Protein phosphatase 2A regulates self-renewal of *Drosophila* neural stem cells

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An incorrect version of Fig. 4, in which the same panel appears twice (upper panel of Fig. 4B and lower panel of Fig. 4C), was provided post-acceptance. The correct Fig. 4 appears below.

The authors apologise to readers for this mistake.
Protein phosphatase 2A regulates self-renewal of Drosophila neural stem cells

Cheng Wang1, Kai Chen Chang2, Gregory Somers3, David Virshup4, Beng Ti Ang5,6, Carol Tang4,5,7,8, Fengwei Yu1,2,9 and Hongyan Wang1,7,*

Drosophila larval brain neural stem cells, also known as neuroblasts, divide asymmetrically to generate a self-renewing neuroblast and a ganglion mother cell (GMC) that divides terminally to produce two differentiated neurons or glia. Failure of asymmetric cell division can result in hyperproliferation of neuroblasts, a phenotype resembling brain tumors. Here we have identified Drosophila Protein phosphatase 2A (PP2A) as a brain tumor-suppressor that can inhibit self-renewal of neuroblasts. Supernumerary larval brain neuroblasts are generated at the expense of differentiated neurons in PP2A mutants. Neuroblast overgrowth was observed in both dorsomedial (DM)/posterior Asense-negative (PAN) neuroblast lineages and non-DM neuroblast lineages. The PP2A heterotrimeric complex, composed of the catalytic subunit (Mts), scaffold subunit (PP2A-29B) and a B-regulatory subunit (Tws), is required for the asymmetric cell division of neuroblasts. The PP2A complex regulates asymmetric localization of Numb, Pon and Atypical protein kinase C, as well as proper mitotic spindle orientation. Interestingly, PP2A and Polo kinase enhance Numb and Pon phosphorylation. PP2A, like Polo, acts to prevent excess neuroblast self-renewal primarily by regulating asymmetric localization and activation of Numb. Reduction of PP2A function in larval brains or S2 cells causes a marked decrease in Polo transcript and protein abundance. Overexpression of Polo or Numb significantly suppresses neuroblast overgrowth in PP2A mutants, suggesting that PP2A inhibits excess neuroblast self-renewal in the Polo/Numb pathway.

KEY WORDS: PP2A, Self-renewal and differentiation, Drosophila, Neural stem cell, Neuroblast, Asymmetric division

INTRODUCTION

Drosophila larval brain neuroblasts, also known as neural stem cells (NSCs), divide asymmetrically to give rise to a self-renewing daughter, that continues to divide asymmetrically, and a ganglion mother cell (GMC), that is committed to differentiation. The mechanisms of neuroblastic asymmetric division have been studied primarily in embryonic neuroblasts; these mechanisms appear to be conserved between embryonic and larval brain neuroblasts (Doe, 2008; Gonczy, 2008; Gonzalez, 2007; Knoblich, 2008; Wu et al., 2008). During asymmetric division of embryonic neuroblasts, cell fate determinants Numb, Prospero (Pros), Brain tumor (Brat), and their adaptor proteins Partner of Numb (Pon) and Miranda (Mira) are basally localized and segregated into the GMC (Ishihama-Katoa et al., 1997; Knoblich et al., 1995; Lu et al., 1998; Rhyu et al., 1994; Shen et al., 1997). The mitotic spindle is oriented along an axis perpendicular to the epithelial layer and an asymmetric spindle is generated to give rise to two unequally sized daughter cells with a distinct cell fate. The localization of basal proteins and mitotic spindle orientation are controlled by apically localized proteins that include Bazooka (a Drosophila homolog of Par3), Par6 and Atypical protein kinase C (aPKC) (Kuchinke et al., 1998; Petronczki and Knoblich, 2001; Wodarz et al., 2000), Incuteable (Insc) (Kraut et al., 1996), and heterotrimeric G protein Gozi (Schaefer et al., 2001; Yu et al., 2003) and its regulators Partner of Insc (Pins, also known as Raps) (Yu et al., 2000), Locomotion defects (Loco) (Yu et al., 2005) and a Pins-interacting protein known as Mushroom body defect (Mud) (Bowman et al., 2006; Izumi et al., 2006; Siller et al., 2006). Cortically localized Gβ and Gγ regulate asymmetric localization of Gozi (Schaefer et al., 2001; Yu et al., 2003), and Ric8a (DmRic8) is required for Gozi membrane localization (Hampoez et al., 2005; Wang et al., 2005). Basal protein localization and segregation are mediated by apical proteins through cortically localized tumor suppressors Discs large, Scribbled and Lethal (2) giant larvae (Albertson et al., 2004; Albertson and Doe, 2003; Ohshiro et al., 2000; Peng et al., 2000).

Drosophila larval brain neuroblasts have recently emerged as a model for studying stem cell self-renewal and tumorigenesis. Failure of asymmetric cell division can result in their hyperproliferation, a phenotype resembling brain tumors. Mutant larval brain tissue from pins, mira, numb or pros, when transplanted into wild-type adults, can form malignant tumors that rapidly kill the host (Caussinus and Gonzalez, 2005). Recent studies suggest that neuroblasts utilize the asymmetric localization/segregation machinery to distribute ‘proliferation factor’ to the neuroblast daughter and ‘differentiation factor’ to the GMC daughter during asymmetric division. aPKC, a neuroblast proliferation factor, which acts at least partially through regulating Numb asymmetry, leads to neuroblast overgrowth when overexpressed in the entire cortex (Lee et al., 2006a; Lee et al., 2006b; Wang et al., 2006). Proteins that are asymmetrically segregated into the GMC, including Numb, Pon, Pros, Brat and Mira, act as ‘differentiation factors’ and have brain tumor-suppressor function to prevent neuroblast overgrowth (Bello et al., 2006; Betschinger et al., 2006; Caussinus and Gonzalez, 2005; Choksi et al., 2006; Lee et al., 2006a; Lee et al., 2006b; Lee et al., 2006c; Wang et al., 2006; Wang et al., 2007). Numb antagonizes Notch signaling to inhibit neuroblast overproliferation, whereas Notch promotes...
neuroblast self-renewal at larval central brains (Wang et al., 2006). Cell cycle regulators Aurora A and Polo also have brain tumor-suppressor function and both inhibit neuroblast overproliferation primarily by regulating Numb asymmetry (Lee et al., 2006a; Wang et al., 2006; Wang et al., 2007). Polo can directly phosphorylate Pon on S611, which localizes Pon and subsequently Numb asymmetrically (Wang et al., 2007). Aurora A has been shown recently to phosphorylate Par6 to allow aPKC to phosphorylate and asymmetrically localize Numb (Wirtz-Peitz et al., 2008).

Despite studies of protein kinases during asymmetric division of neuroblasts, very little is known about the role of protein phosphatases in this process. Mammalian protein phosphatase 2A (PP2A, also known as Ppp2ca) is a tumor suppressor that regulates cell cycle regulation, various signaling pathways and tumorigenesis (Li et al., 2002; Westermark and Hahn, 2008). Somatic mutations of PP2A have been reported in human lung, breast, and colon cancers as well as melanomas (Westermark and Hahn, 2008). PP2A was shown to bind to viral oncoprotein simian virus (SV40) small t (ST) splicing form that is able to transform mammalian cells (Chen et al., 2007b; Cho et al., 2007). In addition, RalA and cMyc have been shown to be tumorigenic substrates of PP2A (Junttila et al., 2007; Sablina et al., 2007). However, it is unclear whether PP2A regulates neural stem cell homeostasis. Here we show that Drosophila PP2A behaves as a brain tumor-suppressor that regulates the balance of neural stem cell self-renewal and differentiation.

MATERIALS AND METHODS

Fly stocks

Fly crosses and cultures were performed according to standard procedures and flies were raised at 25°C unless otherwise indicated. Drosophila stocks used in this study are: mts<sup>599</sup> (this work); tws<sup>60</sup> (T. Uemura, Kyoto University, Yoshida Konoe-cho, Sakyo-ku, Kyoto, Japan); Asc-Gal4 (Y. Lee, University of Massachusetts Worcester Medical School, Worcester, MA, USA); UAS-Mts, wdb<sup>Φ</sup> and wdb<sup>Δ</sup> (S. Eaton, Max Planck Institute of Molecular Cell Biology and Genetics, Potschhausen, Dresden, Germany); par1<sup>Δ16</sup> and UASPar1 (D. St Johnston, Wellcome/CRC Institute and Department of Genetics, University of Cambridge, Cambridge, UK); aPKC<sup>66403</sup> (C. Doe, University of Oregon, USA, Eugene, OR, USA); GFP-Polo (C. Sunkel, Universidade do Porto, Porto, Portugal); UAS-venus-Polo (this study); wdb<sup>Δ12000</sup> (H. Shen, Texas A&M Biocenter, College Station, TX, USA); UAS-Numb-GFP (Y. N. Jan, UCSF, San Francisco, CA, USA). PP2A RNAi stocks are from the Vienna Drosophila RNAi Center and all other fly stocks are from Bloomington.

Antibodies and immunohistochemistry

Immunohistochemistry on larval brain tissues was performed as described (Wang et al., 2006). The primary antibodies used were: guinea pig anti-Dpn (1:1000), J. Skeath, Washington University School of Medicine, St. Louis, MO, USA), mouse anti-Mira (1:50, F. Matsuzaki, Riken Center for Developmental Biology, Chuo-ku, Kobe, Japan), mouse anti-Worniu (1:500), rat anti-Elav (1:10, DSHB), mouse anti-Pro (1:10, DSHB), mouse anti-CycE (1:10, H. Richardson, Peter MacCallum Cancer Centre, Melbourne, Australia), rabbit anti-phospho-Histone H3 (1:1000, Sigma), mouse anti-dMyc (1:5, B. Edgar, Fred Hutchinson Cancer Research Center (FHCRC), Seattle, WA, USA), mouse anti-BrdU (1:20, Roche), anti-Baz (1:500, A. Wodarz, Universitätsmedizin Göttingen, Göttingen, Germany), rabbit anti-PKCζ C20 (1:500, Santa Cruz Biotechnology), rabbit anti-Par6 (1:500, J. Knoblich, Institute of Molecular Biotechnology GmbH, Vienna, Austria), rabbit anti-Insc (1:1000), guinea pig anti-Numb (1:1000, J. Skeath), rabbit anti-Pon (1:500, Y. N. Jan), rabbit anti-GFP (1:500, Molecular Probes), rabbit anti-S7Numb (1:500, K. Kaibuchi, Nagoya University, Showa, Nagoya, Aichi, Japan). Antibodies for western blotting were: guinea pig anti-Numb (1:1000, J. Skeath), mouse anti-Pon (1:100, C. Sunkel), rabbit anti-pS611Pon (1:500, B. Lu, Stanford University, Palo Alto, CA, USA), rabbit anti-PKζ C20 (1:1000; Santa Cruz Biotechnology), mouse anti-α-tubulin (1:1000, Millipore), rabbit anti-p-aPKC (1:1000, Abcam).

Production of dsRNA

Individual DNA fragments ranging from approximately 400 to 800 bp in length were amplified either from cDNA clones from the Drosophila Genomics Resource Center (for mts, PP2A-29B and wdb) or an S2 cell cDNA library (for tws, B56-1 and PR-72/CG7433). PCR primers contain a T7 RNA polymerase binding site at the 5′ end (Table 1). Double stranded RNA (dsRNA) was synthesized from 1 μg of the purified PCR product by incubating a 20 μl reaction at 37°C for 24 hours using the MEGAscript T7 Transcription Kit (Ambion). The RNA products were ethanol precipitated at −20°C and resuspended in diethyl pyrocarbonate-treated water. To anneal the single stranded RNA, samples were incubated for 30 minutes at 65°C and cooled slowly (4 hours to overnight) to room temperature.

Cell culture, dsRNA and drug treatment

Drosophila S2 cells were maintained in Shields and Sang M3 insect medium (Sigma-Aldrich), and supplemented with 10% fetal bovine serum (FBS; Hyclone). For dsRNA treatment, a final concentration of 20 μg/ml of the specified dsRNA was used. Calyculin A (Calbiochem) and the proteasome inhibitor MG132 were used at 30 nM and 100 μM, respectively. Production of dsRNA was performed as described previously (Sathyanarayanan et al., 2004).

Reverse transcriptase (RT)-PCR

Total RNA was isolated from S2 cells with TRI reagent (Sigma-Aldrich) followed by DNase I treatment as described by the manufacturer. Target messages were reverse transcribed using the ProtoScript First Strand cDNA Synthesis Kit (NEB). PCR was performed using the Expand High Fidelity PCR System (Roche). Targets to be amplified were approximately 250-750 bp in length, with PCR primers designed to traverse at least 1 intron.

Table 1. Primers used for making dsRNA

<table>
<thead>
<tr>
<th>Gene</th>
<th>CG number</th>
<th>Primers* (5’ to 3’)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP2A-A (PP2A-29B)</td>
<td>CG17291</td>
<td>F GACCTTCGCCCAAAATCTGGAC R ATCAATGACCCTGCTTCCCA G</td>
</tr>
<tr>
<td>PP2A-C (mts)</td>
<td>CG7109</td>
<td>R ATGATCCTGCTTACGATACAG F GTACACCTGTTGATCCTGGC</td>
</tr>
<tr>
<td>PR55 (tws)</td>
<td>CG6235</td>
<td>F ATGCATCGCTAATCGATACAC R CGTTCAAAAACATAACCTCC</td>
</tr>
<tr>
<td>B56-1</td>
<td>CG7913</td>
<td>R CGTTCAAAAACATAACCTCC F CGTTCAAAAACATAACCTCC</td>
</tr>
<tr>
<td>B56-2 (wdb)</td>
<td>CG5643</td>
<td>R CGTTCAAAAACATAACCTCC F CGTTCAAAAACATAACCTCC</td>
</tr>
<tr>
<td>PR72</td>
<td>CG4733</td>
<td>R GAAACCCACAAAGGCCTTG</td>
</tr>
</tbody>
</table>
Western blotting
Larval brains or S2 cells were homogenized in RIPA buffer (50 mM Tris HCl pH 7.5, 150 mM NaCl, 1 mM EDTA, 1% Triton X-100, 0.5% sodium deoxycholate, 0.1% SDS) and western blotting was carried out according to standard procedures.

Neuroblast quantification and brain orientation
Quantifications of larval central brain neuroblast numbers were done on samples 24 hours to 96 hours after larval hatching (ALH) at 25°C. For each genotype, 4- to 6-hour embryo collections were obtained from a bottle with 100-200 flies. Embryos were allowed to develop for 20 hours at 25°C before hatching. Thereafter, time-course experiments were performed 24 hours, 48 hours, 72 hours and 96 hours ALH according to the midpoint of the 4- to 6-hour time window. Around 15-20 larvae from each time point were dissected, and stained with anti-Dpn antibody (1:1000). Larval brains were mounted with their dorsal side up. Central brain neuroblasts can be distinguished from optic lobe neuroblasts on the basis of their medial-superficial location in the brain, larger size and dispersed pattern.

BrdU labeling
Dissected larval tissue was given a 40-minute pulse of 37.5 mg/ml BrdU in Shields and Sang 3M insect medium, and fixed for 15 minutes in 3.7% formaldehyde. DNA was denatured with 2 M HCl for 40 minutes, and tissue was washed with PBS and incubated with anti-BrdU.

Spindle orientation quantification
Larval neuroblasts were stained with rat anti-α-Tubulin (1:250, Abcam) and rabbit anti-Insc. Confocal images were captured and were used for quantification. One line was drawn parallel to the metaphase spindle (indicated by Tubulin) and another line perpendicular to the apical crescent (marked by Insc). The angle at which the two lines met was then measured.

RESULTS

Microtubule star (Mts) is a novel brain tumor-suppressor in Drosophila
We identified Microtubule star (Mts), which encodes the catalytic subunit of Protein phosphatase 2A (PP2A), as a brain tumor-suppressor from a genetic screen in Drosophila. We isolated mts [158], a hypomorphic allele of mts, that produced supernumerary neuroblasts [marked by Deadpan (Dpn), Fig. 1A] and highly enlarged larval brain lobes (Fig. 1B) and has a mis-sense mutation (aspartic acid 197 to asparagine) in mts299 mutants (right panels). (C) mts RNAi expressed using the Insc-Gal4 driver results in supernumerary neuroblasts in the larval brains.

(D) Overexpression of wild-type mts can completely rescue the brain tumor phenotype of mts299. Neuroblasts are marked by Dpn or Mira, white dotted lines mark the margin between the central brain and the optic lobe; central brain to the left in A,C,D; 1 μm in B.

PP2A can inhibit excess self-renewal of neuroblasts
To examine the role of Mts in neuroblast self-renewal and differentiation, we first quantified central brain neuroblast numbers in mts299/mts2289 trans-heterozygotes. Both wild type and mts mutants have similar numbers of central brain neuroblasts at 24 hours after larval hatching (ALH). However, mts mutants generated around 1000 neuroblasts that are marked by Mira or Worniu at 96 hours ALH, whereas the wild type had only around 100 neuroblasts (Fig. 2A-C). Conversely, neuronal differentiation in mts mutants is impaired, as neurons marked by Embryonic lethal abnormal vision (Elav) or nuclear Prospero (Pros) are drastically reduced (Fig. 2D,E). Consistent with mts mutants producing a neuroblast overgrowth phenotype, the number of cells expressing markers associated with proliferation, including CycE (Fig. 2F), phospho-
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mRNAi using an Ase-Gal4 driver expressed only in Ase-positive non-DM neuroblast lineages caused neuroblast overproliferation in larval brains (Fig. 3B), although this was weaker than the phenotype derived from mts RNAi by Insc-Gal4, which drives expression in both neuroblast lineages (Fig. 1D). In addition, mosaic analysis with a repressible cell marker (MARCM) (Lee and Luo, 1999) clone analysis in mtsRNAi also suggests neuroblast overgrowth in both neuroblast lineages (Fig. 3C,D). The mts-null mutant is unable to generate MARCM clones (not shown), consistent with the cell lethal phenotype described previously (Hannus et al., 2002). When mtsMARCM MARCM clones that were induced during the early larval stage were kept to adulthood, some of the clones in the adult brains had multiple phospho-Histone H3+ and/or Dpn+ cells; this was never seen in wild-type MARCM clones in adult brains (Fig. 3E), suggesting that some of the mutant cells continue to proliferate until adulthood. These results indicate that Mts can inhibit excess self-renewal of Drosophila neural stem cells.

The protein product of Mts, the catalytic subunit of PP2A, normally functions in a heterotrimeric protein complex (Janssens et al., 2005). To ascertain the function of the A and B regulatory subunits of PP2A during larval brain neuroblast self-renewal, we examined the single A subunit (PP2A-29B) as well as the multiple B subunits [twins (twts), widerborst (wdb), B56-1 and PR-72] using in vivo RNAi or by mutations. Subunit A of PP2A can inhibit neuroblast overgrowth, as PP2A-29B RNAi, as well as trans-heterozygotes between two lethal P elements PP2A-29B²S and PP2A-29B²EP, which survive to the third instar larval stage, displayed neuroblast overproliferation in larval brains (Fig. 3F and see Fig. S1C,E in the supplementary material). In twts mutant brains, the number of neuroblasts is also slightly increased compared with wild type (see Fig. S1D,E in the supplementary material). This weak phenotype observed in twts is likely to be due to other defects including apoptosis and/or cell division in twts. Consistently, a significant number of cells in twts larval brains are labeled by activated Caspase 3 (also known as Decay), in contrast with wild-type brains in which very few cells are labeled (see Fig. S1F in the supplementary material). Furthermore, a weak adult-lethal twts mutant was shown to cause bristle duplication (Shiomi et al., 1994), suggesting that a mild perturbation of Twts function can lead to cell fate transformation. 

Other B regulatory subunits including Wdb, B56-1 and PR-72 do not obviously influence neuroblast self-renewal. wdb²P or wdb²H MARCM clones, as well as B56-1 and PR-72 RNAi knockdown, do not generate any defects in the self-renewal of larval brain neuroblasts (data not shown). It is possible that some B subunits are redundant for the regulation of neuroblast self-renewal, as both B56 subunits were shown to have redundant functions in regulating cell death (Li et al., 2002). However, in a double mutant of B56 wdb (wdb²P and wdb²H), we did not observe any defect in asymmetric division or self-renewal of neuroblasts (data not shown). Therefore Twts appears to be the B regulatory subunit of PP2A that controls the self-renewal of larval brain neuroblasts.

**PP2A regulates asymmetric protein localizations as well as mitotic spindle orientation**

To explore whether PP2A regulates asymmetric cell division of neuroblasts, the distribution of asymmetrically localized proteins were examined in PP2A mutants. The asymmetric localization of most polarity proteins, including aPKC (Fig. 4A; 70.0%, n=30), Par6 (Fig. 4B; 33.3%, n=30), Baz (Fig. 4C; 36.4%, n=48) and Insc (Fig. 4D; 35.4%, n=48) are affected to various degrees in mts²99 and...
disrupted. It was shown recently in S2 cells that PP2A regulates NSC self-renewal. In larval brains of a wild-type mts trans-heterozygotes (mts-null). Among the basal proteins, localizations of Numb (Fig. 4E; 71.7%, n=46) and Pon (Fig. 4F; 68%, n=25) are most severely disrupted, whereas Mira (Fig. 4G; 14.6%, n=48) and Brat (Fig. 4H; 33.3%, n=30), are mildly perturbed in mts mutants. Phenotypic penetrance follows the order of mts299/mts®-2258 = mts299/mts®-5268 = mts299. Mitotic spindle orientation was also compromised in mts mutants (Fig. 4K,L). The mitotic spindle was misaligned with the cortical crescent in 44% of cells in the mts®-2258 mutant (Fig. 4K,L; n=30). These asymmetric division defects of mts mutants were fully rescued by a wild-type mts transgene (see Fig. S1B in the supplementary material).

We then ascertained that PP2A subunits A and B also regulate asymmetric division of neuroblasts. In larval brains of PP2A-29B®/PP2A-29B® mutants, asymmetric distributions of aPKC (Fig. 5A; 84.2%, n=19), Numb (Fig. 5B; 56.3%, n=16) and Pon (Fig. 5C; 80%, n=15) were lost. Mitotic spindle misorientation can be observed in PP2A-29B®/PP2A-29B® (Fig. 5E). In fyu040 (pupal lethal) and fyu0242 (embryonic lethal) trans-heterozygotes, asymmetric localization of aPKC, Numb and Pon, as well as mitotic spindle orientation, was also affected (Fig. 5A-C). In a fyu040/fyu0242 mutant, asymmetric localizations of aPKC (Fig. 5A; 75%, n=20), Numb (Fig. 5B; 74.1%, n=27) and Pon (Fig. 5C; 71.4%, n=21) were disrupted. It was shown recently in S2 cells that PP2A RNAi leads to defects in cell cycle progression (Chen et al., 2007a), so our current data do not rule out cell cycle delays as the cause of neuroblast polarity defects. It was shown in C. elegans embryos that DNA replication defects delay cell division and disrupt cell polarity (Encalada et al., 2000). However, metaphase-arrested neuroblasts induced either by a microtubule depolymerizing drug or by mutations in cdc20 (fzv) or cdh1 (rap) display normal cortical polarity (Broaddus and Doe, 1997; Slack et al., 2007). Our data suggest that the PP2A heterotrimeric complex is required for neuroblast polarity and appears to act upstream of polarity proteins including aPKC to control neuroblast asymmetry.

**PP2A and Polo enhance Numb phosphorylation and asymmetric localization**

The PP2A-dependent defects in the asymmetric division of neuroblasts resemble those seen in polo loss-of-function mutants. Polo kinase was previously identified as a brain tumor-suppressor that mediates the asymmetric localization and segregation of Numb by phosphorylating Pon, an adaptor protein for Numb (Wang et al., 2007). This prompted us to ascertain whether PP2A might act to prevent excess self-renewal by regulating Numb asymmetry, similar to Polo (Wang et al., 2007). The neuroblast overgrowth phenotype was significantly, although not completely, suppressed by overexpression of Numb-GFP in mts mutants (Fig. 6A-C). These data indicate that PP2A suppresses neuroblast overgrowth, at least in part, by regulating Numb asymmetry/function. We therefore tested if Numb might be a substrate for PP2A dephosphorylation. Numb proteins were detected as two bands, with the higher band representing the modified form of Numb (Rhyu et al., 1994). If Numb is a substrate of PP2A, the modified form of Numb, which is the putative phosphorylated form, will increase in PP2A mutants. However, surprisingly, hyperphosphorylated Numb is reduced in larval brains of mts®/mts®-2258 trans-heterozygotes or by mts in vivo RNAi (Fig. 6D and data not shown), indicating that Numb is unlikely to be a direct substrate of PP2A. A similar reduction in the levels of phosphorylated Numb was also observed in PP2A-29B® and fyu040/fyu0242 larval brains (data not shown).

We speculate that PP2A may activate a kinase that phosphorylates Numb. Three protein kinases, aPKC, Polo and Aurora A, were previously shown to regulate asymmetric division of Drosophila.
neural stem cells (Betschinger et al., 2003; Lee et al., 2006a; Rolls et al., 2003; Wang et al., 2006; Wang et al., 2007). aPKC phosphorylates Numb and leads to its asymmetric localization (Lee et al., 2006b; Smith et al., 2007). Five aPKC phosphorylation sites, including Serine (Ser) 52 of Numb (corresponding to Ser7 in murine Numb), are evolutionarily conserved. Aurora A phosphorylates Par6 and allows aPKC to phosphorylate Numb and release it from one side of the cell cortex (Wirtz-Peitz et al., 2008). Polo can phosphorylate Pon directly, which leads to the asymmetric localization of Pon and subsequently Numb (Wang et al., 2007). Loss of Numb phosphorylation in \textit{PP2A} mutants is unlikely to be due to the compromised function of aPKC, as aPKC protein levels are upregulated in both PP2A and \textit{polo} mutants (Fig. 7B). Furthermore, phosphorylation of Numb by aPKC, which is recognized by anti-pSer7Numb antibody, is enhanced despite the overall reduction of Numb phosphorylation in PP2A mutants (Fig. 7C). Therefore, loss of Numb phosphorylation in PP2A mutants appears to be aPKC-independent. However, aPKC activity that is probed by an antibody against the autophosphorylated aPKC remains unchanged after \textit{mts} knockdown (Fig. 7C), indicating that increased Numb phosphorylation is not due to increased aPKC activity in PP2A mutants. The neuroblast overproliferation phenotype of \textit{mts} brains was partially suppressed by the loss-of-function mutation \textit{aPKC}^{68483} (see Fig. S4 in the supplementary material). This suppression is consistent with the role for aPKC in neuroblast proliferation. In this double mutant the expected loss of Numb phosphorylation at the Ser52 aPKC site may contribute to this suppression.

We thus tested whether bulk Numb phosphorylation requires Polo or Aurora A kinases, two brain tumor-suppressors that regulate Numb asymmetry. Interestingly, Numb phosphorylation is similarly lost in \textit{polo} mutant larval brains, whereas it is not obviously affected in \textit{aurA} mutant trans-heterozygous [\textit{aurA}^{6839} (strong hypomorphic allele)/\textit{aurA}^{37Ac-3} (amorph allele)] brains (Fig. 6D). Therefore Polo,
but not Aurora A, is crucial for the bulk phosphorylation of Numb (Wang et al., 2007). Although Aurora A is required for phosphorylation of Numb by aPKC (Wirtz-Peitz et al., 2008), other kinase(s) can also phosphorylate Numb on phosphorylation sites that might be different from aPKC phosphorylation sites, and could therefore account for Numb phosphorylation in 

\[ \text{aurora A} \]

mutants. Phosphorylation of Ser611Pon is also strongly reduced in 

\[ \text{mts} \]

mutants (Fig. 7A), similar to 

\[ \text{polo} \]

mutants. Thus, both PP2A and Polo are crucial for Numb and Pon phosphorylation. We also explored the possible involvement of several other kinases, such as Par1 kinase, in neuroblast self-renewal. However, neither overexpression of Par1 nor 

\[ \text{par1} \]

null MARCM clones showed any neuroblast proliferation phenotype (see Fig. S3 in the supplementary material). Therefore, similar to Polo, PP2A regulates asymmetric localization of aPKC, Pon and Numb, as well as mitotic spindle orientation. In addition, both PP2A and Polo decrease aPKC protein levels and enhance Numb and Pon phosphorylation. Thus, they may act in the same pathway during neuroblast asymmetric divisions.

**PP2A acts in Polo/Numb pathway to inhibit neuroblast overgrowth**

We next examined how PP2A might regulate Polo function to facilitate asymmetric division. In 

\[ \text{mts}^{299}/\text{mts}^{XE-2258} \]

mutant or 

\[ \text{mts} \]

RNAi larval brains Polo protein levels were dramatically reduced (Fig. 7B and data not shown), suggesting that PP2A is required for Polo expression. Polo protein levels were also strongly reduced in 

\[ \text{PP2A-29B}^{R5}/\text{PP2A-29B}^{EP} \]

and 

\[ \text{tw}^{80}/\text{tw}^{2414} \]

mutant larval brains.

**Fig. 6. PP2A primarily acts upstream of Numb to regulate neuroblast self-renewal.** (A-C) Ectopic expression of Numb-GFP using Insc-Gal4 significantly suppresses the neuroblast overgrowth phenotype in 

\[ \text{mts}^{299}/\text{mts}^{55286} \]

mutants (A) and 

\[ \text{Insc-Gal4 mts}^{299}/\text{mts}^{55286} \]

(B) was used as control. Dpn marks neuroblasts. Scale bar: 10 μm. (C) Quantification of neuroblast numbers at 72 hours ALH and 96 hours ALH. O/E, overexpressed. (D) Numb phosphorylation is abolished in 

\[ \text{mts}^{299}/\text{mts}^{XE-2258} \]

and 

\[ \text{polo}^{9}/\text{polo}^{17} \]

larval brains. Numb phosphorylation appears to be largely present in a weaker 

\[ \text{mts}^{299}/\text{mts}^{55286} \]

trans-heterozygote. Ectopic expression of Mts (Insc-Mts) results in increased Numb phosphorylation. Numb phosphorylation is present in 

\[ \text{aurA}^{8839}/\text{aurA}^{87Ac-3} \]

(aurA–).

**Fig. 7. Polo protein abundance depends on PP2A.** (A) Phosphorylation of Pon on Ser611 is strongly reduced in 

\[ \text{mts}^{299}/\text{mts}^{XE-2258} \]

mutants. (B) In 

\[ \text{mts}^{299}/\text{mts}^{XE-2258} \]

larval brains, Polo protein levels are strongly decreased, whereas aPKC levels are increased. aPKC protein levels are increased in 

\[ \text{polo}^{9}/\text{polo}^{17} \]

larval brains. (C) Numb phosphorylation by aPKC (pS7Nb) is increased but aPKC autophosphorylation remains unchanged after 

\[ \text{mts} \]

knockdown in S2 cells. (D) Polo protein levels are reduced in 

\[ \text{PP2A-29B}^{R5}/\text{PP2A-29B}^{EP} \]

and 

\[ \text{tw}^{80}/\text{tw}^{2414} \]

larval brains. (E) Polo protein levels are significantly reduced in S2 cells upon treatment with Calyculin A (CalA), or cotreatment with CalA and MG132. α-Tubulin served as a loading control. The quantifications of changes of protein levels are normalized by the loading controls in the following ratios: (A) wt:mts–, 1:0.38; (B) wt:mts, 1:0.34 (Polo); wt:mts, 1:1.39 (aPKC); wt:mts, 1:1.43 (aPKC); (C) wt:mts, 1:4.58 (pS7Nb); wt:mts, 1:0.93 (p-aPKC); (D) wt:PP2A-29B, 1:0.4; wt:tws, 1:0.26 (E) control:mts dsRNA, 1:0.27; control:tws:5′B56-1, 1:0.31:0.36; (F) control:mts, 1:0.35:0.35.
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Mammalian PP2A is a tumor suppressor that participates in malignant transformation by regulating multiple pathways (Westermarck and Hahn, 2008). However, it is unknown whether PP2A controls neural stem cell self-renewal. Our data explicitly show that the Drosophila PP2A trimeric complex confers brain tumor-suppressor activity and controls the balance of self-renewal and differentiation of neural stem cells. We show that PP2A mutation leads to neural stem cell overproliferation in Drosophila larval brains, which is associated with dramatically reduced neuronal differentiation. Cell cycle genes including CycE, and phospho-Histone H3 and growth factor Myc are upregulated in PP2A mutants, consistent with the neuroblast overgrowth phenotype. Neuroblasts overproliferate in PP2A mutant MARCM clones. When these mutant clones that were generated at larval stages are kept until adulthood, neural stem cells continue to proliferate in adult brains, which is never observed for wild-type clones. Therefore, PP2A can inhibit excess self-renewal and promote neuronal differentiation of neural stem cells.

This overgrowth of neural stem cells in PP2A mutants is a consequence of defects in the asymmetric division of neural stem cells. PP2A regulates asymmetric protein localization as well as mitotic spindle orientation. In our previous study, we showed that Polo kinase is a brain tumor-suppressor that regulates Numb/Pon and aPKC asymmetric localization, as well as mitotic spindle orientation (Wang et al., 2007). Although polo mutants displayed pleiotropic phenotypes during asymmetric divisions, Polo primarily regulates asymmetric division of neural stem cells by regulating Numb asymmetry (Wang et al., 2007). Polo directly phosphorylates Pon on Ser611, which leads to the asymmetric localization of Pon and subsequently Numb (Wang et al., 2007). Strikingly similar to Polo, PP2A also regulates the asymmetric localization of aPKC, Pon and Numb, and is required for Pon phosphorylation on Ser611. Interestingly, both PP2A and Polo are required for Numb phosphorylation, which may be important for Numb asymmetric localization or activity on the cortex. Thus, Numb is a major downstream factor for both PP2A and Polo in regulating neural stem cell self-renewal. Consistent with this, overexpression of Numb, but not PonS611D, a phospho-mimetic form of Pon, in polo mutants significantly rescues the neuroblast overgrowth phenotype (Wang et al., 2007).

We further discovered that PP2A functions upstream of Polo/Numb in the same pathway to control self-renewal of neuroblasts. Polo transcript and protein abundance is dependent on PP2A function. The expression of several other genes, including numb, baz and lgl, are not affected by PP2A knockdown, suggesting that the downregulation of polo in PP2A mutants appears to be specific. Moreover, overexpression of GFP-Polo or Numb can largely suppress neuroblast overgrowth in PP2A mutants, suggesting that PP2A primarily acts in the Polo/Numb pathway to inhibit neuroblast overgrowth. Our discovery suggests that PP2A and Polo, both of which are crucial brain.
PP2A regulates NSC self-renewal


