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 heterozygous loss of PTEN in the nontumorigenic 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]

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Introduction

Phosphatase and tensin homologue deleted on chromosome 10 (PTEN) is a tumor suppressor gene that dephosphorylates phos-
Somatic cell gene knockout was accomplished via homologous recombination between the genomic locus and the targeting vector to delete exon II of \textit{PTEN} and replace it with a promoterless, \textit{ires-neo}\(^\beta\) gene flanked by LoxP sites (Fig. 1A). For each round of targeting, positive clones were verified by PCR. Subsequent removal of the \textit{ires-neo}\(^\beta\) cassette was accomplished by treatment with Cre recombinase. At least three single, independent isogenic \textit{PTEN}\(^{−/−}\) and \textit{PTEN}\(^{−/−}\) clones from separate infections were isolated and used to account for any clonal variations.

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

\textbf{PTEN loss confers growth factor–independent proliferation.} To determine whether the activation of the PI3K and MAPK pathways altered proliferation rates, MCF-10A, \textit{PTEN}\(^{+/−}\), and \textit{PTEN}\(^{−/−}\) clones were analyzed over a period of 9 days. Interestingly, at early passage, \textit{PTEN}\(^{+/−}\) and \textit{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 \textit{PTEN}\(^{−/−}\) and \textit{PTEN}\(^{+/−}\) clones increase over time (Fig. 2A). The parental MCF-10A, \textit{PTEN}\(^{+/−}\), and \textit{PTEN}\(^{−/−}\) clones do not undergo any significant cell death over the first 7 days due to the absence of a sub-G\(_1\) 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-G\(_1\) 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 G\(_1\)-S cell cycle progression (reviewed in ref. 14).

A well-known characteristic of MCF-10A MECs is their epithelial 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 \textit{PTEN}\(^+/−\) and \textit{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 \textit{PTEN}\(^{−/−}\) clones, \textit{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 \textit{PTEN}\(^{+/−}\) and \textit{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 \textit{PTEN}\(^{−/−}\) clones showed reduced growth (Fig. 2C). However, \textit{PTEN}\(^{+/−}\) cells survived and continued to slowly proliferate although considerably slower than in medium supplemented with EGF. At later passage, \textit{PTEN}\(^{−/−}\) cell proliferation in the absence of mitogens became more robust (Supplementary Fig. S2).
growth medium, the levels of pAKT are highest in GAPDH. Activated ERK (pERK1/2) levels are also increased in the clones. Loading control.

The levels of pAKT are increased in 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 do not show 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 while allowing the cells to maintain attachment to the tissue culture dishes (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

Figure 2. PTEN loss confers growth in minimal medium. A, early- and late-passage growth of MCF-10A cells and PTEN-/- and PTEN-/- clones in normal MCF-10A growth medium. Points, mean of two independent experiments done in quadruplicate; bars, SD. B, cell growth of MCF-10A cells and PTEN-/- and PTEN-/- clones after exposure to increasing doses of the EGF receptor antagonists gefitinib and erlotinib. Points, mean of three independent experiments done in quadruplicate; bars, SD. C, cell growth in minimal medium. Points, mean of two independent experiments done in quadruplicate; bars, SD. On day 6, MCF-10A, PTEN-/-, and PTEN-/- cells were fixed and stained with a solution of 10% PBS-buffered formalin and 0.25% crystal violet. Representative wells from MCF-10A, PTEN-/-, and PTEN-/- cells are shown. D, MCF-10A, two PTEN-/-, and two PTEN-/- clones were plated in either normal growth medium (NG) or minimal assay medium and harvested at the indicated times by direct addition of radioimmunoprecipitation assay lysis buffer.
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 correlate 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 × 10^5) 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 μmol/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 counterpart. 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 increase PIK3CA expression to levels not observed in primary tumors or derived cell lines. In support of this hypothesis, knockin of the same PIK3CA activating mutations, H1074R and E545K, did not cause anchorage-independent growth of MCF-10A cells (26). Similar to MCF-10A PTEN−/− cells, knockin mutant PIK3CA cells were not tumorigenic, did not form colonies in soft agar, and did not alter acinar growth in three-dimensional Matrigel culture.

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

Figure 5. PTEN loss promotes resistance to apoptosis on cell rounding and anoikis. A, MCF-10A, a PTEN+/− clone, a PTEN−/− clone, and MCF-10A.Bcl2 cells were plated in minimal assay medium. The next day, the medium was changed to fresh minimal medium with or without 5 μmol/L latrunculin-A (LA) to induce cell rounding for 24 h or 1 μg/mL TRAIL for 2 h and harvested at the indicated times by direct addition of radioimmunoprecipitation assay lysis buffer. B, MCF-10A, two representative PTEN+/− clones, two representative PTEN−/− clones, and MCF-10A.Bcl2 cells were incubated in suspension in normal growth medium for 24 h. C, flow cytometry analysis of MCF-10A, PTEN+/− clone 1, and PTEN−/− clone 1 incubated in suspension in DMEM/F-12 for 24 h. A larger percentage of MCF-10A (42.8%) and PTEN−/− cells (49.4%) undergo apoptosis than PTEN+/− cells (29.6%).
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 over-expressed 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, MCF-7 breast adenocarcinoma line, which expressed 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.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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References


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