Deletion of PTEN Promotes Tumorigenic Signaling, Resistance to Anoikis, and Altered Response to Chemotherapeutic Agents in Human Mammary Epithelial Cells

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Abstract

Many cancers, including breast cancer, harbor loss-of-function mutations in the catalytic domain of phosphatase and tensin homologue deleted on chromosome 10 (PTEN) or have reduced PTEN expression through loss of heterozygosity and/or epigenetic silencing mechanisms. However, specific phenotypic effects of PTEN inactivation in human cancer cells remain poorly defined without a direct causal connection between the loss of PTEN function and the development or progression of cancer. To evaluate the biological and clinical relevance of reduced or deleted PTEN expression, a novel in vitro model system was generated using human somatic cell knockout technologies. Targeted homologous recombination allowed for a single and double allelic deletion, which resulted in reduced and deleted PTEN expression, respectively. We determined that homozygous loss of PTEN in the nonneoplastic human mammary epithelial cell line MCF-10A was sufficient for activation of the phosphoinositide 3-kinase/AKT and mitogen-activated protein kinase pathways, whereas the homozygous absence of PTEN expression led to a further increased activation of both pathways. The deletion of PTEN was able to confer growth factor–independent proliferation, which was confirmed by the resistance of the PTEN−/− MCF-10A cells to small-molecule inhibitors of the epidermal growth factor receptor. However, neither heterozygous nor homozygous loss of PTEN expression was sufficient to promote anchorage-independent growth, but the loss of PTEN did confer apoptotic resistance to cell rounding and matrix detachment. Finally, MCF-10A cells with the reduction or loss of PTEN showed increased susceptibility to the chemotherapeutic drug doxorubicin but not paclitaxel. [Cancer Res 2009;69(21):8275–83]

Introduction

Phosphatase and tensin homologue deleted on chromosome 10 (PTEN) is a tumor suppressor gene that dephosphorylates phosphatidylinositol 3,4,5-trisphosphate, the product of the lipid kinase phosphoinositide 3-kinase (PI3K). PTEN antagonizes activated PI3K to maintain normal cell growth or arrest, survival, or apoptosis. PTEN and PI3K exist in a tight regulatory loop, and a reduction in pathway activation led to growth factor independent proliferation that was suppressed with either PI3K or MAPK inhibitors. PTEN loss in MCF-10A cells also increased anchorage-independent survival but was insufficient to confer anchorage-independent growth. Also, of potential clinical importance, PTEN loss confers susceptibility to the chemotherapeutic drug, doxorubicin, but not paclitaxel, two agents commonly used for breast cancer therapy.
In summary, the results show that PTEN heterozygous and homozygous loss promotes activation of both PI3K and MAPK pathways in MECs. Reduction of PTEN expression or complete loss is observed in ~40% of human breast cancers (2, 5, 13). To determine the oncogenic phenotype of reduced or absent PTEN expression in human breast epithelial cells, we generated isogenic human MECs using MCF-10A cells. MCF-10A breast epithelial cells were chosen for targeted PTEN knockout because these cells are human, mostly diploid, nontumorigenic cell line and karyotype analysis of late-passage cells show genetic stability (data not shown). The use of nontumorigenic cell lines allows us to assess any oncogenic effects directly resulting from loss of PTEN. Several independently derived heterozygous knockout clones (PTEN+/−) were identified containing one active PTEN allele. Subsequent targeting of the second allele was accomplished to yield homozygous PTEN (PTEN−/−) knockout clones.

Somatic cell gene knockout was accomplished via homologous recombination between the genomic locus and the targeting vector to delete exon II of PTEN and replace it with a promoterless, IRES-neo+ gene flanked by LoxP sites (Fig. 1A). For each round of targeting, positive clones were verified by PCR. Subsequent removal of the IRES-neo+ cassette was accomplished by treatment with Cre recombinase. At least three single, independent isogenic PTEN+/− and PTEN−/− clones from separate infections were isolated and used to account for any clonal variations.

MCF-10A PTEN+/− clones showed a decrease in PTEN levels (Fig. 1B, lanes 2–4) and PTEN−/− clones completely lacked PTEN expression (Fig. 1B, lanes 5–7). The absence of PTEN mRNA in PTEN+/− clones was verified by real-time PCR (data not shown). All PTEN−/− clones maintained increased pAkt levels over their PTEN+/− and parental counterparts. Interestingly, activated ERK (pERK1/2) levels were also increased in PTEN−/− clones over the MCF-10A parental cells. Although PTEN+/− clones showed an increase in activated ERK levels from the parental cells, the increase was less dramatic or consistent among PTEN−/− clones (Fig. 1B). However, in conjunction with an increase in pERK1/2 in PTEN+/− clones, decreased total ERK levels were consistently observed.

PTEN loss confers growth factor–independent proliferation. To determine whether the activation of the PI3K and MAPK pathways altered proliferation rates, MCF-10A, PTEN+/−, and PTEN−/− clones were analyzed over a period of 9 days. Interestingly, at early passage, PTEN+/− and PTEN−/− clones with reduced or deleted PTEN grew significantly slower than parental MCF-10A cells (Fig. 2A; P < 0.05), whereas, at later passage, MCF-10A cells maintain a similar growth rate to that of their earlier-passage counterparts; the proliferation rates of PTEN+/− and PTEN−/− clones increase over time (Fig. 2A). The parental MCF-10A, PTEN+/−, and PTEN−/− clones do not undergo any significant cell death over the first 7 days due to the absence of a sub-G1 population (Supplementary Fig. S1). However, once the cells achieve contact inhibition by day 7, all cells begin to die as shown by a drop in viability and the presence of a sub-G1 peak. The increase proliferation rate is likely due to a variety of mechanisms downstream of AKT activation, such as increased cyclin D1 expression, inhibition of forkhead transcription factors, or reduction of p27kip1, all of which positively regulate G1/S cell cycle progression (reviewed in ref. 14).

A well-known characteristic of MCF-10A MECs is their epidermal growth factor (EGF) requirement for cellular proliferation. Growth factor–independent proliferation is a common hallmark in cancer cells containing oncogenic phenotypes and aberrantly activated signaling (15). Because PTEN+/− and PTEN−/− clones have an increase in activated PI3K and MAPK pathways, we examined whether the increased activation of these pathways was sufficient to confer EGF-independent growth by treating the cells with increasing concentrations of the clinically administered EGF receptor small-molecule inhibitors gefitinib and erlotinib (Fig. 2B).

Compared with the parental and PTEN+/− clones, PTEN−/− clones were significantly more resistant to growth inhibition via the EGF receptor inhibitors, indicating a decreased requirement of EGF for proliferation. To confirm this observation, MCF-10A cells and PTEN+/− and PTEN−/− clones were maintained in minimal assay medium devoid of exogenous growth factors for 9 days. As observed previously using compounds to disrupt EGF signaling, MCF-10A cells and PTEN−/− clones showed reduced growth (Fig. 2C). However, PTEN−/− cells survived and continued to slowly proliferate although considerably slower than in medium supplemented with EGF. At later passage, PTEN−/− cell proliferation in the absence of mitogens became more robust (Supplementary Fig. S2).
Immunoblots confirmed the increased activity of each pathway in the presence and absence of mitogens (Fig. 2D). After 24 h in growth medium, the levels of pAKT are highest in PTEN−/− clones and slightly more elevated in PTEN+/− clones compared with the MCF-10A parental cells. Assessment of the same set of cells grown in medium without mitogens showed reduced levels of pAKT. Although there is a minimal level of detectable pAKT in the parental and PTEN−/− clones, PTEN+/− clones continue to maintain elevated pAKT levels at 24, 48, and 72 h.

pERK levels were also slightly elevated in all PTEN−/− and PTEN+/− clones compared with the MCF-10A parental cells when grown in normal culture medium (Fig. 2D). The levels of activated ERK were similar between PTEN−/− and PTEN+/− clones. This result differed from the earlier immunoblot results (Fig. 1B) likely due to different harvest times after replating. Cells in Fig. 1B were harvested during exponential growth 3 days after replating, whereas cells in Fig. 2D were harvested only 24 h after replating when they are not yet in exponential growth. However, after 3 days in medium devoid of growth factors, PTEN−/− cells have increased pERK levels over the MCF-10A parental cells, and PTEN−/− cells have pERK levels higher than PTEN+/− clones, similar to the pattern of ERK phosphorylation seen after 3 days in culture medium (Fig. 1B). This pattern of increasing levels of activated ERK, from MCF-10A parental cells to their PTEN−/− isogenic counterparts, indicates that, even under growth factor–reduced conditions, loss of PTEN allows for activation of the ERK signaling pathway.

To determine if the improved cell growth in PTEN−/− cells resulted from differences in cell cycling or reduced apoptosis, we performed flow cytometry measurements of DNA content throughout the growth in minimal medium (Fig. 3). These results showed that both MCF-10A and PTEN+/− cells undergo apoptotic DNA cleavage beginning on day 3 that increases to 87% and 81%, respectively, by day 9, whereas PTEN−/− cells show no signs of apoptosis. The increased viability of PTEN−/− cells is primarily from resistance to apoptosis rather than a difference in cell cycling. The elevation of apoptosis in MCF-10A and PTEN−/− cells during exposure to minimal medium is clearly sufficient to offset any cell growth and keep the cell population from increasing.

Growth factor–independent proliferation due to PTEN loss can be inhibited by pharmacologic blockade of PI3K and MAPK pathways. To confirm the requirement of active PI3K and MAPK pathways for continued cell proliferation in the absence of growth factors, PTEN−/− cells were treated with inhibitors of each pathway and growth factor–independent proliferation was assessed. Only PTEN−/− cells were used in this experiment because the parental and heterozygote clones do not grow under these conditions (Fig. 2C). Increasing concentrations of the PI3K inhibitor, LY294002, in minimal assay medium was added to the cells, and after 5 days, a dose-dependent inhibition of growth was observed. The addition of 10 μmol/L LY294002 led to nearly complete inhibition of proliferation of all PTEN−/− clones (Fig. 4A). Similarly, PTEN−/− clones were grown in the presence of the MEK1/2 inhibitor, U0126 (Fig. 4B). There was also a dose-dependent growth inhibition of PTEN−/− cells following exposure to the MEK inhibitor. In the presence of 1 μmol/L U0126, growth factor–independent proliferation was inhibited by 50% and almost completely inhibited with 2.5 μmol/L U0126.

To verify inhibition of the PI3K and MAPK pathways by LY294002 and U0126, respectively, immunoblots were done. In the absence of the PI3K or MEK1/2 inhibitors, PTEN−/− clones displayed high levels of pAKT and pERK (Fig. 4A). After LY294002 treatment, all PTEN−/− clones showed a significant drop in pAKT levels. Following U0126 treatment, the levels of pERK dropped to almost undetectable levels.

Anchorage-independent survival and growth. Because PTEN loss highly correlates with increased breast cancer lymph node metastasis (16–18), it was next determined if PTEN loss alone would lead to the transformation of nontumorigenic breast epithelial cells. Anchorage-independent growth in soft agar is a property of transformed cells that best correlates with in vivo tumorigenicity (19). MCF-10A nontumorigenic parental cells and PTEN−/− clones were plated in soft agar and incubated for 21 days. MCF-7 breast cancer line was used as a positive control for colony growth and only incubated for 14 days due to the formation of multiple, large colonies. As expected, MCF-10A cells did not form colonies. Likewise, PTEN−/− cells were unable to form colonies in soft agar and unable to form tumors in severe combined immunodeficient mice (n = 5) after 24 weeks (data not shown). However, colony formation in soft agar and in vivo tumor growth rely on anchorage-independent proliferation but are not a sufficient test for increased resistance to anoikis or apoptosis after matrix detachment. Because previous data have shown that activation of the PI3K pathway contributes to cell survival after detachment (20), MCF-10A, PTEN−/−, and PTEN+/− cells were next tested for apoptotic resistance during cell rounding and detachment. Included in these
studies, as a control for resistance to cell rounding and anoikis, were MCF-10A cells overexpressing the antiapoptotic gene Bcl2 (8). PARP cleavage, an indicator of apoptosis, was examined after the cells were treated with latrunculin-A to induce cell rounding (Fig. 5A). Latrunculin-A is a specific inhibitor of actin polymerization that has been used to induce rapid rounding of MCF-10A cells (8). MCF-10A, PTEN+/−, and PTEN−/− cells treated with vehicle control in minimal assay medium showed similar, low levels of PARP cleavage. MCF-10A.Bcl2 cells, with verified resistance to apoptosis, had undetectable PARP cleavage. On addition of latrunculin-A, the MCF-10A parent line and PTEN+/− clones undergo significant PARP cleavage, whereas PTEN−/− cells maintain high levels of full-length PARP, similar to that of MCF-10A.Bcl2 cells. To examine whether PTEN−/− cells exhibited a general resistance to apoptosis, all cells were treated with the death receptor ligand, tumor necrosis factor–related apoptosis-inducing ligand (TRAIL). Binding of TRAIL to transmembrane death receptors stimulates apoptosis via the extrinsic pathway, which is independent of AKT and the mitochondria. Within 2 h of TRAIL-related apoptosis inducing ligand treatment, all MCF-10A cells and variants began to undergo apoptosis confirmed by the increase of cleaved PARP levels. The apoptotic resistance of PTEN−/− cells therefore seems restricted to the intrinsic apoptosis pathway, because it cannot prevent apoptosis that occurs downstream of mitochondrial apoptosis signaling. Additionally, to determine anoikis resistance, the cells were plated over low-attachment plates. Without tissue culture–treated plastic, the cells remained in suspension. After detachment for 24 h, MCF-10A parental cells and PTEN+/− clones undergo massive cell death as shown by high levels of cleaved PARP and the presence of a sub-G1 peak (Fig. 5B and C). PTEN−/− cells maintained high levels of full-length PARP and a lower percentage of cells in sub-G1, indicating their resistance to anoikis. pERK levels are only very slightly elevated in PTEN+/− clones; these cells maintained similar levels of PARP cleavage to the parental cells. Although the first PTEN−/− clone revealed an increase in pERK levels compared with the other PTEN−/− clone, no differences in the levels
of cleaved PARP were observed between clones. Therefore, whereas MEK activation was required for continued cell growth (Fig. 4), the levels of ERK activation were relatively independent from apoptosis during detachment. It is more likely that AKT activation was responsible for the resistance to anoikis, because high levels of pAKT were maintained in the suspended PTEN−/− cells.

PTEN loss sensitizes cells to the chemotherapeutic drug doxorubicin but not paclitaxel. Studies suggest that loss of PTEN expression correlates with poor prognosis as well as resistance to chemotherapies (21, 22). To determine whether PTEN loss mediates chemotherapeutic resistance and increases cell survival, the PTEN isogenic MCF-10A cells were exposed to increasing concentrations of doxorubicin and paclitaxel. Primary normal breast epithelial cells are alive and metabolizing but not actively proliferating. To mimic healthy, growth-arrested epithelial cells, MCF-10A cells were plated at high density (1.5 × 10⁴) per well in a 96-well plate in minimal assay medium. After 24 h, the cells attached as ∼90% confluent monolayer. Although PTEN−/− cells have the ability to grow in minimal medium, they remain contact-inhibited and growth-arrested at confluence; therefore, the plating densities used matched those of the MCF-10A parental cells. Drugs were added after growth arrest to determine cell survival. Interestingly, PTEN−/− and PTEN+/− cells responded differently to the drugs. Doxorubicin similarly reduced the percentage of surviving cells in both PTEN+/− and PTEN−/− cells (Fig. 6A). Even at the low concentration of 5 mmol/L, doxorubicin reduced PTEN+/− and PTEN−/− clones by 10% and 24%, respectively. No difference in susceptibility was observed between the isogenic cells following exposure to paclitaxel (Fig. 6B).

Discussion
The loss of PTEN expression or the acquisition of activating PI3K mutations (PIK3CA) occurs in ∼50% to 75% of breast cancers, illustrating the importance of the PI3K pathway in breast cancer. Notably, loss of PTEN expression and PIK3CA mutation are mutually exclusive events (23) likely because PTEN and PI3K exist in a tight, regulatory loop, strictly controlling phosphatidylinositol trisphosphate to its phosphatidylinositol 4,5-bisphosphate counter-part. Our findings support the role of PTEN loss in breast cancer based on the ability of PTEN−/− cells to proliferate in the absence of growth factors and their resistance to anoikis. However, PTEN loss is insufficient to promote active tumorigenesis of the MCF-10A cells, suggesting a need for other oncogenic events (24). This result is contradictory to recent data in which the overexpression of two clinically relevant PI3K mutations (H1047R and E545K) conferred anchorage-independent growth of MCF-10A cells in soft agar (25). However, in these studies, the expression of the PIK3CA mutant cDNA is under control of a cytomegalovirus promoter that may remove the selective pressure for a PTEN−/−/− cells.

Although metastasis is the cause of 90% of human cancer deaths (27), the metastatic process presents numerous challenges to tumor cells, including apoptosis that results from detachment (anoikis) or cell shape change (amorphosis; ref. 28). Resistance to apoptosis allows tumor cells to survive these challenges (29) but does not promote immediate tumor outgrowth at the secondary site, yielding a period of tumor dormancy (30). There is currently tremendous clinical interest in such dormant tumor cells, because their presence in the bloodstream strongly predicts poor patient outcome in breast cancer (31, 32). The importance of defining the mechanisms that promote tumor dormancy is also emphasized.
by the observation that breast tumor patients who are diagnosed early with no detectable regional metastases have >30% chance of recurrence when followed for 10 to 15 years (33, 34). Our results indicate that PTEN loss induces a dormant tumor cell phenotype by promoting resistance to apoptosis without inducing complete anchorage-independent growth. Recent evidence shows that MECs that have not fully transformed to anchorage-independent growth are still fully capable of metastasizing to the lung in a dormant state and then recurring once growth-initiating oncogenes are activated (35, 36). Systems based on fibroblasts or exogenous overexpression of PI3KCA display active tumor growth, whereas our system based on homologous knockout of PTEN in MCF-10A MECs more effectively models the dormant phenotype of carcinoma cells. However, such dormant tumor cells are typically difficult to treat with traditional chemotherapies, because they persist without active cell division. Defining which types of chemotherapy are able to effectively target tumor cells in such a dormant state will be critical to treating metastatic recurrence.

A variety of chemotherapeutic agents converge on a common final pathway leading to apoptotic cell death. Certain studies have shown that activation of the PI3K pathway enhances the survival of cancer cells in response to such agents and contribute...
to chemotherapy resistance. However, these previous studies employed an overexpressed, constitutively active AKT1 (37, 38), which may not recapitulate the physiologically active AKT levels due to PTEN loss or PIK3CA mutations, whereas other studies overexpressed an oncogene such as constitutively active Ras (39) or HER-2 (40) in the MCF-7 breast adenocarcinoma line, which already contains a PIK3CA mutation (E545K; ref. 41). Here, to more closely recapitulate physiologic levels of active AKT, we used the MCF-10A isogenic PTEN knockout clones to determine chemotherapeutic response to doxorubicin and paclitaxel. Surprisingly, PTEN“−” clones were more susceptible to doxorubicin than their parental PTEN-expressing counterparts. However, no difference in survival was observed between the isogenic clones when treated with paclitaxel. The susceptibility of PTEN“−/−” and PTEN“+/−” cells to doxorubicin and not paclitaxel may be explained by the different mechanisms of action of each drug. Paclitaxel is a microtubule-stabilizing compound that interferes with the normal breakdown of this cytoskeletal component. This drug immediately and adversely affects cell function as microtubule-inherent dynamic instability is necessary for their function to transport other cellular components. Doxorubicin is known to intercalate within the DNA and inhibition of topoisomerase II progression, eliciting DNA damage. On DNA damage, normal cells undergo growth arrest to either repair the damage or undergo apoptosis if the damage is substantial. However, constitutively active PI3K and pathway components have been shown to override DNA damage-induced cell arrest (42–44). Haploinsufficiency and deletion of PTEN may allow for cell cycle progression and death due to massive DNA damage. Further work to elucidate the mechanisms by which PTEN expression loss may contribute to chemotherapy susceptibility is warranted.

There is a significant clinical relevance for the creation and characterization of this PTEN isogenic model system. Using this model, we have shown that PTEN expression loss in MECs results in constitutive AKT activation and induces multiple phenotypic alterations characteristic of breast tumor cells, including growth factor–independent proliferation and protection from anoikis. PTEN expression loss also confers increased susceptibility to doxorubicin but not paclitaxel. Together, these data support the notion that the cancer-associated PTEN expression loss may significantly contribute to breast cancer cell survival and tumor dormancy.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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References


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