt1 conditional knockout mice has been described by Fan et al. (Fan et al., 2001). The use of transgenic mice is approved by UCLA Institutional Animal Research Committee. Mouse neural precursor cells from E11.5 cortices or CNS (containing fore-, mid- and hind-brain, and cervical spinal cord) were dissected, dissociated and cultured in DMEM/F12 chemically defined medium supplemented with B27 as described previously (Ge et al., 2002). FGF2 was added to the culture on the day of plating. After fixation (methanol:acetonitrile, 1:1-v:v, for 2 minutes), cells were stained with antibodies against precursor, neuronal and astroglial markers, including Nestin (rabbit anti-Nestin, a kind gift from Ron McKay at NIH), MAP2 (rabbit anti-MAP2, Peninsula), S100β and GFAP (mouse anti-S100β, mouse anti-GFAP from Sigma and rabbit anti-GFAP from Accurate). Rabbit anti-Dnmt1 antibody (PATH52; 1:2000) was a gift from Dr Tim Bestor (Columbia University). Rabbit anti-β-gal antibody (1:500 dilution) was purchased from Calbiochem. Images were captured with an Olympus fluorescent microscope.

DNA methylation analysis

Bisulfit genomic sequencing analysis was performed essentially as described Clark et al. (Clark et al., 1994). Methylation-specific SNuPE assay was used to quantify the percentage of methylation at a particular CpG site as described in detail by Gonzalgo and Jones (Gonzalgo and Jones, 1997). The quantification of radioactive signals was performed with a phosphor-imager system (Molecular Dynamics).

Electrophoretic-mobility-shift assay (EMSA) and chromatin-immunoprecipitation (ChIP) analyses

Purification of nuclear extracts and EMSA assays were carried out as described (Bonnì et al., 1997). For ChIP analysis, NPCs were left untreated or treated with LIF for 30 minutes and crosslinked with 1% formaldehyde for 20 minutes at room temperature. Experiments were performed as previously described (Martinowich et al., 2003). Normal rabbit serum or anti-β-gal antisera was routinely used in ChIP assays for negative controls (data not always shown). Antibodies used for pull downs were anti-MeCP2 (Upstate), anti-H3 dmK9, anti-H3 dmK4 (Upstate), anti-STAT1 (generated by Ke Shuai’s laboratory at UCLA) (ten Hoeve et al., 2002) and anti-STAT3 (Santa Cruz). DNA samples obtained before (Input) and after (ChIP) immunoprecipitation were subjected to PCR amplification. PCR primer sequences for ChIP analyses are listed as follows. Gfap gene promoter encompassing the −1.5 kb STAT binding element: forward 5′ TAA GCT GAA GAC CTT GCA GTG 3′; reverse, 5′ GCT GAA TAG AGC CTT GTC CTC 3′. Stat1 gene promoter set I (−1748 bp to −1478 bp) encompassing one of the STAT binding elements, used for anti-STAT3 ChIP: forward, 5′ AAG TGG TGC TGT TCA ACG 3′; reverse, 5′ CAG AGG TAA GCT GAT TCC 3′. Stat1 gene promoter set II (−670 bp to −449 bp) encompassing one of the STAT binding elements, used for anti-STAT3 ChIP: forward, 5′ ATT TGG TAC TGT TCA ACG 3′; reverse, 5′ CAG AGG TAA GCT GAT TCC 3′. Stat1 gene promoter set II (−670 bp to −449 bp) encompassing one of the STAT binding elements, used for anti-STAT3 ChIP: forward, 5′ AAG TGG TGC TGT TCA ACG 3′; reverse, 5′ CAG AGG TAA GCT GAT TCC 3′. Stat1 gene promoter set II (−670 bp to −449 bp) encompassing one of the STAT binding elements, used for anti-STAT3 ChIP: forward, 5′ ATT TGG TAC TGT TCA ACG 3′; reverse, 5′ CAG AGG TAA GCT GAT TCC 3′. Stat1 gene promoter set II (−670 bp to −449 bp) encompassing one of the STAT binding elements, used for anti-STAT3 ChIP: forward, 5′ ATT TGG TAC TGT TCA ACG 3′; reverse, 5′ CAG AGG TAA GCT GAT TCC 3′.
DNA constructs, cell transfection, and promoter activity luciferase-reporter assay

The construction of the 1.9 kb rat GFAP-luciferase and β-gal reporter plasmids has been described before (Bonni et al., 1997). The mouse Dnmt1 expression plasmid was kindly provided by Dr En Li (Chen et al., 2003). Plasmids were transfected into neural precursor cells using the Fugene-6 reagent as instructed by the manufacturer (Roche). For the promoter activity assay, fly-luciferase reporter plasmids were co-transfected into cells using Fugene-6 (Roche) along with a TK-renilla luciferase plasmid (Promega), which serves as a cell transfection control. Cultures were treated with or without LIF (50 ng/ml) for ~24 hours post-transfection and were lysed and subjected to dual luciferase assays (Promega). Statistical analysis of luciferase assay data and cell counting results was performed with StatView 5.0 software (SAS Institute).

TUNEL staining method

Cultured cells were fixed with 4% PFA/PBS and stained for TUNEL analysis using the Apoptag Fluorescein In Situ Apoptosis Detection Kit (Chemicon) following the supplied manufacturer’s protocol. TUNEL-positive cells were counted at 40× magnification (20 fields/coverslip) and reported as a ratio of total cell number as determined by DAPI staining.

Western and northern blot analysis

Proteins were extracted with NP40 lysis buffer and concentrations measured using the Bradford method. After denaturing with SDS lysis buffer, protein samples were fractionated on a SDS-PAGE gel (BioRad) and transferred to nitrocellulose membrane for immunoblotting. To measure phosphorylation of STAT1/3, cell lysis buffer, protein samples were fractionated on a SDS-PAGE gel, and the percentage of MAP2/β-gal-positive cells over the total number of β-gal-positive cells was scored.

Retroviral lineage tracing assay

E11.5 NPCs from control and Dnmt1−/− CNS were infected with a replication-deficient retrovirus containing a β-galactosidase gene at the time of plating as described before (Bonni et al., 1997). At 4 DIV, cells were triple-labeled with antibodies against MAP2, GFAP and β-gal, and the percentage of MAP2/β-gal and GFAP/β-gal double-positive cells over the total number of β-gal positive cells was scored.

Results

In vivo and in vitro precocious astroglial differentiation induced by DNA hypomethylation in the developing CNS

NPCs sequentially give rise to neurons, astrocytes and oligodendrocytes in vivo during development. To determine whether DNA methylation influences astroglial differentiation in vivo, we examined transgenic mice bearing a cre-loxP conditional mutation in the maintenance DNA methyltransferase gene, Dnmt1 (Fan et al., 2001). The Cre recombinase is driven by the Nestin enhancer, which allows for specific cre expression in the CNS ventricular/germinal zone nestin-positive NPCs (Fan et al., 2001). When the Dnmt1 gene is deleted specifically in NPCs in the developing CNS at embryonic day 9-10 (E9-10), extensive DNA hypomethylation is detected in over 90% of the CNS cells, starting at E11-12 (Fan et al., 2001). We collected spinal cord and brain tissues from E12 to 18.5 mouse embryos and examined the expression of the astrocytic marker proteins GFAP and S100β. Through immunohistochemical analyses, we found that radially distributed S100β and GFAP fibers were apparent in E15.5 Dnmt1−/− (mut) cervical spinal cord, whereas both S100β and GFAP immunoreactivities were minimal in their wild-type counterparts (Fig. 1A). At E18, when radially distributed immature astrocytic fibers (S100β+, GFAP+) were detectable in the wild-type spinal cord, more stellate S100β-positive and GFAP-positive astrocytes were detectable in the mutant spinal cord, indicating the differentiation of more mature astrocytes (Fig. 1B). Using relatively more sensitive Western blot analyses, we detected GFAP protein in Dnmt1−/− spinal cord samples as early as E12. GFAP protein was below the detection threshold in samples from wild-type spinal cord until E14, at which point the level of this astrocyte marker in mutant samples was much higher (Fig. 1C). Consistent with the immunohistochemistry data, western blot analyses also indicated that the expression of both GFAP and S100β was enhanced in mutant spinal cords at E17-18 (Fig. 1C,D). To address whether precocious astroglial differentiation is widespread throughout the CNS in Dnmt1−/− animals, we examined GFAP levels in other regions of the CNS. Immunohistochemical analyses indicated that in mutant mice between E15-18, enhanced GFAP-positive fibers were present in multiple brain regions such as the cortical ventricular region and hippocampal primordial area, as shown in Fig. 1E,F. Consistent with these data, in E18 mutant embryos GFAP protein levels were increased in the olfactory bulb, cortex, striatum, thalamus and cerebellum when compared with control tissues (Fig. 1G). There was also an increase in GFAP mRNA in E18 Dnmt1−/− brains relative to controls (Fig. 1H). Together, these observations strongly support the notion that precocious activation of the astroglial differentiation program occurs in Dnmt1−/− NPCs. We noticed that GFAP expression was excluded from MAP2-positive neurons (data not shown), suggesting that DNA methylation does not interfere with lineage segregation of neurons and glia in vivo.

To uncover the underlying mechanism by which hypomethylation leads to precocious astrogliogenesis, we established an E11.5 mouse cortical NPC culture system, in which the neuro- to gliogenic switch can be recapitulated in vitro. Previous studies have demonstrated that cultured NPCs derived from early (E11.5) mouse cortices differentiate mainly down the neurogenic pathway, whereas NPCs derived from late (E14.5 and later) cortices have increased potential for glial differentiation (Qian et al., 2000). We found that when E11.5 mouse cortical NPCs were cultured for an extended period, they switched to producing GFAP-positive astrocytes after 4-5 days in vitro (DIV) (Fig. 2A). The generation of astrocytes in E11.5 cortical NPC cultures can be further promoted by treatment with LIF (Fig. 2A). However, even in the presence of LIF, no GFAP-positive astrocytes were observed in short-term (fewer than 4-5 DIV) mouse E11.5 cortical cultures, suggesting that there is an intrinsic mechanism blocking the initiation of astroglial differentiation in early NPCs.

In contrast to the lack of GFAP positive astrocytes in control (Dnmt1+/+) cultures, GFAP-positive cells with astrocytic morphologies were observed in E11.5 Dnmt1−/− cultures at 2 DIV with LIF treatment (Fig. 2B). The precocious induction of GFAP expression as well as another astrocyte marker S100β in Dnmt1−/− NPC cultures was also evident (Fig. 2C,D). In
these cultures, virtually all of the cells from mutant mouse CNS lacked Dnmt1 (Fan et al., 2001). Using a monoclonal antibody against 5′-methylcytosine (5′meC), we found that the intensity of 5′meC staining was significantly weaker in Dnmt1–/– cells than that in control cells after three days in culture, which is consistent with decreased DNA methylation in Dnmt1–/– cells (Fig. 2E). However, immunostaining with the 5′-methylcytosine antibody is not quantitative enough to allow us to address whether newly generated GFAP-positive astroglial cells are exclusively derived from those Dnmt1–/– NPCs with a more extensively demethylated genome. Finally, we also carried out TUNEL staining and compared cell death phenotypes between cultured control and Dnmt1 mutant NPCs after 5 DIV. There was no apparent difference in the percentage of TUNEL-positive cells when mutant cultures were compared with control cultures [CON=2.7% (75/2728); MUT=3.9% (92/2347)], indicating that the increase in GFAP and S100β positive cells in Dnmt1–/– cultures did not result from changes in cell survival in vitro.

To determine whether the enhanced astrocyte differentiation detected in E11.5 Dnmt1–/– CNS progenitors was at the expense of neurogenesis, replication-deficient recombinant retrovirus carrying a transgene encoding the green fluorescent protein (GFP) was used to infect E11.5 wild-type and mutant CNS cultures at 1 DIV. The differentiation of the virally infected cells was analyzed 2 days later. These experiments demonstrated that the enhanced astrogliogenesis in Dnmt1–/– NPC cultures occurred at the expense of neurogenesis, suggesting that a precocious neuro- to gliogenic switch is achieved through DNA hypomethylation (Fig. 2F). Demethylation-induced GFAP expression persists into the gliogenic phase, as cortical cultures generated from E15 animals also show substantially higher numbers of GFAP-positive cells in mutant cultures than in control cultures with or without LIF treatment (Fig. 2G). Consistent with the in vivo observation, GFAP staining did not overlap with any MAP2 staining in both control and Dnmt1–/– E15 cortical cells (Fig. 2G). This finding indicates that DNA hypomethylation did not induce any aberrant/ectopic expression of glial marker genes in neurons. Thus, the effect of Dnmt1 deficiency on GFAP gene expression is restricted to the gliogenic NPCs that give rise to more GFAP-positive astrocytes.

**Enhanced activation of the JAK/STAT astrogliogenic pathway due to DNA hypomethylation**

Astroglial differentiation is regulated by LIF-induced activation of the JAK-STAT pathway. The major STAT proteins expressed in the nervous system are STAT1 and STAT3. Importantly, increased STAT1/3 expression and...
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phosphorylation in E11.5 NPCs is correlated with the neuro- to gliogenic switch in vitro (Fig. 3A) (He et al., 2005). In addition, we noticed that genes encoding various components of the JAK-STAT pathway including STAT1, STAT3, gp130 receptor, as well as JAK1 contain STAT-binding elements in their promoters that can be activated by STATs, suggesting that an autoregulatory/positive feedback loop of this pathway exists. This positive-feedback loop may be important for the rapid and robust activation of JAK-STAT signaling during the neuro- to gliogenic transition (He et al., 2005).

We reasoned that the precocious onset of astroglial differentiation observed in the hypomethylated CNS may be mediated in part by increased activation of the JAK-STAT pathway. To test this hypothesis, we examined whether DNA hypomethylation induces hyperactivation of the JAK/STAT pathway. We found that upon transient LIF treatment the levels of activated/phosphorylated STAT1/3 (pSTAT1/3) were significantly higher in 4-day cultured E11.5 Dnmt1–/– cells than in control cells (Fig. 3B). The increased in STAT3 levels was moderate in mutant cells (Fig. 3B). All three splice variants of STAT1 mRNA were upregulated in E18.5 mutant brains (Fig. 3C), consistent with increased gene transcription of the STAT1 gene in hypomethylated cells. In addition, quantitative RT-PCR and western blot analyses indicated that both mRNA (data not shown) and protein levels of gp130 were elevated in Dnmt1–/– cells (Fig. 3D), which may contribute to the increase in STAT3 phosphorylation.

To examine whether the elevated STAT phosphorylation observed in Dnmt1–/– E11.5 CNS cultures had any functional consequences in the activation of astrocyte marker genes, we analyzed levels of total STAT proteins in control and mutant cells. STAT1 protein levels were elevated in cultured Dnmt1–/– cells in comparison with those in control cells (Fig. 3B). The increase in STAT3 levels was moderate in mutant cells (Fig. 3B). All three splice variants of STAT1 mRNA were upregulated in E18.5 mutant brains (Fig. 3C), consistent with increased gene transcription of the STAT1 gene in hypomethylated cells. In addition, quantitative RT-PCR and western blot analyses indicated that both mRNA (data not shown) and protein levels of gp130 were elevated in Dnmt1–/– cells (Fig. 3D), which may contribute to the increase in STAT3 phosphorylation.

To examine whether the elevated STAT phosphorylation observed in Dnmt1–/– E11.5 CNS cultures had any functional consequences in the activation of astrocyte marker genes, we transfected a 1.9 kb GFAP promoter-luciferase reporter construct (Bonni et al., 1997) into 3 DIV cultures from either control or mutant E11.5 mouse CNS. The cells were either left untreated or treated with LIF (50 ng/ml) immediately following transfection and analyzed for luciferase activity 24 hours later. LIF treatment induced a stronger activation of the GFAP promoter in Dnmt1–/– cells than in Dnmt1+/+ cells (Fig. 4A). To
Dnmt1 deficiency accelerates the developmentally regulated demethylation of glial differentiation-related genes

Multiple CpG sites within the rat Gfap promoter are methylated early on during CNS development and become less methylated during gliogenic stages in vivo (Teter et al., 1996). Takizawa et al. also reported that a single CpG site within the STAT-binding element in the mouse Gfap promoter undergoes demethylation during the neuro- to gliogenic switch in the developing CNS. To further examine the relationship between changes in DNA methylation and gliogenesis, we analyzed the methylation status of the mouse Gfap, Stat1 and S100β genes in neurogenic and gliogenic NPCs. Within the Gfap promoter, we focused on a region from −1557 bp to −1280 bp, which is highly conserved across species of mouse, rat and human. In fact, this region in the rat GFAP gene has been designated as the neuroectoderm/astrocyte methylation domain (Fig. 5A), because it undergoes demethylation during the neurogenic to gliogenic phase transition (Teter et al., 1996). Importantly, the relative position and sequence of the STAT-binding element (5′TTCCGAGAA3′) within this neuroectoderm methylation region is 100% conserved among the three species. We performed bisulfite genomic sequencing analyses on 8 CpG sites within this promoter region. Our analysis showed that selective demethylation occurred at five out of the eight CpG sites in E11.5 cortical NPCs over 4 days in culture, including the CpG within the STAT-binding element (Fig. 5A). Similarly, selective CpG demethylation was also observed on the Stat1 and S100β promoters in E11.5 cortical culture during the neuro- to gliogenic switch (Fig. 5B, see Fig. S1 in the supplementary material).

Loss of Dnmt1 activity would be predicted to cause accelerated demethylation of the Gfap, Stat1 and S100β promoters in the developing CNS. To directly examine the methylation status of the STAT-binding element within the Gfap promoter in both control and Dnmt1 mutant cells, we performed bisulfite genomic sequencing analyses and the methylation-site-specific single nucleotide primer extension (SNuPE) assays (Gonzalgo and Jones, 1997). The SNuPE assay showed a significant decrease in methylation of the STAT-binding site in cultured E12.5 Dnmt1−/− CNS cells compared with control cells (Fig. 5C). The CpG site within the Gfap STAT-binding site is virtually completely unmethylated in E18.5 Dnmt1−/− brains in vivo (Fig. 5C), suggesting that demethylation of this CpG site also occurs in the neuronal population. However, neuronal Gfap expression was not detected, supporting the notion that demethylation of the CpG within the STAT binding element is not sufficient to induce GFAP expression. It is likely that additional mechanisms exist in neurons to actively suppress the demethylated GFAP gene promoter in Dnmt1−/− neurons. Substantial demethylation of the Stat1 and S100β promoters was also observed in Dnmt1−/−
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brains during development, which could contribute to the induction of STAT1 and S100β in hypomethylated NPCs and/or astroglia (Fig. 5D, see Fig. S1 in the supplementary material).

To examine whether re-introducing Dnmt1 gene expression in E11 Dnmt1−/− NPCs would abrogate the phenotype of precocious astroglial differentiation, we cultured E11 control and Dnmt1−/− CNS NPC cultures. After 24 hours, cells were lysed and subjected to dual-luciferase assays (Promega). *P<0.001 compared with the control group (Dnmt1+/+) without LIF treatment. **P<0.01 compared with the group of Dnmt1−/− cells without LIF treatment (ANOVA with Post-hoc tests). (B) EMSA assay using a 25 bp unmethylated probe containing the STAT-binding element within the GFAP promoter with nuclear extracts from cultured control and Dnmt1−/− E11.5 CNS cells as in A. The identity of the DNA-protein complex (*) was characterized using anti-STAT1 and anti-STAT3 supershift assays (arrows). (C) Left panel, bFGF expanded (gliogenic) cortical progenitor cells were left untreated or treated with LIF for 30 minutes and subjected to chromatin immunoprecipitation (ChIP) assay with an antibody against STAT3 (Santa Cruz). A control antibody, anti-β-galactosidase, was used to control for ChIP assay specificity. In the right two panels, ChIP assays were performed on 3-day-old cultured control (con) and Dnmt1−/− (mut) E11.5 CNS cells using the STAT1 and STAT3 antibodies. (D,E) E11.5 control Dnmt1+/+ and Dnmt1−/− CNS NPCs were cultured for 48 hours and co-transfected with a β-gal-expressing construct and a control plasmid (con) or a dominant-negative STAT3F plasmid (STAT3F). After another 48 hours, cells were fixed and double-stained with antibodies against GFAP (green) and β-gal (red), and counted for the percentage (mean±s.e.m.) of GFAP and β-gal double-positive cells over total β-gal positive cells. *P<0.01 compared with the Dnmt1+/+ (con) group. **P<0.01 compared with the group of Dnmt1−/− cells with β-gal transfection (con) (ANOVA with Post-hoc tests).

Fig. 4. Precocious astroglial differentiation is mediated by enhanced activation of JAK/STAT signaling in Dnmt1−/− NPCs. (A) Wild-type or a STAT-binding mutant form of the 1.9 kb rat GFAP promoter-luciferase reporter constructs were co-transfected with the renilla-TK control plasmid into 3 day cultured E11.5 control and Dnmt1−/− CNS NPC cultures. After 24 hours, cells were lysed and subjected to dual-luciferase assays (Promega). *P<0.001 compared with the control group (Dnmt1+/+) without LIF treatment. **P<0.01 compared with the group of Dnmt1−/− cells without LIF treatment (ANOVA with Post-hoc tests). (B) EMSA assay using a 25 bp unmethylated probe containing the STAT-binding element within the GFAP promoter with nuclear extracts from cultured control and Dnmt1−/− E11.5 CNS cells as in A. The identity of the DNA-protein complex (*) was characterized using anti-STAT1 and anti-STAT3 supershift assays (arrows). (C) Left panel, bFGF expanded (gliogenic) cortical progenitor cells were left untreated or treated with LIF for 30 minutes and subjected to chromatin immunoprecipitation (ChIP) assay with an antibody against STAT3 (Santa Cruz). A control antibody, anti-β-galactosidase, was used to control for ChIP assay specificity. In the right two panels, ChIP assays were performed on 3-day-old cultured control (con) and Dnmt1−/− (mut) E11.5 CNS cells using the STAT1 and STAT3 antibodies. (D,E) E11.5 control Dnmt1+/+ and Dnmt1−/− CNS NPCs were cultured for 48 hours and co-transfected with a β-gal-expressing construct and a control plasmid (con) or a dominant-negative STAT3F plasmid (STAT3F). After another 48 hours, cells were fixed and double-stained with antibodies against GFAP (green) and β-gal (red), and counted for the percentage (mean±s.e.m.) of GFAP and β-gal double-positive cells over total β-gal positive cells. *P<0.01 compared with the Dnmt1+/+ (con) group. **P<0.01 compared with the group of Dnmt1−/− cells with β-gal transfection (con) (ANOVA with Post-hoc tests).
Fig. 5. Changes of DNA methylation on the GFAP and STAT1 promoters when NPCs become gliogenic in control and Dnmt1−/− cells. (A) Bisulfite sequencing analysis on eight CpG sites surrounding the STAT1/3 binding elements within the mouse Gfap promoter. The percentage of methylation at each of the 8 CpG sites was plotted. (B) Bisulfite sequencing analysis shows selective demethylation occurs at the −499 CpG site but not at the −594 CpG site during 24-96 hours of culturing period of wild-type E11.5 cortical cells. (C) Methylation-specific SNuPE assay was used to independently quantify the extent of methylation at the single CpG site lying within the STAT binding element in 1- and 4-day-old cultured E12.5 control (con) and Dnmt1−/− (mut) CNS cells and in E18.5 brain samples in vivo. (D) Bisulfite sequencing analysis of eight CpG sites within the Stat1 promoter (between −731 bp and −409 bp promoter region of the gene) in E18 control and Dnmt1−/− CNS samples. (E,F) E11 control (con) or Dnmt1−/− (mut) NPCs were transfected with either a β-gal expression vector or a CAG-promoter-Dnmt1 expression plasmid (Chen et al., 2003) within the first 24 hours of cell culturing. After an additional 4 days of culturing in the presence of LIF (50 ng/ml) to promote glial differentiation, cells were double-labeled with GFAP/β-gal or GFAP/Dnmt1 (E) and quantified for the percentage of GFAP+/β-gal+ or GFAP+/Dnmt1+ cells as plotted in F. Dnmt1 overexpression cells can be easily detected by the strong Dnmt1 staining signals (arrows). Two arrowheads in the control culture indicate the typical nuclear staining pattern of the endogenous Dnmt1 protein. *P<0.001 compared with control (Dnmt1+/+) with β-gal plasmid transfection. **P<0.001 compared with Dnmt1−/− cells with β-gal plasmid transfection (ANOVA with Post-hoc tests).
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The DNA methylation of the Gfap promoter, the STAT-binding elements of the Stat1 and S100β promoters do not contain any CpG sites. Therefore, the aforementioned mechanism, i.e. reduced binding affinity between STATs and the methylated STAT cis-element, cannot contribute to DNA methylation mediated suppression of Stat1 and S100β genes. Therefore, we examined whether DNA methylation inhibits expression of Stat1, S100β and Gfap through a general gene silencing mechanism, i.e. inactive chromatin remodeling.

**DNA methylation inhibits glial differentiation genes through a methyl-CpG binding protein mediated chromatin remodeling process**

DNA methylation induced gene silencing is usually mediated through binding of methyl-CpG-binding proteins that recruit histone deacetylases and histone methyltransferases to trigger inactive chromatin remodeling. Using ChIP assays, we determined whether STAT3 and methyl-CpG binding proteins reciprocally associate with Gfap, Stat1 and S100β promoters, based on the methylation status of these genes. We found that in early neural progenitors (E11.5, 1 DIV), a time at which glial genes are more methylated, the Gfap, Stat1 and S100β promoters are more tightly associated with the methyl-CpG binding protein, MeCP2, but not the transcriptional activator STAT3 (Fig. 6A-E). However, in late, more gliogenic, cells (E11.5, 6-7 DIV), where glial genes are demethylated, all three glial differentiation-related genes are more closely associated with STAT3, but not with MeCP2. These findings are consistent with the notion that methylation of glial differentiation-related promoters may lead to gene silencing through methyl-CpG-binding protein mediated inactive chromatin remodeling. Using western analysis as well as immunostaining, we established that MeCP2 is expressed in E11.5 CNS progenitors (see Fig. S3 in the supplementary material). In addition, the level of MeCP2 expression in our E11.5 mouse cortical cultures does not appear to dramatically change over the culturing period (see Fig. S3 in the supplementary material). MeCP2 is known to recruit histone modification enzymes such as histone H3 lysine9 methyltransferases and histone deacetylases (Lunyak et al., 2002), which may function to modify histone tails, resulting in inactive chromatin remodeling. To assess whether the chromatin structure of glial genes is inactive or active during the neurogenic (E11.5, 1 DIV) and the gliogenic (E11.5, 6-7 DIV) phases of the CNS culture, we probed the status of histone codes such as dimethyl-lysine 9 of histone H3 (H3dmK9) for inactive chromatin and di- or tri-methyl-lysine4 of histone H3 (H3d/tmK4) as an indicator for active chromatin. As anticipated for neurogenic progenitors, the Gfap, Stat1 and S100β promoters displayed more inactive chromatin modifications (Fig. 6F-H). Conversely, in gliogenic cells, the promoters are more associated with the active chromatin code (Fig. 6F-H).

To examine whether DNA hypomethylation leads to active chromatin remodeling in Gfap, Stat1 and S100β promoters in the absence of Dnmt1 in vivo, we performed ChIP assays and compared the code of histone modifications in E16-18 control and Dnmt1−/− CNS. As shown in Fig. 6I,J, Dnmt1−/− cortical cells exhibited an increase in H3-K4 di/tri-methylation and a dramatic decrease in H3-K9 dimethylation in Gfap and Stat1 promoters.

**Fig. 6.** Effect of DNA methylation on pSTAT association and activation of the Gfap, Stat1 and S100β promoters. (A-E) ChIP assays to analyze the association of MeCP2 and STAT3 with the Gfap, Stat1 and S100β promoters. (F-H) ChIP assays of histone H3 di-methyl lysine 9 (K9) and di- or tri-methyl lysine 4 (K4) within the Gfap, Stat1 and S100β promoters. (I,J) E16 control and Dnmt1−/− cortical tissues were analyzed by ChIP assays for histone H3 di-methyl lysine 9 (K9) and di- or tri-methyl lysine 4 (K4) within the Gfap and Stat1 promoters.
promoters. A moderate increase in H3-K4 di/tri-methylation was also observed on the S100β promoter (data not shown). Taken together, these data indicate that enhanced active chromatin remodeling occurs on those genes involved in astroglial differentiation in Dmnt1−/− cells in vivo.

Discussion

Epigenetic modifications such as DNA methylation have been proposed to regulate cell differentiation during development (Paulsen and Ferguson-Smith, 2001); however, the molecular mechanism by which DNA methylation regulates specific cell differentiation programs have just begun to be characterized (Lunyak et al., 2002; Stancheva et al., 2003; Stancheva et al., 2002; Stancheva and Meehan, 2000). Here, we have shown that in the absence of Dnmt1 there is precocious onset of astrogliogenesis in the developing CNS as measured by the early appearance of GFAP- and S100β-positive glial cells. Our finding suggests that precocious astroglial differentiation in Dmnt1−/− NPCs is predominantly mediated by enhanced activation of the astrogenic JAK-STAT signals through accelerated demethylation of gene promoters associated with the JAK-STAT pathway. Mechanistically, accelerated demethylation promotes active chromatin remodeling/derepression of the JAK-STAT pathway genes as well as astroglial marker genes. When Dnmt1 expression is restored in Dmnt1−/− NPCs, precocious astroglial differentiation is prevented, suggesting a causal relationship between Dnmt1 expression and the control of the onset of astrogliogenesis in NPCs. Our data support a model in which DNA methylation, through inhibition of STAT activity, plays an important role in regulating the timing of astroglial differentiation in mammalian CNS progenitor cells both in vitro and in vivo (Fig. 7).

We hypothesize that during CNS development, the generation of neurons in the absence of glia relies on the suppression of glial differentiation programs during the neurogenic period. Many glial inducing factors, including LIF, BMP, NOTCH and the oligodendrogliogenic bHLH factor, OLIG2, are unable to induce glial differentiation during the neurogenic period (Ge et al., 2002; Sauvageot and Stiles, 2002; Sun et al., 2003; Viti et al., 2003a). The ability of these factors to regulate cell fate is thought to depend on the intrinsic state of the precursor cell. Our study suggests that the JAK/STAT pathway is a crucial control point for regulating the intrinsic responsiveness of neural progenitors to astrogliogenic factors. We previously demonstrated that the expression of a proneural bHLH factor, NGN1, which is exclusively expressed in progenitor cells during the neurogenic period, inhibits STAT1/3 phosphorylation and prevents pSTATs from activating glial gene transcription by sequestering the transcription co-activator, p300/CBP, away from glial specific promoters (Sun et al., 2001). This present study indicates that DNA methylation is another key mechanism inhibiting the expression of the various components of the astrogliogenic JAK-STAT pathway. Thus, JAK-STAT activation in neural precursor cells is under the tight control of several independent mechanisms.

Recently, other investigators have challenged the importance of JAK/STAT activation in the regulation of gliogenesis by emphasizing that pSTATs can be detected in the neurogenic CNS (Molne et al., 2000; Takizawa et al., 2001). However, our study, as well as those of others, indicate that the pSTAT1/3 signals detected in the neurogenic culture are minimal (Viti et al., 2003a; He et al., 2005). Weakly phosphorylated STATs in early neural progenitors cannot effectively activate glial gene transcription, even if the glial promoter is not methylated, as demonstrated in luciferase reporter assay (He et al., 2005). However, using a constitutively dimerized and nuclear localized form of STAT3, STAT3C, in combination with LIF stimulation, we observed precocious astrocyte differentiation in 2 DIV E11.5 and E12 cortical cells (He et al., 2005). Taken together, these data suggest that robust activation of STATs may either override the methylation inhibition of glial genes or accelerate the demethylation process of glial genes.

CpG methylation can directly inhibit gene transcription when methylation blocks the association of transcription factor to the cis-element, as demonstrated for the association of the GFAP promoter with STAT3 (Takizawa et al., 2001) and STAT1 (see Fig. S2 in the supplementary material). However, the canonical STAT-binding elements in many other genes...
involved in astrogial differentiation such as STAT1, STAT3, gp130, JAK1 and S100β do not contain a CpG site (He et al., 2005), suggesting that the direct effect of CpG methylation on the binding of STATs is not a general mechanism in the inhibition of JAK-STAT signaling. Instead, our data (Fig. 6) demonstrate that DNA methylation suppresses the gliogenic pathway genes via methyl-CpG-binding protein-mediated inactive chromatin remodeling. Indeed, the association of methyl-CpG-binding proteins such as MeCP2, which recruit histone modification enzymes associated with inactive chromatin remodeling, could be involved in glial gene silencing (Bird and Wolffe, 1999; Jones et al., 1998; Martinowich et al., 2003). Our ChIP study showed that MeCP2 was associated with methylated glial lineage genes in neurogenic cells. However, we cannot rule out the possible involvement of other methyl binding proteins (e.g. MBD1-3) in the nervous system for their potential role in glial gene silencing during early CNS development (Heinrich and Bird, 1998) (reviewed by Fan and Hutnick, 2005).

DNA methylation may be one of the many repressive mechanisms to prevent superfluous transcription to achieve cell-specific gene expression during differentiation. In this regard, methylation of the GFAP promoter is proposed to be one of the key silencing mechanisms for inhibiting GFAP expression in peripheral non-neural cell types such as fibroblasts (Condorelli et al., 1997). In the current study, we discovered that demethylation in the GFAP promoter in E18 Dmnt1−/− CNS neurons does not lead to ectopic expression of GFAP in neuronal cells (Fig. 1 and Fig. 5B), arguing for the existence of additional repression mechanism(s) in neurons that blocks ectopic GFAP gene transcription.

In this study, we have demonstrated that nestin-cre-mediated Dmnt1 gene deletion in mitotic E11 NPCs leads to rapid demethylation in daughter cells in culture (Fig. 2E), indicating the essential role for Dmnt1 in maintaining DNA methylation in embryonic CNS cells (Fan et al., 2001). The observed phenotype of precocious activation and active chromatin remodeling of gliogenic genes is consistent with the demethylation phenotype in Dmnt1−/− NPCs. However, it is worth noting that Dmnt1 molecule has also been shown to directly inhibit gene transcription with its N-terminal transcription repression domain, which interacts with other transcription repressor components, including histone deacetylases and histone lysine-methyltransferases for inactive chromatin remodeling (Rountree et al., 2000; Fuks et al., 2000). To determine whether Dmnt1 molecule itself would repress any astrogliogenic genes such as GFAP, STAT1 and S100β in vivo, one potential experiment is to generate a new conditional Dmnt1 mutant allele that introduces mutations in Dmnt1 flanking region of the glial fibrillary acidic protein gene. (1997). Rapid quantitation of methylation differences at specific sites using methylation-sensitive single nucleotide primer extension (Ms-SNuPE). Nucleic Acids Res. 25, 2529-2531.

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Supplementary material
Supplementary material for this article is available at http://dev.biologists.org/cgi/content/full/132/15/3345/DC1

References