Conditional Loss of Uterine Pten Unfailingly and Rapidly Induces Endometrial Cancer in Mice

Takiko Daikoku,1 Yasushi Hirota,1 Susanne Tranguch,1 Ayesha R. Joshi,3 Francesco J. DeMayo,4 John P. Lydon,1 Lora H. Ellenson,1 and Sudhansu K. Dey1,2,3

Departments of Pediatrics, Cell and Developmental Biology, and Pharmacology, Division of Reproductive and Developmental Biology, Vanderbilt University Medical Center, Nashville, Tennessee; Department of Molecular and Cellular Biology, Baylor College of Medicine, Houston, Texas; and Department of Pathology and Laboratory Medicine, New York Presbyterian Hospital-Weill Medical College of Cornell University, New York, New York

Abstract

Etiology of endometrial cancer (EMC) is not fully understood. Animal models with rapidly and spontaneously developing EMC will help explore mechanisms of cancer initiation and progression. Pten+/− mice are currently being used as a model to study EMC. These females develop atypical endometrial hyperplasia of which ~20% progresses to EMC. In addition, tumors develop in other organs, complicating the use of this model to specifically study EMC. Here, we show that conditional deletion of endometrial Pten results in EMC in all female mice as early as age 1 month with myometrial invasion occurring by 3 months. In contrast, conditional deletion of endometrial p53 had no phenotype within this time frame. Whereas mice with endometrial Pten deletion had a life span of ~5 months, mice with combined deletion of endometrial Pten and p53 had a shorter life span with an exacerbated disease state. Such rapid development of EMC from homozygous loss of endometrial Pten suggests that this organ is very sensitive to this tumor suppressor gene for tumor development. All lesions at early stages exhibited elevated Cox-2 and phospho-Akt levels, hallmarks of solid tumor development. Varieties of target molecules that control cell survival and growth. Type II EMC, while uncommon, is more aggressive (1, 2). In human type I EMCs, the most common genetic mutations are detected in the phosphatase and tensin homologue (Pten)gene (1, 3). Pten mutations are observed in 30% to 80% of type I EMCs and in ~20% of complex atypical hyperplasia (CAH), a precursor to type I EMC. Mutations of p53 are also found in type I EMC, but this alteration occurs in ~50% of poorly differentiated carcinomas and some moderately differentiated type I EMCs, suggesting that p53 mutations are later events that contribute to progression of the disease (1). On the other hand, the majority of type II EMCs, which are more aggressive and less common, mainly contain p53, but not Pten, mutations (1, 2).

The most widely used animal model for studying EMC is Pten heterozygous mice (5). Although Pten homozygous null mice are unavailable due to their embryonic lethality, all Pten heterozygous females develop atypical endometrial hyperplasia with 20% progressing to well-differentiated EMC by age 10 months. The timing and incidence of hyperplasia and carcinoma vary from mouse to mouse in this model (3, 4). Furthermore, Pten heterozygous mice also develop other types of cancer, creating limitations to exclusively study EMC in this model. With respect to p53, both p53 heterozygous and homozygous mice develop many types of cancers, with most homozygous mice dying by age 6 months due to development of widespread lymphoma (5–7). However, EMCs are rarely observed in p53 null mice (5–7). Therefore, endometrial-specific Pten and/or p53-deleted mice would be more preferred models to study endometrial-specific cancer.

Pten is a dual-specificity phosphatase with phosphatidylinositol-3,4,5-phosphate (PIP3) a major substrate. PIP3 is dephosphorylated to phosphatidylinositol-4,5-phosphate by Pten, an event that opposes phosphatidylinositol-3-kinase (PI3K) signaling (8). Loss of Pten function, resulting in stimulation of PI3K signaling, is widely found in many types of cancers. PI3K activates Akt, a serine-threonine kinase, and phosphorylated/activated Akt regulates a variety of target molecules that control cell survival and growth. It was recently shown that introducing Akt deficiency in Pten heterozygous mice impedes tumor development including that of EMC (9), suggesting pAkt to be an immediate downstream molecule of Pten. Cox-2 is a major target of Akt signaling in cancer, overexpressed in tumors and carcinomas of the colon, breast, and lung (10). We and others have shown that human EMCs and endometria with hyperplasia express elevated Cox-2 (11–13). Moreover, Cox-2 expression is also elevated in human EMC cell lines harboring Pten mutations and activated Akt (14, 15). These studies collectively indicate that elevated pAkt and Cox-2 levels resulting from Pten mutations probably contribute to EMC development.

Note: Supplementary data for this article are available at Cancer Research Online (http://cancerres.aacrjournals.org/).

Current address for T. Daikoku: Cincinnati Children’s Hospital Medical Center, Cincinnati, Ohio.

Requests for reprints: Takiko Daikoku or Sudhansu K. Dey, Vanderbilt University, 1161 21st Avenue South, Nashville, TN 37232. Phone: 615-322-8642; Fax: 615-822-4794; E-mail: takiko.daikoku@chmc.org or sk.dey@vanderbilt.edu.

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In this study, endometrial-specific Pten and/or p53 deletion were generated by crossing floxed Pten (Pten$^{loxP/loxP}$) and/or floxed p53 (p53$^{loxP/loxP}$) mice with mice expressing Cre under the regulation of the progestosterone receptor promoter (PRcre; ref. 16). We found that 100% of Pten$^{loxP/loxP}$/PRcre/+ (Ptenpr$^{-/-}$) and Pten$^{loxP/loxP}$/p53$^{loxP/loxP}$/PRcre/+ (Ptenpr$^{-/-}$/p53pr$^{-/-}$) mice develop in situ carcinoma as early as ages 3 weeks to 1 month. Although the development of hyperplasia was similar between Ptenpr$^{-/-}$ and Ptenpr$^{-/-}$/p53pr$^{-/-}$ mice, the loss of both Pten and p53 exacerbated the disease state and was associated with a shorter life span. In contrast, p53$^{loxP/loxP}$/PRcre/+ (p53pr$^{-/-}$) mice had apparently normal endometrial histology even through age 5 months. We found that Cox-2 and phospho-Akt (pAkt) mice were generated as described previously (16, 18, 19). PCR analysis of tail was used to examine whether endometrial deletion of Pten and/or p53 was efficient. We used cDNA clones for Pten, p53, or both in the mouse endometrium. We have previously described by us (21). In brief, formalin-fixed paraffin-embedded sections (6 μm) were subjected to immunostaining using antibodies to cytokeratin 8 (CK8; Developmental Studies Hybridoma Bank), Pten, pAkt, Cox-2, Ki-67 (Lab Vision Corporation), or α-smooth muscle actin (α-SMA; Abcam). After deparaffinization and hydration, sections were subjected to antigen retrieval by autoclaving in 10 mmol/L sodium citrate solution (pH = 6) for 10 min. A Histostain-Plus kit (Invitrogen) was used to visualize antigens.

### In situ hybridization

cDNA clones for Cox-2 have previously been described (22, 23). cDNA clones for p53 were generated by reverse transcription-PCR (RT-PCR). Sense and antisense 32P-labeled cDNA probes were generated using SP6 or T7 RNA polymerases. Frozen uterus sections were used for in situ hybridization. Uteri from 10-d-old and 3-wk-old mice were placed inside a small groove made on a piece of kidney as a holding cassette because they are extremely tiny, and then snap frozen for cryosectioning. In situ hybridization was performed as previously described (21). Sections hybridized with sense probes did not exhibit any positive signals and served as negative controls.

RT-PCR. RT-PCR was performed as previously described (21). Primers to detect p53 are 5’ ACAGGAACCTGTCCACGGACC 3’ and 5’ GACCCTCGT-CATGTGCTGAC 3’.

### Northern hybridization.

Northern blotting of mRNA was performed as previously described (17). Total RNA (20 μg) was resolved through a 12.5% urea-polyacrylamide gel, transferred onto GeneScreen Plus membranes (PerkinElmer), and UV crosslinked. Antisense oligonucleotide (IDT) was labeled with 32P with a StarFire labeling kit (IDT). Hybridization, hybridization, and washing were performed at 42°C.

### Results

**PR-Cre efficiently deletes endometrial Pten and p53.** Our objective was to study endometrial-specific cancer by conditional deletion of Pten, p53, or both in the mouse endometrium. We therefore crossed Pten (Pten$^{loxP/loxP}$), p53 (p53$^{loxP/loxP}$), or Pten/p53 (Pten$^{loxP/loxP}$/p53$^{loxP/loxP}$) floxed mice with PRcre/+ mice. We have previously used PRcre/+ mice to delete endometrial genes to examine the roles of Hbegf and Bmp2 in pregnancy (20, 24). As shown in Supplementary Fig. S1, endometrial Pten and p53 are deleted by PR-driven Cre activity as confirmed by conventional genotyping.

We next confirmed loss of Pten protein in Ptenpr$^{-/-}$ uterine lysates by Western blotting. As shown in Fig. 1A (top), Pten levels were drastically reduced in Ptenpr$^{-/-}$ uteri from age 3 wk with concomitant increases in Akt phosphorylation (pAkt). This observation of Akt activation with the loss of Pten is consistent with previous findings in other systems (25). We also used immunohistochemistry to monitor cell-specific down-regulation of Pten and up-regulation of Akt activation (Fig. 1A, bottom). Pten levels were efficiently down-regulated in uteri of Ptenpr$^{-/-}$ mice from as early as age 10 days substantiating the Western blot results. Although levels of pAkt were low to undetectable in wild-type uteri with normal levels of Pten, pAkt levels were remarkably up-regulated in Ptenpr$^{-/-}$ uteri in both 10-day-old and 3-week-old mice (Fig. 1A, bottom). Similar analyses were carried out using Ptenpr$^{-/-}$/p53pr$^{-/-}$ uteri. Western blotting and in situ hybridization showed decreased p53 expression in Ptenpr$^{-/-}$/p53pr$^{-/-}$ uteri as expected (Fig. 1B). Loss of both Pten and p53 in these mice was also accompanied by heightened levels of pAkt (Fig. 1B, left). Loss of p53 in p53$^{-/-}$ uteri was confirmed by RT-PCR (Fig. 1C). Collectively, PR-Cre efficiently deletes endometrial Pten and p53.

**Endometrial deletion of Pten induce EMC.** Our next objective was to examine whether endometrial deletion of Pten in mice results in EMC. To address this question, we examined histology of Ptenpr$^{-/-}$ and/or p53$^{-/-}$ uteri. Ptenpr$^{-/-}$ uteri showed endometrial epithelial hyperplasia as early as age 10 days (Fig. 2A). Staining with CK8, an epithelial cell-specific marker, showed luminal and glandular epithelial hyperplasia in Pten-deleted uteri from mice as

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**Materials and Methods**

**Mice.** All mice were housed in the Institutional Animal Care Facility according to NIH and institutional guidelines for laboratory animals. Pten$^{loxP/loxP}$ mice were obtained from Jackson Laboratory, and p53$^{loxP/loxP}$ mice were obtained from the Mouse Models of Human Cancers Consortium (National Cancer Institute). PR-Cre (PRcre; C57BL6/129SV) mice were obtained from John B. Lydon (Baylor College of Medicine). PRcre/+ mice have Cre recombinase introduced into exon 1 of the PR gene (16). Therefore, Cre expression is regulated by the endogenous progestosterone receptor (PR) promoter. PR-Cre heterozygous (PRcre/) mice are phenotypically indistinguishable from wild-type mice (16). Pten$^{loxP/loxP}$ and Pten$^{loxP/loxP}$/p53$^{loxP/loxP}$ mice were generated as described previously (16, 18, 19). PCR analysis of tail genomic DNA determined the genotypes of mutant mice. Standard breeding strategies were used to generate conditional deletion of Pten and/or p53 using transgenic mice (20). Bilateral ovariectomy was performed under appropriate anesthesia. Because the currently used Ptenpr$^{-/-}$/p53pr$^{-/-}$ mouse models are on mixed backgrounds, we consistently used littermate floxed (wild-type) mice in all of our experiments. This ensures that results obtained within each experimental set are meaningful.

**Western blot analysis.** Tissue samples were prepared as previously described (21). After measuring protein concentrations, supernatants mixed with SDS sample buffer were boiled for 5 min. The samples were run on 10% SDS-PAGE gels under reducing conditions and transferred onto nitrocellulose membranes. Membranes were blocked with 10% milk in TBST and probed with antibodies to Pten (Cell Signaling), pAkt (Cell Signaling), p53 (Cell Signaling), Cox-2 (Cayman), or actin (SantaCruz) overnight at 4°C. After washing, blots were incubated in peroxidase-conjugated donkey-anti-goat IgG, donkey-anti-rabbit IgG, or donkey-anti-mouse IgG (Jackson Immuno Research Laboratories, Inc.). For secondary antibody detection of P53, mouse-IgG Trueblot (eBioscience) was used to remove IgG signals. All signals were detected using chemiluminescent reagents (GE Healthcare). Actin served as a loading control.

**Immunohistochemistry.** Immunohistochemistry was performed as previously described by us (21). In brief, formalin-fixed paraffin-embedded sections (6 μm) were subjected to immunostaining using antibodies to cytokeratin 8 (CK8; Developmental Studies Hybridoma Bank), Pten, pAkt, Cox-2, Ki-67 (Lab Vision Corporation), or α-smooth muscle actin (α-SMA; Abcam). After deparaffinization and hydration, sections were subjected to antigen retrieval by autoclaving in 10 mmol/L sodium citrate solution (pH = 6) for 10 min. Histostain-Plus kit (Invitrogen) was used to visualize antigens.

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**Cancer Research 2008; 68: (14). July 15, 2008**

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young as 10 days. Hyperplasia progressed to carcinoma by age 1 month with invasion into the myometrium occurring by 3 months (Fig. 2A). Myometrial invasion was confirmed by α-SMA immunostaining (Supplementary Fig. S2). Detailed characterization of tumor types and grades are shown (Table 1). These results show that conditional deletion of endometrial Pten specifically results in EMC rapidly with 100% penetrance, a much more drastic phenotype than observed in mice heterozygous for Pten deletion.

**Figure 1.** PR-Cre efficiently deletes endometrial Pten and p53. A, Western blot analysis of Pten, pAkt, and total Akt in wild-type and Ptenpr$^{−/−}$ uteri (top). Immunohistochemistry of Pten and pAkt in 10-d-old (10 d) and 3-wk-old (3 wk) Ptenpr$^{−/−}$ and wild-type uteri (bottom). Bar, 200 μm. le, luminal epithelium; ge, glandular epithelium; s, stroma; myo, myometrium. B, Western blot analysis of p53, Pten, pAkt, and total Akt in wild-type and Ptenpr$^{−/−}$/p53$^{−/−}$ uteri (left). Actin serves as a loading control. In situ hybridization of p53 in 3-wk-old wild-type and Ptenpr$^{−/−}$/p53$^{−/−}$ uteri (right). Because of extremely tiny sizes of uteri, all wild-type and Ptenpr$^{−/−}$ uteri from 10-d-old and 3-wk-old mice were placed into small grooves made in kidney slices to serve as cassettes for making frozen sections. Bar, 400 μm. Kid, kidney. C, RT-PCR of p53 in wild-type and p53pr$^{−/−}$ uteri. β-Actin is a housekeeping gene.
We next examined the effects of combined deletion of p53 and \( \text{Pten} \). Histologic analyses of \( \text{Pten}^{\text{loxP/loxP}}/\text{Pten}^{\text{loxP/loxP}}/\text{PRcre/+} \) (\( \text{Pten}^{\text{pr/C0/C0}}/\text{Pten}^{\text{pr/C0/C0}} \)) uteri after staining with H&E showed that \( \text{Pten}^{\text{pr/C0/C0}/\text{Pten}^{\text{pr/C0/C0}}} \) uteri were enlarged compared with those of \( \text{Pten}^{\text{pr/C0/C0}} \), with luminal and glandular hyperplasia (Fig. 2B). Lesions were observed as early as age 10 days similar to the time frame noted in \( \text{Pten}^{\text{pr/C0/C0}} \) uteri (Fig. 2B). Furthermore, these lesions progressed to \textit{in situ} carcinoma by age 3 weeks (Table 1). Uteri from wild-type mice did not exhibit any pathology. We next examined \( \text{p53}^{\text{pr/C0/C0}} \) uteri. Although loss of endometrial p53 expression was seen in mice as young as age 3 weeks (Fig. 1C), endometrial morphology and histology seemed normal through age 5 months (Supplementary Fig. S3; Supplementary Table S1).

Endometrial deletion of both \textit{Pten} and \textit{p53} advances mortality. In human, loss of \textit{Pten} and \textit{p53} increases severity of \textit{EMC} development when compared with those with only \textit{Pten} mutation (1, 2). However, we observed similar histology between \( \text{Pten}^{\text{pr/C0/C0}} \) and \( \text{Pten}^{\text{pr/C0/C0}/\text{p53}^{\text{pr/C0/C0}}} \) uteri during EMC initiation. A close monitoring of conditionally deleted mice for sickness during the tenure of these experiments revealed that loss of both \textit{Pten} and \textit{p53} affects their survival as early as age 2 months, whereas loss of \textit{Pten} alone does not affect longevity until around 5 months, with deletion of \textit{p53} alone affecting viability even later (Fig. 2C). H&E staining of uterine sections from \( \text{Pten}^{\text{pr/C0/C0}/\text{p53}^{\text{pr/C0/C0}}} \) uteri indicate that the cause of early death in these mice is due to excess uterine bleeding due to invasion of uterine blood vessels by tumor cells (Supplementary Fig. S4). At sacrifice, extensive blood clots on the surface of the entire uterus were visible in these mice.

Endometrial deletion of \textit{Pten} or of both \textit{Pten} and \textit{p53} induces epithelial Cox-2 expression and proliferation. Cox-2 is a downstream target of \textit{pAkt} signaling and associated with development of many types of cancers (14, 26). Thus, we examined Cox-2 expression in \( \text{Pten}^{\text{pr/C0/C0}} \) uteri. As shown in Fig. 3A, levels of Cox-2 protein increased in \( \text{Pten}^{\text{pr/C0/C0}} \) uteri compared with wild-type uteri from age 3 weeks. Interestingly, uterine levels of Cox-1 were very low to undetectable at these time points irrespective of genotype (Fig. 3A). Levels of Cox-2 transcripts as determined by RT-PCR correlated well with Cox-2 protein levels (Fig. 3B). We also used \textit{in situ} hybridization (Fig. 3C) and immunohistochemistry.
Deletion of Pten and p53 and Endometrial Cancer

We observed increased Cox-2 mRNA and Cox-2 protein levels primarily in endometrial epithelia of Pten<sup>pr</sup> or Pten<sup>pr</sup> mice. As expected, Cox-2 expression was low to undetectable in wild-type uteri. This observation is similar to higher Cox-2 expression that is observed in human type I EMC (12, 13).

Heightened levels of Cox-2 protein and mRNA were also observed in Pten<sup>pr</sup>/p53<sup>pr</sup> uteri (Fig. 4A–C and D, top). In contrast, levels of Cox-2 transcripts remained very low and unaltered in endometria deleted with p53 alone (Supplementary Fig. S5). Because Cox-2 is known to stimulate cell proliferation in other cancers, we performed Ki67 immunostaining in uterine sections of wild-type, Pten<sup>pr</sup> or Pten<sup>pr</sup>/p53<sup>pr</sup> mice at age 3 weeks. We observed increased Ki67-positive cells primarily in the epithelia of both Pten<sup>pr</sup> and Pten<sup>pr</sup>/p53<sup>pr</sup> uteri compared with wild-type mice (Fig. 4D, bottom). Because levels of Cox-2 expression were lower in Pten<sup>pr</sup>/p53<sup>pr</sup> uteri of 2-month-old mice, we also performed Ki67 immunostaining to determine the proliferation status (Fig. 4D, bottom). We found a correlation between Cox-2 expression and proliferation index. Uteri with low Cox-2 expression at 2 months also had reduced Ki67 staining. This is in contrast with the observed higher Cox-2 expression and Ki67 staining in 3-week-old tumors (Fig. 4D, bottom). It is important to note, however, that immunostaining of Ki67 was noted at the leading edge of tumors in uteri of older mice. This agrees with previous studies showing that the middle of tumors is hypoxic and necrotic (27). These findings in our Pten<sup>pr</sup> and Pten<sup>pr</sup>/p53<sup>pr</sup> mice are exciting and identify these two mouse models as suitable systems for studying human type I EMC.

**Table 1.** EMCs in mice with uterine loss of Pten and/or p53

<table>
<thead>
<tr>
<th>Age (d)</th>
<th>Genotype</th>
<th>No of mice examined</th>
<th>Uterine histology</th>
<th>No of mice with indicated histology (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Pten&lt;sup&gt;+/+&lt;/sup&gt;</td>
<td>6</td>
<td>Normal epithelium (no lesion)</td>
<td>6 (100%)</td>
</tr>
<tr>
<td></td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;</td>
<td>6</td>
<td>Hyperplasia with cytologic atypia</td>
<td>6 (100%)</td>
</tr>
<tr>
<td></td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;/p53&lt;sup&gt;+/+&lt;/sup&gt;</td>
<td>6</td>
<td>Normal epithelium (no lesion)</td>
<td>6 (100%)</td>
</tr>
<tr>
<td></td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;/p53&lt;sup&gt;pr&lt;/sup&gt;</td>
<td>6</td>
<td>Hyperplasia with cytologic atypia</td>
<td>6 (100%)</td>
</tr>
<tr>
<td>21</td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;</td>
<td>8</td>
<td>Normal epithelium (no lesion)</td>
<td>8 (100%)</td>
</tr>
<tr>
<td></td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;/p53&lt;sup&gt;pr&lt;/sup&gt;</td>
<td>8</td>
<td>CAH with acute inflammation</td>
<td>8 (100%)</td>
</tr>
<tr>
<td></td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;/p53&lt;sup&gt;+/+&lt;/sup&gt;</td>
<td>8</td>
<td>Normal epithelium (no lesion)</td>
<td>8 (100%)</td>
</tr>
<tr>
<td></td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;/p53&lt;sup&gt;pr&lt;/sup&gt;</td>
<td>8</td>
<td>CAH with in situ carcinoma, Fallopian tube hyperplasia</td>
<td>8 (100%)</td>
</tr>
<tr>
<td>30</td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;</td>
<td>8</td>
<td>Normal epithelium (no lesion)</td>
<td>8 (100%)</td>
</tr>
<tr>
<td></td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;/p53&lt;sup&gt;pr&lt;/sup&gt;</td>
<td>8</td>
<td>CAH with in situ carcinoma</td>
<td>8 (100%)</td>
</tr>
<tr>
<td></td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;/p53&lt;sup&gt;pr&lt;/sup&gt;</td>
<td>8</td>
<td>Normal epithelium (no lesion)</td>
<td>8 (100%)</td>
</tr>
<tr>
<td></td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;/p53&lt;sup&gt;+/+&lt;/sup&gt;</td>
<td>8</td>
<td>Grade II carcinoma, disease more severe than Pten&lt;sup&gt;pr&lt;/sup&gt; uteri</td>
<td>7 (87.5%)</td>
</tr>
<tr>
<td></td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;/p53&lt;sup&gt;pr&lt;/sup&gt;</td>
<td>8</td>
<td>Cribriform appearance of glands, invasion into myometrium</td>
<td>1 (12.5%)</td>
</tr>
<tr>
<td>60</td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;</td>
<td>8</td>
<td>Normal epithelium (no lesion)</td>
<td>8 (100%)</td>
</tr>
<tr>
<td></td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;/p53&lt;sup&gt;pr&lt;/sup&gt;</td>
<td>7</td>
<td>Carcinoma</td>
<td>4 (50%)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;/p53&lt;sup&gt;pr&lt;/sup&gt;</td>
<td>7</td>
<td>CAH with focal carcinoma</td>
<td>1 (12.5%)</td>
</tr>
<tr>
<td></td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;/p53&lt;sup&gt;pr&lt;/sup&gt;</td>
<td>7</td>
<td>CAH with squamous metaplasia</td>
<td>3 (37.5%)</td>
</tr>
<tr>
<td>90</td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;</td>
<td>9</td>
<td>Normal epithelium (no lesion)</td>
<td>8 (88.9%)</td>
</tr>
<tr>
<td></td>
<td>Pten&lt;sup&gt;pr&lt;/sup&gt;/p53&lt;sup&gt;pr&lt;/sup&gt;</td>
<td>9</td>
<td>Carcinoma</td>
<td>8 (88.9%)&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Abbreviation: CAH, complex atypical hyperplasia.

<sup>a</sup>One mouse showed invasion.

<sup>1</sup>Two mice showed invasion.

<sup>1</sup>One mouse showed extensive carcinoma; one showed well differentiated adenocarcinoma with invasion into the serosa and two showed carcinoma with squamous metaplasia.
miR-101a expression (Fig. 5A). The expression of these miRNAs is also reduced in Ptenpr/C0/C0/p53pr/C0/C0 uteri with elevated Cox-2 expression (Fig. 5B). These data suggest that miR-199a* and miR-101a play roles in regulating Cox-2 expression in EMC.

Discussion

Mutations of tumor suppressor genes are linked to carcinogenesis in various organ systems. Unfortunately, systemic deletion of these genes in mice often results in embryonic lethality. The loxp-Cre system allows for tissue-specific and temporal deletion of tumor suppressor genes (32, 33). The goal of this study was to take advantage of the loxp-Cre system to generate conditional deletion of Pten and/or p53 in the uterus to study the initiation and progression of endometrial carcinoma. Because there is no endometrial-specific promoter identified as of yet, PR-Cre mice are being widely used to delete floxed genes in the uterus (16, 20, 24). It is to be noted, however, that PR is also expressed in tissues such as oviduct, ovary, mammary gland, and pituitary. Our current study shows that EMC develops in Ptenpr/C0/C0 or Ptenpr/C0/C0/p53pr/C0/C0 mice within age 3 weeks to 1 month with no evidence of cancers in other tissues, including those that express PR. One reason for development of endometrial-specific cancer could perhaps be attributed to increased sensitivity of the uterus to Pten loss.

Nonetheless, this endometrial-specific phenotype demonstrates the importance of Pten loss in the initiation of EMC. Studies in humans have shown that type I EMC originates mainly from the epithelial components and not the stroma; however PR is expressed in both epithelia and stroma (1). Therefore, whether EMC in Ptenpr/C0/C0 or Ptenpr/C0/C0/p53pr/C0/C0 mice originates from epithelial or stromal components remains to be determined. Because Pten is expressed primarily in endometrial epithelia during early neonatal development, it is speculated that cancer is initiated in this compartment due to the loss of Pten. Definitive answers to the specific roles of epithelial versus stromal Pten in EMC will require epithelial-specific loxp-Cre and stromal-specific loxp-Cre systems for deletion of Pten.

We observed that the combined loss of Pten and p53 resulted in a shorter life span compared with mice with single deletion of either Pten or p53. Previous reports suggested a role for p53 in advanced type I EMC in women (1). Therefore, we speculated that superimposing p53 mutation on Pten deletion would aggravate the disease condition. Our findings of shorter life span of Ptenpr/C0/p53pr/C0/C0 mice supports this hypothesis, with the cause of early death attributed to excessive uterine bleeding due to invasion of uterine blood vessels by invasive tumor cells. As a note, type II EMC, which comprises only 10% to 15% of all EMCs, shows a high frequency of p53 mutations. This is contrary to our observation.
that uterine deletion of p53 does not cause cancer in mice (1). Therefore, understanding the role of p53 mutations in EMC requires further studies.

Our findings of deletion of both p53 and Pten aggravating the mortality rate are consistent with a similar study that used conditional deletion of Pten to induce prostate cancer (32). In this study, the investigators used Ptenlox/lox/probasin-Cre mice and showed that Pten deletion alone did not increase the incidence of mortality, but the combined deletion of both Pten and p53 did. Their explanation for this observation was that deletion of Pten alone resulted in p53 up-regulation, which protected cells from senescence (32). We also observed p53 up-regulation primarily in endometrial epithelia of Ptenpr−/− mice (data not shown), consistent with their explanation. Another possibility is that PR-Cre driven deletion of Pten and p53 results in deleterious effects on immune cells. Studies have shown that T-cell or B-cell–specific deletion of Pten results in T-cell lymphomas or defects in class switch recombination (reviewed in ref. 34). It seems unlikely that local immune complications contribute to the progression of EMC in Ptenpr−/−/P53pr−/− mice because neither estrogen receptor nor

Figure 4. Cox-2 expression and cell proliferation in Ptenpr−/−/P53pr−/− uteri. A, Western blot analysis of Cox-2 and Cox-1 in Ptenpr−/−/P53pr−/− uteri. Actin serves as control. B, RT-PCR of Cox-2 in Ptenpr−/−/P53pr−/− uteri. β-Actin is a housekeeping gene. C, in situ hybridization of Cox-2 in Ptenpr−/−/P53pr−/− and wild-type uteri. Bar, 400 μm. D, immunohistochemistry of Cox-2 in 3-wk-old Ptenpr−/−/P53pr−/− and wild-type mice (top). Immunohistochemistry of Ki67 in 3-wk-old and 2-mo-old Ptenpr−/− and Ptenpr−/−/P53pr−/− and wild-type uteri (bottom). Arrowheads, leading edge. Bar, 200 μm. le, luminal epithelium; ge, glandular epithelium; s, stroma; myo, myometrium; Kid, kidney; T, tumor.
Figure 5. Levels of mir-199a* and mir-101a expression are reduced in uteri with EMC. Northern blot analysis of (A) Pten+/− (WT) versus Pten−/− (KO) uteri and (B) Pten+/−/p53+/− (WT) versus Pten−/−/p53−/− (KO) uteri. Stained gels served as loading controls.

PR is expressed in uterine lymphocytes, macrophages, or natural killer cells (35, 36).

Because EMC is also known to be influenced by hormonal components (1), we ovariectomized Pten−/−/p53+/− mice age 3 weeks to evaluate the contribution of ovarian steroid hormones. We found that ovariectomizing these mice did not minimize tumor development when examined at 2 months (Supplementary Fig. S6), suggesting limited contribution of ovarian steroid hormones to EMC progression induced by Pten and p53 mutations.

Cox-2 is thought to play an important role in carcinogenesis and is overexpressed in a number of solid tumors, including colorectal, breast and lung cancers (10). Treatments with nonsteroidal anti-inflammatory drugs (NSAIDs) that inhibit Cox activity have been shown to be effective in the chemoprevention of many types of solid tumors. In fact, even their daily consumption reduces the risk of certain cancers (37–40). Our study showed elevated Cox-2 expression at the early stages of hyperplasia and carcinoma in both Pten−/− and Ptenpr−/−/p53pr−/− mice suggests that NSAIDs could be considered potential treatment options for type I EMC patients at early stages. Unfortunately, recent clinical studies show that prolonged use of highly selective Cox-2 inhibitors, such as Vioxx, leads to increased myocardial infarctions and stroke. However, NSAIDs such as aspirin or naproxen show lesser side effects and are still being widely used to combat inflammatory diseases and to reduce the risk of developing cancers.

Although Cox-2 expression was elevated in the early stages of hyperplasia and carcinoma, we were initially surprised to observe its gradual disappearance with cancer progression. However, it has been shown that Cox-2 is often associated with early stages of cancer in both liver and uterine cancers, and then is down-regulated with tumor advancement (41, 42). In uterine cancers, levels of Cox-2 correlate with vascular endothelial growth factor expression, implicating their roles in angiogenesis at early stages (42). These studies suggest the potential for NSAIDs treatment to prevent recurrence of EMCs.

Our observations of increased levels of pAkt and Cox-2 at early stages of EMC suggest that the Pten-Akt-Cox-2 signaling axis is important for the initiation of tumor growth. The accelerated growth perhaps occurs due to increased cell proliferation that is evident from Ki67 staining even at age three weeks. Our results showing decreased expression of mir-199a* and mir-101a with enhanced Cox-2 levels in Pten−/− and Ptenpr−/−/p53pr−/− uteri also suggests their close relationship with Cox-2 status in the uterus as we have previously shown (17). However, it is not known whether Pten directly regulates the expression of these miRNAs or their down-regulation is a consequence of the development of EMC with enhanced Cox-2 expression. Nonetheless, these miRNAs are potential targets for anticancer therapy because of their role in down-regulating Cox-2 levels.

In conclusion, the present study presents mouse models that rapidly and unfailingly produce EMC, many characteristics of which mimic human EMC. These models will help delineate other downstream signaling pathways critical to the initiation and progression of human EMC.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Acknowledgments

Received 4/7/2008; revised 5/13/2008; accepted 5/15/2008.

Grant support: United States Public Health Service Grants, P01-CA-77389 (R.N. DuBois); VICC-Meharry U54CA91405-06 and HD12304 (S.K. Dey) and U01 CA105352-01 (F. DeMayo); Vanderbilt-Ingram Cancer Center Support Grant P30CA68485 and Gynecologic Cancer Foundation Awards/Ann Schreiber Ovarian Cancer Research Grant (T. Daikoku); a Research Fellowship from the Japan Society for the Promotion of Science for Young Scientists (Y. Hirota), and the National Institute of Child Health and Human Resources Training Grant 2T1HD877043 (S. Trangan). The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked advertisement in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

We thank Dr. Satoshi Umezawa (Musashino Red Cross Hospital, Tokyo, Japan) for his scientific advice.

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Cancer Res 2008; 68: (14). July 15, 2008 5626 www.aacrjournals.org

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Takiko Daikoku, Yasushi Hirota, Susanne Tranguch, et al.


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