

PTEN negatively regulates neural stem cell self-renewal by modulating G₀-G₁ cell cycle entry

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Previous studies have demonstrated that a small subpopulation of brain tumor cells share key characteristics with neural stem/progenitor cells in terms of phenotype and behavior. These findings suggest that brain tumors might contain "cancer stem cells" that are critical for tumor growth. However, the molecular pathways governing such stem cell-like behavior remain largely elusive. Our previous study suggests that the phosphatase and tensin homologue deleted on chromosome 10 (*PTEN*) tumor suppressor gene, one of the most frequently mutated genes in glioblastomas, restricts neural stem/progenitor cell proliferation *in vivo*. In the present study, we sought to determine the role of *PTEN* in long-term maintenance of stem cell-like properties, cell cycle entry and progression, and growth factor dependence and gene expression. Our results demonstrate an enhanced self-renewal capacity and G₀-G₁ cell cycle entry and decreased growth factor dependency of *Pten* null neural/stem progenitor cells. Therefore, loss of *PTEN* leads to cell physiological changes, which collectively are sufficient to increase the pool of self-renewing neural stem cells and promote their escape from the homeostatic mechanisms of proliferation control.

tumor suppressor | conditional knockout mouse model | growth factor dependency | brain tumor

The phosphatase and tensin homologue deleted on chromosome 10 (*PTEN*) tumor suppressor gene was the first phosphatase identified to be frequently mutated/deleted somatically in various human cancers, including glioblastoma multiforme (1–3). In addition, germline mutations in the *PTEN* gene have been associated with Cowden syndrome and related diseases in which patients develop macrocephaly of the brain and hyperplastic lesions in multiple organs with increased risks of malignant transformation (4, 5).

PTEN contains a sequence motif that is highly conserved in the members of the protein tyrosine phosphatase family. *PTEN* possesses phosphatase activity on phosphotyrosyl and phosphothreonyl-containing substrates (3, 6) *in vitro* and on phosphatidylinositol (3–5) trisphosphate, a product of phosphatidylinositol 3-kinase, both *in vitro* and *in vivo* (7–11). *PTEN*-deficiency leads to accumulation of PIP₃ and activation of signaling molecules that are critical in controlling cell size, cell migration, cell death, cell proliferation, and differentiation, all of which are involved in normal development and tumorigenesis (12).

We and other groups have used Cre-loxP technology to conditionally delete *Pten* in different regions of the brain and at different developmental stages (13–18). By crossing *Pten* conditional knockout mice with the Nestin-Cre line, we generated mutant mice with a substantially increased brain size and a doubled brain weight (13), similar to macrocephalic phenotypes found in humans with inherited *PTEN* mutations. Further studies indicated that the enlarged brain resulted from increased cell proliferation, decreased cell death, and enlarged cell size. Because all neural cell types are thought to be derived from a common stem cell, the neural stem cell, the overall size increase

of the mutant brain prompted us to study the neural stem cell population. Our *in vitro* neurosphere culture analysis indicated that there were more stem cells in the mutant brain. Moreover, *PTEN*-deficient neural stem/progenitor cells have a greater proliferation capacity, which is due, at least in part, to a shortened cell cycle time (13).

One explanation for this phenomenon is that *PTEN* truly controls the stem cell self-renewing state and *Pten* deletion promotes neural stem cell self-renewal. In this case, we would expect to see a persistence of sphere-forming activity and maintenance of multilineage potential of *Pten* null neural stem cells in a long-term culture. Alternatively, effects of *Pten* deletion, seen both *in vivo* and *in vitro*, could have been due to enhanced proliferation of progenitors that were more limited in their differentiation potential. In this case, the number of *Pten* null spheres should remain the same, yet the size of the spheres should be greatly reduced. To distinguish between these two possibilities, in the current study, we performed stringent serial neurosphere passage experiments. Our results indicate that the loss of *PTEN* results in a prolonged self-renewal of neural stem/progenitor cells, without an appreciable change in their capacity for multipotential differentiation, whereas cortical stem/progenitor cells derived from WT animals had a limited capacity for self-renewal and gradually lost their capacity to produce neurons during the same culture period. Microarray analysis revealed prominent dysregulation of cell cycle-related genes in *PTEN*-deficient neurospheres. Furthermore, flow cytometric analysis indicated that *PTEN*-deficiency mediates enhanced neural stem/progenitor cell self-renewal by promoting exit from G₀/G₁A, and entrance into the cell cycle, in addition to the enhanced G₁-S transition reported in ref. 11. Taken together, these data suggest that the loss of *PTEN* confers an increased self-renewal capacity to neural stem/progenitor cells, a potentially important mechanism for brain tumorigenesis.

Results

***PTEN* Negatively Regulates Neural Stem Cell Self-Renewal *in Vitro*.** To directly compare the properties of mutant (MUT) and WT stem/progenitors, we first examined the effect of *PTEN* deficiency on embryonic day (E) 14.5 cortices, an age when *Pten* deletion is just complete. Cells were subjected to serial stringent, low-density passaging (Fig. 1A), and their ability to form neurospheres was recorded after each passage. As shown in Fig. 1B, although spheres from ≈80% of the MUT animals were capable

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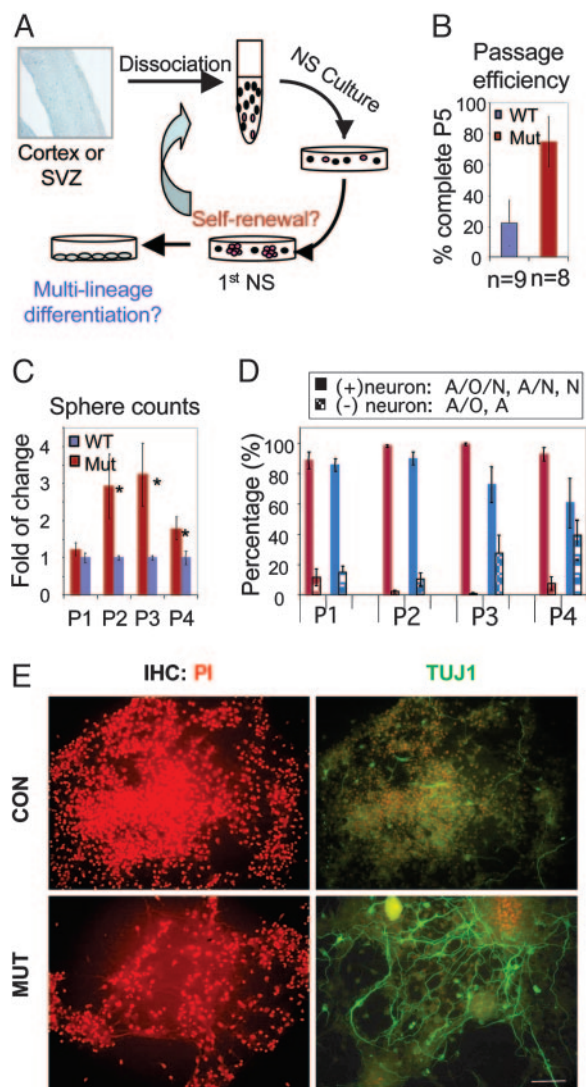
Abbreviations: En, embryonic day *n*; MUT, mutant; *PTEN*, phosphatase and tensin homologue deleted on chromosome 10.

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of forming spheres for at least five passages (P5), only $\approx 20\%$ of the WT cultures could do the same, owing to a lack of sufficient viable cells for reseeded.

To further explore the role of PTEN in neural stem/progenitor cell self-renewal, we quantified the number of spheres produced during each passage. *Pten* deletion resulted in a greater number of spheres, especially at passages 2, 3, and 4 (Fig. 1C). This result indicates that MUT cultures have a greater percentage of sphere-forming cells at each passage after initial plating, consistent with an increased self-renewal capacity. Because our neurosphere cultures were reseeded at a specific cell density, the results shown in Fig. 1C underestimate the total sphere-forming potential of MUT stem cells over time. To account for this underestimation, we estimated the total sphere-

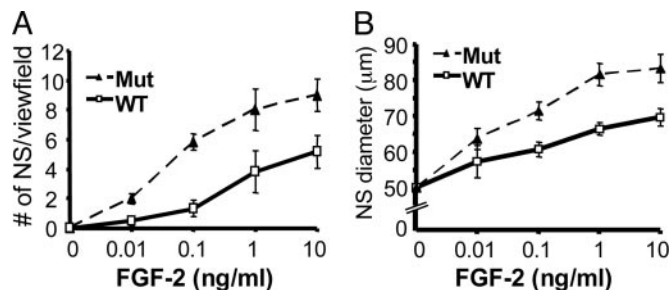


Fig. 2. *Pten* null neurospheres are hypersensitive to growth factor stimulation. Identical number of cells from WT and MUT E14.5 front brains were seeded in neurosphere cultures with the indicated concentration of FGF2. Neurosphere numbers (A) and size (B) were measured 7 days after initial culture and presented as mean \pm SD.

PTEN Null Spheres Are Multipotent and Have Greater Proliferation Capacity. Neural stem cells can undergo multilineage differentiation and give rise to neurons, astrocytes, and oligodendrocytes (19). To verify that the effects observed above are indeed on neural stem cells, rather than committed progenitors, we evaluated the differentiation potential of WT and MUT spheres after each passage. As shown in Fig. 1 *D* and *E* (see also Fig. 6, which is published as supporting information on the PNAS web site), MUT spheres were multipotent and retained a similar capacity to produce neurons and glia throughout the experiment, suggesting that self-renewal was maintained. In contrast, WT spheres demonstrated a loss of neurogenic potential over time with serial, low-density passages (Fig. 1 *D* and *E*), consistent with the findings by others that cortically derived progenitors become more glial-restricted over time (20). These data indicate that PTEN loss not only supports persistent self-renewal, but maintains multilineage cell differentiation potential, resulting in a sustained neural stem cell-like state.

MUT spheres were significantly larger at all passages measured (Fig. 7, which is published as supporting information on the PNAS web site), similar to our previous study (13). As the passage number increased, the differences in sphere size became more significant (Fig. 7). In those few cases in which WT spheres could be passaged beyond four times, the differences in sphere size were quite striking (Fig. 7 *Left*). These data are consistent with the notion that PTEN loss enhances neural stem/progenitor proliferation over multiple passages, although concomitant effects on cell survival and cell size (see below) could account for some of the differences seen in neurosphere size.

Pten Null Neural Stem/Progenitor Cells Have Diminished Requirement for Growth Factor Stimulation. In the neurosphere culture system, neural stem cells undergo self-renewing cell divisions in basic medium supplemented with FGF2. To further understand PTEN controlled stem cell self-renewal, we conducted growth curve analyses by supplementing neurosphere cultures with different concentrations of FGF2. More neurospheres can be generated from MUT cortices than those of WT, even at suboptimal concentrations (Fig. 2*A*), indicating that MUT stem/progenitor cells are hypersensitive to FGF2 stimulation. Similarly, MUT spheres are larger, even in the presence of 100-fold less growth factor (0.1 ng/ml, Fig. 2*B*), although PTEN loss alone did not render neural stem/progenitor cell growth factor-independent. These results indicate that PTEN is a potent

negative regulator of the FGFR signaling pathway and neural stem cell self-renewal and proliferation. Furthermore, decreased reliance on growth-factor signals, a hallmark of cancer cell biology (21), might also be important for mobilizing stem cells from the quiescent stage (see below).

PTEN Negatively Regulates Entry into Cell Cycle. Somatic stem cells rapidly respond to stress, such as tissue damage, by generating progenitors and terminally differentiated cell types to replenish damaged areas. Concurrently, stem cells also generate additional stem cells, via amplification, before returning to quiescence. Although stem cell cell cycle entry and exit happen naturally *in vivo*, little is known about the genes and molecular mechanisms controlling this process.

Using a CFSE washout experiment, we previously demonstrated that PTEN deficiency leads to an increased number of cell divisions in neural stem cells (13). This observation prompted us to assess whether PTEN plays an important role in controlling exit from the G_0/G_1A (quiescent) stage of the cell cycle, and entry into the G_1B and $S/G_2/M$ stages of the cell cycle (see *Materials and Methods*). Using two-color flow cytometry, we labeled DNA and RNA simultaneously within fresh, dissociated brain (Fig. 3*A Upper*) and in cultured neurospheres (Fig. 3*A Lower*) (22).

A significant fraction of WT cells, either from the E14 forebrains or derived from dissociated first passage of neurosphere cultures, were in the quiescent G_0/G_1A cell cycle stage (Fig. 3*A Left*), consistent with previous studies (23). *Pten* null brains or neurosphere cultures, however, contained significantly fewer cells in the G_0/G_1A cell cycle stage, as compared to their age- and genetic background-matched littermates (Fig. 3*A Right*). Fig. 3*B Left* presents results from all experiments performed (*, statistically significant).

Our previous study suggests that PTEN negatively controls cell growth or size (13). To investigate whether cell size control is correlated with cell cycle regulation, especially exit from quiescence and cell cycle entry, we measured relative cell size at different cell cycle stages flow cytometrically by assessing forward scattered light. All cycling cells (G_1B , S , and G_2/M) from WT E14 forebrain or neurosphere cultures had higher forward scatter values than G_0/G_1A cells, indicating that the G_0/G_1A cells were smaller (Fig. 3*B Right*, in red). Similar to our previous report, cells from *Pten* null brain are, on average, bigger at every phase of cell cycle (Fig. 3*B Right*, in blue), although at the quiescent G_0/G_1A cell cycle stage, the mean forward scatter value measured for *Pten* null cells was not substantially different from that of the WT (Fig. 3*B, Right*). This result suggests that enhanced cell growth may push *Pten* null cells to enter the G_1B phase of the cell cycle, resulting in a decreased G_0/G_1A cell population. This finding is generally in agreement with the notion that cell growth or size control is largely regulated at the translational level (24).

PTEN Negatively Regulates Genes Involved in Cell Growth and Cell Cycle Control. The data described above support the hypothesis that loss of PTEN results in a greater self-renewal capacity of neural stem/progenitor cells. To further examine potential mechanisms of PTEN controlled neural stem/progenitor cell proliferation, we undertook an unbiased approach by analyzing the gene expression profiling of MUT and WT neurospheres.

We identified 257 genes that differ between MUT and WT neurosphere cultures at a confidence level of $P < 0.001$. We then performed hierarchical clustering (25) of differentially expressed genes. As expected, the six arrays clustered into two major groups according to the genotype (Fig. 4*A*). These differentially expressed genes can be further clustered into two major groups (marked by white boxes): genes that are up-

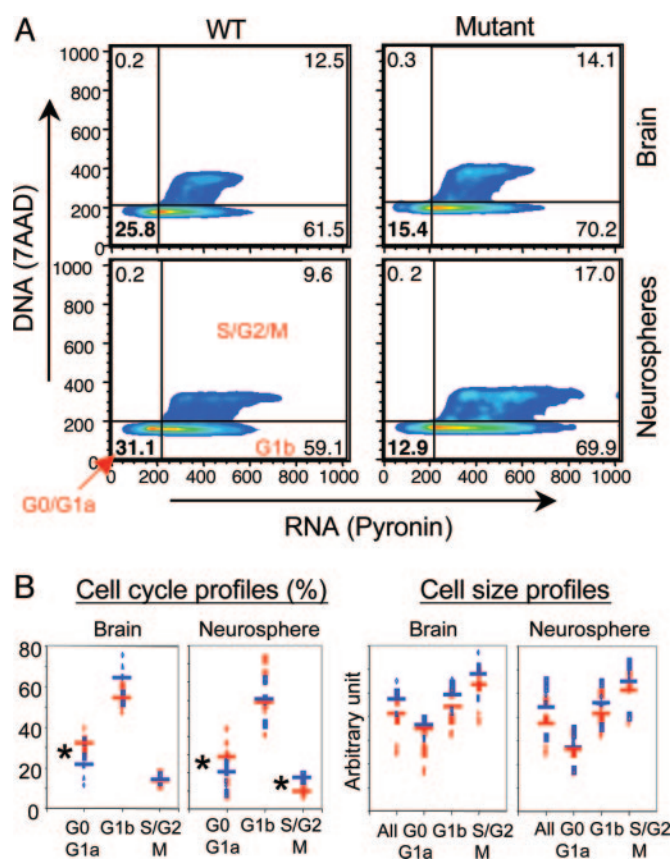


Fig. 3. Loss of PTEN leads to increased G_0/G_1A to G_1B cell cycle transition as well as increased cell growth. (A) Flow cytometric analysis of cell cycle status in primary cells from E14.5 cortices (*Upper*) and cells that have gone through one generation of neurosphere culture (*Lower*). *Left*, WT; *Right*, MUT. *N*-butylate treated neurosphere cultures, which are arrested at the G_1A to G_1B transition, were used to demarcate the line (vertical axes) between cells falling into the G_0/G_1A stage (quiescence, *Lower Left*) and cells which have entered the G_1B stage of the cell cycle (*Lower Right*). (B *Left*) A comparison of cell cycle profiles. Statistic analysis for brain: G_0/G_1A , $P = 0.05$; G_1B , $P = 0.08$; $S/G_2/M$, $P = 0.43$; neurosphere: G_0/G_1A , $P = 0.05$; G_1B , $P = 0.72$; $S/G_2/M$, $P = 0.00003$. *, statistically significant. (Right) Cell size profiles at different cell cycle stages. Data include all experiments conducted. For brain, WT, $n = 10$; Mut, $n = 5$; for neurosphere, WT, $n = 11$; Mut, $n = 7$.

regulated in the MUT (upper box) and genes that down-regulated in the MUT (lower box).

The most significantly up-regulated genes in the MUT spheres were cell cycle- and DNA replication-related genes, such as cyclin B1, cyclin B2, cyclin D1, cyclin E1, Ki-67, and DNA primases. Other examples of genes found to be up-regulated in MUT spheres include PBK/TOPK and maternal embryonic leucine zipper kinase, which have previously been identified by our group as being enriched in neural progenitors (26). Examples of genes found to be up-regulated in WT spheres were primarily related to cell differentiation and metabolism such as doublecortin, glutamate receptor (AMPA2), GABA receptor, and glutamate dehydrogenase.

To gain a more systematic understanding of the results of the gene expression analysis, we used the National Institutes of Health's DAVID software to classify our results into Gene Ontology categories (Fig. 4*B*, EASE $P < 0.5$). This analysis would help to identify biological processes that are significantly different between MUT and control cells. Results from Gene Ontology analysis identified a highly significant ($P < 2.7 \times 10^{-22}$, EASE statistic) overrepresentation of genes involved in regula-

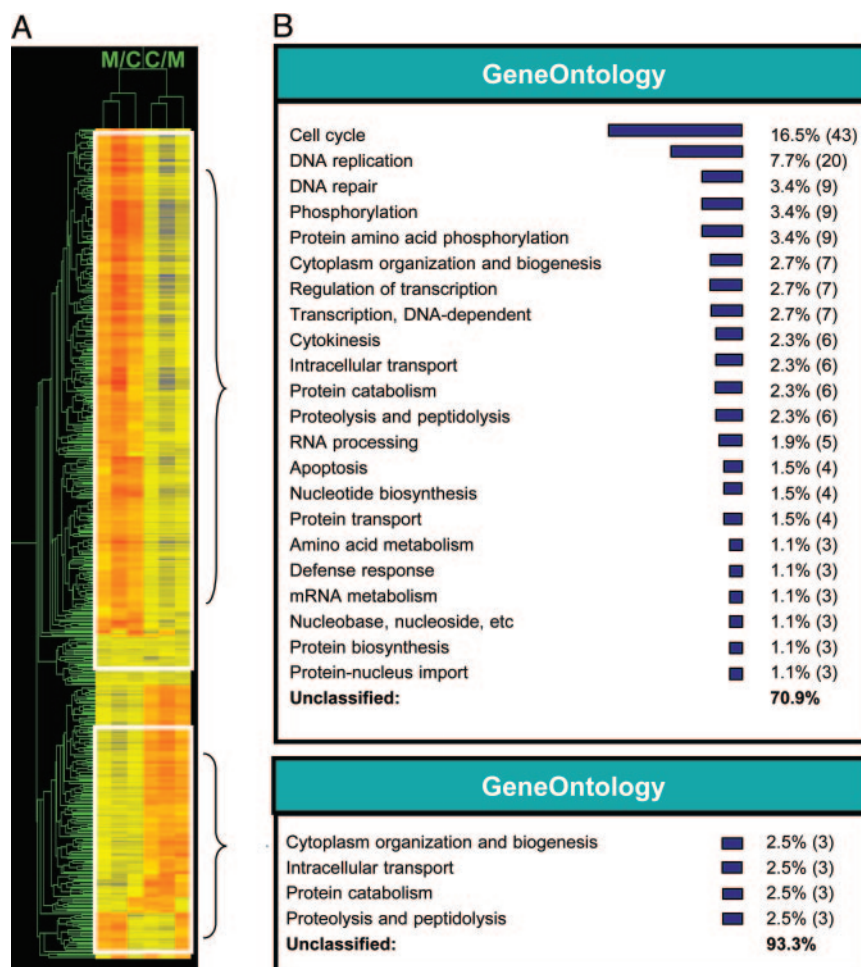


Fig. 4. Gene expression analysis. (A) Microarray data can be classified into two major groups, genes that are up-regulated in *Pten* null neurosphere cultures (upper box) and genes that are down-regulated in *Pten* null neurosphere cultures (lower box). (B) Gene Ontology analysis.

tion of the cell cycle as a key theme in the suite of gene expression of the knockout cultures, along with DNA replication, repair and cytokinesis. A complete list of those differentially regulated genes is shown in Tables 1 and 2, which are published as supporting information on the PNAS web site.

Discussion

To escape normal tissue homeostasis, tumor cells must acquire multiple genetic aberrations that collectively establish the malignant phenotype (21). For glioblastoma multiforme, this protracted process might encompass several years and requires brain tumor cells to maintain self-renewal capacities over extended periods. Previously, we and others have demonstrated that only a fraction of brain tumor cells have the ability to self-renew and to maintain brain tumor growth (27–29). Although these observations are now well documented, the molecular mechanisms governing these stem cell-like capabilities in brain tumors remain largely elusive (29). *PTEN* mutation is one of the most frequent genetic alterations associated with glioblastoma multiforme (30–32). Our previous study indicates that deletion of *Pten* in the embryonic brain leads to increased neural stem/progenitor cell proliferation (13). In the present study, we sought to determine whether loss of PTEN in neural/stem progenitor cells promotes the long-term maintenance of stem cell characteristics and the mechanisms underlying this maintenance.

Loss of PTEN in neural progenitors confers on them a greater capacity for persistent self-renewal. Although sphere forming

activity in WT neurosphere cultures diminishes over time, consistent with previous studies (33), *Pten*^{−/−} neurosphere cultures can be stably maintained, suggesting that loss of PTEN is sufficient for the propagation of self-renewal properties. Consistent with this hypothesis, Sinor *et al.* (34) recently demonstrated that overexpression of Akt-1, a critical downstream target of PTEN signaling, results in enhanced self-renewal of cortical progenitor cells.

It is unknown at present whether deletion of PTEN would result in a similar phenotype in progenitors derived from other embryonic regions or from the subventricular zone derived from adult brain. Differences in the molecular mechanisms of self-renewal are clearly present in embryonic and fetal neural stem cells. For example, Bmi-1, a polycomb transcription factor, regulates neural stem cell self-renewal *in vivo* at postnatal, but not prenatal, stages, probably because fetal neural stem cells do not express the cell cycle inhibitory proteins that are regulated by Bmi-1 *in vivo* (35).

PTEN-deficient neurospheres retained their neurogenic potential, and we did not observe stem cell “exhaustion” in PTEN-deficient neurospheres derived from the embryonic cortex. These findings, taken together, indicate that a deletion of PTEN truly enhances stem cell self-renewal, rather than simply promoting the proliferation of committed progenitors or those with a limited capacity to self-renew. These findings are seemingly in contrast to those of Kippin *et al.* (36), who studied P21^{−/−} neurospheres derived from postnatal subventricular

