Critical Tumor Suppressor Function Mediated by Epithelial Mig-6 in Endometrial Cancer

Tae Hoon Kim1, Dong-Kee Lee2, Sung-Nam Cho2, Grant D. Orvis3, Richard R. Behringer3, John P. Lydon2, Bon Jeong Ku4, Adrienne S. McCampbell4, Russell R. Broaddus4, and Jae-Wook Jeong1,6

Introduction

Endometrial cancer is preceded by endometrial hyperplasia, unopposed estrogen exposure, and genetic alterations, but the precise causes of endometrial cancer remain uncertain. Mig-6, mainly known as a negative regulator of the EGF receptor, is an important mediator of progesterone signaling in the uterus, where it mediates tumor suppression by modulating endometrial stromal–epithelial communications. In this study, we investigated the function of Mig-6 in the uterine epithelium using a tissue-specific gene knockout strategy, in which floxed Mig-6 (Mig-6fl/fl) mice were crossed to Wnt7a-Cre mice (Wnt7afl/fl-Mig-6fl/fl). Wnt7afl/fl-Mig-6fl/fl mice developed endometrial hyperplasia and estrogen-dependent endometrial cancer, exhibiting increased proliferation in epithelial cells as well as apoptosis in subepithelial stromal cells. We documented increased expression of NOTCH1 and BIRC3 in epithelial cells of Wnt7afl/fl-Mig-6fl/fl mice and decreased expression of the progesterone receptor (PR) in stromal cells. Progesterone therapy controls endometrial growth and prevents endometrial cancer, but the effectiveness of progesterone as a treatment for women with endometrial cancer is less clear. We noted that the hyperplasic phenotype of Wnt7afl/fl-Mig-6fl/fl mice was prevented by progesterone treatment, whereas this treatment had no effect in PRfl/fl-Mig-6fl/fl mice where Mig-6 was deleted in both the epithelial and stromal compartments of the uterus. In contrast, activation of progesterone signaling in the stroma regulated proliferation and apoptosis in the epithelium via suppression of ERα signaling. In summary, our results establish that epithelial Mig-6 functions as a critical tumor suppressor that mediates the ability of progesterone to prevent the development of endometrial cancer. Cancer Res; 73(16); 1–10. ©2013 AACR.

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Introduction

Endometrial carcinoma, commonly referred to as uterine cancer, is the most common malignancy of the female genital tract. In the United States, approximately 49,560 cases are diagnosed and approximately 8,190 women die from the disease each year (1). The most common type of endometrial carcinoma, approximately 85% of cases, is endometrioid carcinoma (2). Endometrial hyperplasia, which is a proliferative process in the epithelium, is associated with endometrioid carcinoma. This process is commonly associated with unopposed estrogen stimulation (3).

The ability of ovarian steroids to regulate uterine cell proliferation depends upon the ability of hormonal stimulation to regulate growth factor communication networks between the uterine stroma and epithelium. E2 stimulates proliferation of uterine epithelial cells while P4 is inhibitory to estrogen-mediated proliferation of the epithelium. P4 achieves this inhibition of proliferation by coordinating stromal–epithelial crosstalk (4–6). Elucidating the molecular mechanisms by which the steroid hormones control uterine physiology is paramount to understanding female infertility and tumorigenesis of endometrial cancer.

Progesterin therapy has been used in the conservative endocrine treatment of endometrial complex atypical hyperplasia—the direct precursor lesion to endometrial cancer in women in order to preserve their fertility—as well as in palliative treatment to advanced-stage patients who are poor surgical candidates (7–9). Expression of PR has been positively correlated with good prognosis and response to progesterin treatment (10). However, more than 30% of patients do not respond to progesterin due to de novo or acquired progesterin resistance (8, 11–14). The mechanism of progesterin resistance is still unknown.

Mitogen inducible gene 6, Mig-6 (Errfl1, RALT, or gene 33), is an immediate early-response gene that can be induced by various mitogens and commonly occurring chronic stress

Molecular and Cellular Pathobiology

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Mitogen inducible gene 6, Mig-6 (Errfl1, RALT, or gene 33), is an immediate early-response gene that can be induced by various mitogens and commonly occurring chronic stress

Authors’ Affiliations: 1Department of Obstetrics, Gynecology & Reproductive Biology, Michigan State University College of Human Medicine, Grand Rapids, Michigan; 2Department of Molecular and Cellular Biology, Baylor College of Medicine; Departments of 3Genetics and 4Pathology, University of Texas M.D. Anderson Cancer Center, Houston, Texas; 5Department of Internal Medicine, Chungnam National University School of Medicine, Daejeon, South Korea; and 6WCU Biomodulation Program, Seoul National University, Seoul, Republic of Korea

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

Corresponding Author: Jae-Wook Jeong, Department of Obstetrics, Gynecology & Reproductive Biology, Michigan State University College of Human Medicine, 333 Bostwick Avenue NE, Suite 4024, Grand Rapids, MI 49503. Phone: 616-234-0987; Fax: 616-234-0990; E-mail: jaewook.jeong@hc.msu.edu

doi: 10.1158/0008-5472.CAN-13-0241
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stimuli. It contains a CRIB domain, a src homology 3 (SH3) binding domain, a 14-3-3 binding domain, and an EGF receptor-binding domain as an adaptor protein, but no domain with enzymatic activity (15). Ablation of Mig-6 in mice has led to the development of animals with epithelial hyperplasia, adenoma, and adenocarcinomas in organs such as the uterus, lung, gallbladder, and bile duct (16–18). We identified Mig-6 as a target of progesterone receptor (PR) action using a genomewide gene expression profiling (19, 20), and showed that targeted ablation of Mig-6 gene in the mouse uterus led to the development of endometrial hyperplasia and estrogen-induced endometrial carcinoma (18, 20). Using this mouse model, we further showed that Mig-6 suppresses estrogen signaling in the presence of progesterone and that Mig-6 regulates PTEN–phosphoinositide 3-kinase (PI3K)–AKT signaling (21). In searching for relevance of the findings from the animal study to human endometrial cancer, we found a significantly lower MIG-6 expression in human endometrioid carcinoma cells compared with normal uterine cells, suggesting a similar Mig-6-regulated system present in the human uterus (20). Tumor suppressor function of Mig-6 coordinates endometrial stromal–epithelial communication. The expression of Mig-6 in these cellular compartments is under tight temporal and endocrine control. However, the function of Mig-6 in endometrial cancer has remained elusive.

In this study, we used endometrial epithelial–cell-specific Mig-6 knockout (Wnt7a−/−Mig-6−/−) mice to assess the role of epithelial Mig-6 in steroid hormone responsiveness and tumorigenesis (18, 22). We observed that Wnt7a−/−Mig-6−/− mice display normal P4 attenuation of E2-mediated uterine hyperplasia. However, Wnt7a−/−Mig-6−/− mice develop endometrial hyperplasia as well as estrogen-induced endometrial cancer. The development of endometrial hyperplasia in Wnt7a−/−Mig-6−/− mice is prevented by P4 treatment. These data suggest that P4-induced stromal Mig-6 prevents hyperplasia seen in Wnt7a−/−Mig-6−/− mice by regulating estrogen signaling.

Materials and Methods

Animals and tissue collection

Mice were cared for and used in the designated animal care facility according to the Michigan State University institutional guidelines. All animal procedures were approved by the Institutional Animal Care and Use Committee of Michigan State University. We generated uterine epithelial–specific Mig-6 knockout mice using the Wnt7a-cre mouse model (23, 24). Control mice and Wnt7a−/−Mig-6−/− mice were ovariectomized at 6 weeks of age. Two weeks later, ovariectomized control and Wnt7a−/−Mig-6−/− mice were injected with one of the following: vehicle (sesame oil), P4 (1 mg/mouse), E2 (0.1 μg/mouse), and P4 plus E2. Five mice from each group were injected with one of these treatments every 24 hours and uteri were collected at 72 hours. For the determination of the development of endometrial hyperplasia and estrogen/progesterone effects, either vehicle (beeswax), E2 (20 μg/pellet), or P4 (40 mg/pellet) pellets were placed subcutaneously into ovariectomized control and Wnt7a−/−Mig-6−/− mice for every 1 month and aged for 3 months before euthanization. Uterine tissues were flash-frozen at the time of dissection and stored at −80 °C for RNA isolation or fixed with 4% (vol/vol) paraformaldehyde for histologic analysis.

Quantitative real-time PCR

RNA was extracted from the uterine tissues using the RNeasy total RNA isolation kit (Qiagen). Expression levels of mRNA transcripts for Mig-6, estrogen receptor α (ERα) target genes (Mac-1, Cicaa, Ltf, Birc1a, and Birc1b), PR target genes (Mig-6, Fst, and Il13ra2), and 18S RNA (for normalization) were measured by quantitative real-time PCR (qRT-PCR) analysis using the Applied Biosystems StepOnePlus qRT-PCR systems according to the manufacturer’s instructions (PE Applied Biosystems). Prevalidated TaqMan probes and primers were purchased from Applied Biosystems. cDNA was produced from 1 μg of total RNA using random hexamers and MMLV Reverse Transcriptase (Invitrogen Corp.). RT-PCR was carried out using RT-PCR Universal Master Mix reagent (Applied Biosystems) according to the manufacturer’s instructions. All RT-PCR was done by using five independent RNA sets. The relative expression of each transcript was normalized to 18S RNA using ABI rRNA control reagents. Statistical analyses were conducted using Student t test and one-way ANOVA. Differences between multiple groups were determined by Tukey post hoc multiple comparisons test. Statistical analyses were conducted using the Instat package from GraphPad.

Immunohistochemistry

Uterine sections from paraffin-embedded tissue were cut at 5 μm and mounted on silane-coated slides, deparaffinized, and rehydrated in a graded alcohol series. Sections were rehydrated in a graded alcohol series. Sections were preincubated with 10% normal goat serum in PBS at 4°C overnight. The cut uteri were placed into 1% trypsin/HBSS solution for 1.5 hours. The cut uteri were placed into Hanks balanced salt solution minus Mg2+-free and Ca2+-free, and cut into 1-mm segments. The cut uteri were placed into 1% trypsin/HBSS solution for 1.5 hours at room temperature and then washed with cold HBSS. The uteri were placed into 20% FBS/HBSS solution for 5 minutes, and washed with cold HBSS. The uteri were then incubated with DNase I solution for 1 minute to breakdown DNA. The uterine luminal epithelium was gently removed from the uterine stroma under a dissecting microscope.
Results

Generation of epithelial Mig-6 ablation in the murine uterus

Previously, we generated conditional ablation of Mig-6 in all compartments of the uterus (PR<sup>cre</sup>/<sup>−</sup>Mig-6<sup>−/−</sup>), which leads to the development of endometrial hyperplasia and estrogen-induced endometrial cancer (18, 20). Mig-6 is a critical mediator of stromal–epithelial communication in steroid hormone regulation and tumor suppressor function. In order to investigate the role of epithelial Mig-6 in the uterus, we bred Mig-6<sup>−/−</sup> mice to Wnt7a-Cre mice (22–24). Ablation of epithelial Mig-6 in Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice was confirmed by qRT-PCR and immunohistochemical analysis. After isolating epithelium from control (PR<sup>cre/+</sup> and Mig-6<sup>−/−</sup>) mice and Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice, Mig-6 mRNA expression was detected in control epithelium, whereas it was not detected in Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> epithelium (Fig. 1A). In control mice, Mig-6 was expressed in the luminal epithelium, glandular epithelium, and stroma. However, Mig-6 was only detected in stroma but not the epithelial cells of Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice (Fig. 1B). These results suggested that we successfully generated epithelial Mig-6 ablation in the uterus of mice.

Steroid hormone regulation and tumor suppressor function of epithelial Mig-6

We showed that PR<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice result in the inability of P<sub>1</sub> to inhibit E<sub>2</sub>-induced uterine weight gain and expression of E<sub>2</sub>-responsive target genes (20). To examine the effect of ovarian steroid hormone regulation on epithelial Mig-6 expression, ovariectomized control and Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice were injected daily with either vehicle (sesame oil), P<sub>4</sub>, E<sub>2</sub>, and E<sub>2</sub> + P<sub>4</sub> for 3 days (n = 5 per genotype per treatment). Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice displayed a normal P<sub>4</sub> attenuation of E<sub>2</sub>-mediated uterine hypertrophy (Supplementary Fig. S1). These results suggest that stromal Mig-6 has an important role in acute steroid hormone responsiveness.

PR<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice developed endometrial hyperplasia and cancer in a hormone-dependent manner (20). We examined the development of endometrial hyperplasia and steroid hormone-dependent endometrial cancer in the Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice. To investigate the impact of epithelial Mig-6 ablation on endometrial hyperplasia development, control and Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice were sacrificed at 5 months of age. Uterine weight as well as gross and histologic morphology were examined (n = 5 per genotype). Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice showed an increased gross morphology when compared with control mice (Fig. 1C). Uterine weight was significantly increased in Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice when compared with control mice (Fig. 1D). Histologic analysis revealed that Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice developed endometrial hyperplasia (Fig. 1E). In addition, Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice developed estrogen-dependent endometrial cancer (Supplementary Fig. S2). To address whether endometrial hyperplasia in Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice is caused by an alteration in endometrial epithelial cell proliferation, we conducted immunohistochemical analysis for phosphohistone H3, a mitotic marker, in endometrium from mice at 3 and 5 months of age. The levels of phosphohistone H3 were significantly increased in epithelial cells of Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice

Figure 1. Generation of epithelial Mig-6 ablation in the murine uterus and the development of endometrial hyperplasia. A, quantitative RT-PCR analysis of Mig-6 transcripts levels in whole uteri and isolated epithelium from control mice and Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice. The results represent the mean ± SE of five independent RNA sets. Mig-6 transcripts are significantly reduced in the epithelium of Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice compared with controls; ***, P < 0.001. B, immunohistochemical analysis of Mig-6 in control mice (a) and Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice (b). Arrowheads indicate luminal and glandular epithelium. C, gross morphology of control mice (a) and Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice (b) at 5 months of age. D, Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice show an increase in uterine weight compared with control mice at 5 months of age. E, hematoxylin and eosin staining of control mice (a) and Wnt7a<sup>cre/+</sup>-Mig-6<sup>−/−</sup> mice (b) at 5 months of age. The results represent the mean ± SE (n = 5 per genotype). *, P < 0.05.
compared with controls at both 3 and 5 months of age (Fig. 2A and B). However, proliferation in stromal cells of Wnt7aRex−/−Mig−/− mice was not changed. Notch pathway activation leads to increased proliferation and tumor progression in endometrial cancers (25). Because ablation of Notch1 in PR-positive cells showed decreased cellular proliferation (26), we examined NOTCH1 expression in highly proliferative epithelial cells of Wnt7aRex−/−Mig−/− mice. Wnt7aRex−/−Mig−/− uteri showed a robust expression of NOTCH1 in the luminal and glandular epithelium, while the Mig−/− mice display NOTCH1 expression only in the stroma (Fig. 2C).

The number of cleaved caspase–3-positive cells was significantly increased in epithelial cells of Wnt7aRex−/−Mig−/− mice compared with controls. Interestingly, apoptosis in subepithelial stromal cells of Wnt7aRex−/−Mig−/− mice was significantly increased compared with control mice at 3 and 5 months of age (Fig. 2D and 2E). BIRC3 contributes to the survival of endometrial cancer cells against apoptosis mediated by inhibition of AKT (27). Therefore, it was determined whether Wnt7aRex−/−Mig−/− mice altered regulation of BIRC3 during endometrial hyperplasia development. The expression of BIRC3 was increased in the luminal and glandular epithelium of Wnt7aRex−/−Mig−/− mice compared with Mig−/− mice, whereas it was not observed in the subepithelial stromal cells of Wnt7aRex−/−Mig−/− mice (Fig. 2F).

Expression of PR has been reported as a prognostic factor for endometrial carcinoma (28–30). We evaluated the expression of PR by immunohistochemistry in mice at 3 and 5 months of age. Immunostaining of PR showed a significant decrease of stromal PR expression in the endometrium of Wnt7aRex−/−Mig−/− mice when compared with control mice at 5 months of age (Fig. 3A and B). These results indicate that Wnt7aRex−/−Mig−/− mice exhibited development and progression of endometrial cancer as observed in humans. Activation of STAT3 interacts with PR.
Immunostaining of cleaved caspase 3 showed that apoptosis was significantly increased in the endometrial epithelium of Wnt7acre/+Mig-6f/f mice compared with PRcre/+Mig-6f/f mice (Fig. 4B and D). In addition, apoptosis of stromal cells was not observed in Wnt7acre/+Mig-6f/f mice after P4 treatment. These results suggest that activation of P4 signaling including Mig-6 in stroma induces epithelial cell apoptosis.

To determine whether the suppression of the hyperplastic phenotype observed was due to altered ovarian steroid hormone signaling, we examined the expression of ERα and PR using immunohistochemistry. The expression of ERα was significantly decreased in the endometrium of Wnt7acre/+Mig-6f/f mice as compared with control and PRcre/+Mig-6f/f mice after P4 treatment (Fig. 5A). Transcript levels of the ERα target genes, Mac-1, Clec3a, and Ltf, were also significantly decreased in the Wnt7acre/+Mig-6f/f mice as compared with the PRcre/+Mig-6f/f mice after P4 treatment (Fig. 5B). It is known that E2 can tip this balance toward cell survival in uterine epithelial cells by inducing the expression of baculoviral inhibitors of apoptosis repeat-containing 1 (Birc1), a family of antiapoptotic proteins (32). To determine if P4 treatment suppresses uterine epithelial apoptosis by suppressing Birc1 expression, the expression of Birc1a and Birc1b was determined in control, PRcre/+Mig-6f/f, and Wnt7acre/+Mig-6f/f mice treated with P4 for 3 months by real-time RT-PCR. Interestingly, the expression of Birc1a and Birc1b was significantly decreased in the Wnt7acre/+Mig-6f/f mice as compared with the PRcre/+Mig-6f/f mice after P4 treatment (Fig. 5B). These results suggest that P4 treatment induces uterine epithelial apoptosis via downregulation of Birc1 expression.

The expression of PR was not significantly different between control and Wnt7acre/+Mig-6f/f mice after P4 treatment. However, transcript levels of the PR target genes Mig-6, Fst, and Il13ra2 were increased in the Wnt7acre/+Mig-6f/f mice as compared with the PRcre/+Mig-6f/f after P4 treatment (Supplementary Fig. S3). Interestingly, the levels of BIRC3 and NOTCH1...
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f) P4 treatment. B, immunostaining for phosphohistone H3 (a, b, and c) Wnt7acre

and cleaved caspase-3 (d, e, and f) in the uteri of control mice (a and d),

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were decreased in endometrial epithelium of Wnt7a<sup>cre<sup>+</sup></sup>-Mig-6<sup>fl/fl</sup> mice compared with PR<sup>cre/+</sup>-Mig-6<sup>fl/fl</sup> mice after P<sub>4</sub> treatment (Fig. 6). Therefore, BIRC3 and NOTCH1 may play an important role in the development of hyperplasia in Wnt7a<sup>cre<sup>+</sup></sup>-Mig-6<sup>fl/fl</sup> mice. These results suggest that activated stromal P<sub>4</sub> signaling including Mig-6 prevents the development of endometrial epithelial hyperplasia seen in the Wnt7a<sup>cre<sup>+</sup></sup>-Mig-6<sup>fl/fl</sup> mice by regulating estrogen signaling.

Discussion

P<sub>4</sub> and E<sub>2</sub>, acting through their cognate nuclear receptors, play critical roles in uterine functions associated with the establishment and maintenance of pregnancy (33, 34). E<sub>2</sub> is required for proliferation and differentiation of the uterine epithelium whereas the coordinated action of E<sub>2</sub> and P<sub>4</sub> promotes stromal cell differentiation (35). Elucidating P<sub>4</sub>-regulated pathways in the uterus is thus critical for understanding the impairments that underlie disruption of steroid hormone control of uterine cell proliferation and differentiation. The progesterone-induced gene Mig-6 suppresses E<sub>2</sub> signaling as a tumor suppressor by regulating proliferation and apoptosis in endometrial cancer (20, 21). The expression of Mig-6 in these cellular compartments is under tight temporal and endocrine control (15). However, the in vivo role of Mig-6 in uterine epithelium has remained elusive.

To understand the role of epithelial Mig-6 in the uterus, we generated ablation of uterine epithelial Mig-6 using Wnt7aCre mice (Fig. 1). Ablation of epithelial Mig-6 in the murine uterus did not show any alterations in ovarian morphology, ovulation, or fertilization. In addition, there were normal levels of P<sub>4</sub> and E<sub>2</sub> in the serum of Wnt7a<sup>cre<sup>+</sup></sup>-Mig-6<sup>fl/fl</sup> mice (data not shown). One of the endocrine risk factors for developing endometrial cancer and endometriosis is exposure to E<sub>2</sub>; conversely, a lower incidence of these diseases in women is associated with decreased endogenous E<sub>2</sub> production (36). Although Wnt7a<sup>cre<sup>+</sup></sup>-Mig-6<sup>fl/fl</sup> mice have normal acute steroid hormone responsiveness (Supplementary Fig. S1), Wnt7a<sup>cre<sup>+</sup></sup>-Mig-6<sup>fl/fl</sup> mice developed endometrial hyperplasia (Fig. 1). Endometrial hyperplasia is defined as an increased proliferation of the endometrial glands relative to the stroma, resulting in an increased gland-to-stroma ratio when compared with normal proliferative endometrium (37). Endometrial hyperplasia deserves special attention because of its relationship with endometrial carcinoma. Clinicopathologic and epidemiologic studies have supported the malignant potential of endometrial hyperplasia and the concept of a continuum of proliferative glandular lesions culminating, in some cases, in carcinoma. However, details of molecular signaling during development of endometrial hyperplasia have remained elusive. Our mouse models are invaluable for further study of endometrial tumorigenesis.

Proliferation in epithelial cells and apoptosis in subepithelial stromal cells were significantly increased in Wnt7a<sup>cre<sup>+</sup></sup>-Mig-6<sup>fl/fl</sup> mice compared with control mice in epithelial cells at 5 months of age (Fig. 2). These results indicate that these increases lead to the development of endometrial hyperplasia. Notch signaling plays an important role in the regulation of cellular proliferation, differentiation, and apoptosis (38). Deregulation of Notch signaling was found in a variety of cancers (38). Moreover, Notch signaling is prominently regulated by estrogen (39, 40). Here, it is shown that epithelial Mig-6 inhibits epithelial proliferation through its regulation of NOTCH1 protein (Fig. 2C). The inhibitor of apoptosis proteins (IAP) are negative key regulators of apoptosis (41). Alterations in IAPs are found in many types of human cancer and are connected with chemoresistance, disease progression, and poor prognosis (42, 43). IAPs have important roles in suppression of estrogen-mediated apoptosis in the uterine epithelium (32). Because the cellular inhibitor of apoptosis genes including Birc1 and Birc3 can tip toward cell survival in uterine epithelial cells (27, 32). The expression of Birc1 and Birc3 was significantly increased in Wnt7a<sup>cre<sup>+</sup></sup>-Mig-6<sup>fl/fl</sup> mice (Figs. 2 and 5). These
results suggest that an increase of epithelial proliferation in Wnt7a<sup>cre/+</sup>Mig-6<sup>-/-</sup> mice leads to the development of endometrial hyperplasia through BIRC3 and NOTCH1. The mechanism by which this is achieved is suggested to be through the EGFR–ERK and PI3K–AKT signaling pathways (27). Therefore, future studies are needed to determine whether it is through these pathways or others that epithelial Mig-6 regulates proliferation and apoptosis.

As P<sub>4</sub> attenuates E<sub>2</sub> regulation of proliferation and gene expression by regulating the expression of a yet-to-be-identified paracrine signal from the stromal to the epithelial cells, the regulation of the expression of PR in the endometrial stromal cells by epithelial Mig-6 is critical for the ability of P<sub>4</sub> to attenuate the E<sub>2</sub>-regulated proliferation, apoptosis and expression of ERα target genes. Wnt7a<sup>cre/+</sup>Mig-6<sup>-/-</sup> mice exhibited reduced PR expression in stromal cells (Fig. 3), as observed in human endometrial cancer (30, 44). It has been reported that PR is essential for uterine biology as a key regulator of uterine epithelial–stromal crosstalk (45, 46). P<sub>4</sub> was unable to stimulate the expression of its epithelial target genes and inhibit neonatal endometrial glandular development in conditional ablation of epithelial PR in the uterus of Wnt7a<sup>cre/+</sup>PR<sup>−/−</sup> mice (24). PR directly interacts with STAT3 through protein–protein interactions (31, 47). STAT3 signaling pathways are initiated by cytokines and growth factors. The expression of stromal PR was decreased during decidualization and the preimplantation period in PR<sup>−/−</sup>Stat3<sup>−/−</sup> mice, and PR target genes were significantly downregulated after progesterone induction (31). The expression of PR and STAT3 was decreased during the development of endometrial hyperplasia in the stroma of Wnt7a<sup>cre/+</sup>Mig-6<sup>-/-</sup> mice (Fig. 3). There are differential roles in uterine stromal and epithelial compartments, and stromal–epithelial communication is critical in pregnancy, steroid hormone regulation, and in tumor suppressor function. Therefore, these results suggest that dysregulation of STAT3 and PR crosstalk is important for endometrial hyperplasia development.

In contrast, a negative risk factor for these endometrial diseases is exposure to P<sub>4</sub> (48). It is well known that endometrial cancer is an estrogen-dependent disease and...
progesterin therapy has been used successfully to slow the growth of endometrial tumors in women who are poor surgical candidates as well as to reverse endometrial complex atypical hyperplasia in women who wish to retain their fertility (5–8). The mechanism by which progesterins slow the growth of endometrial cancer cell is due to their inhibitory effects on E2 action (49). After P4 treatment, Wnt7acre−/− mice did not develop endometrial hyperplastic lesions (Fig. 4). Proliferation in epithelial cells is significantly decreased in Wnt7acre−/− mice compared with P4+/+ mice after P4 treatment. It is known that baculoviral inhibitors of apoptosis repeat-containing 1 (Birc1), a family of antiapoptotic proteins as functional targets of estrogen through its receptor, can suppress uterine epithelial cells (32). To determine if stromal Mig-6 activated by P4 promotes uterine epithelial apoptosis by suppressing Birc1 expression, we determined transcription levels of Birc1a and Birc1b in mice compared with Mig-6−/− mice after P4 treatment (Fig. 5). Levels of ERα protein and ERα target genes (Muc-1, Cleca3, and Ltf) were decreased in Wnt7acre−/− Mig-6−/− mice compared with P4+/+ mice after P4 treatment (Fig. 5). The PR protein level was not changed between P4+/+ and Wnt7acre−/− Mig-6−/− mice. However, expression of PR target genes, Mig-6, Fst, and Il13ra2 was highly increased in Wnt7acre−/− Mig-6−/− compared with P4+/+ mice after P4 treatment (Supplementary Fig. S3). BIRC3 is induced by progesterins through PRB and contributes to the survival of endometrial cancer cells against apoptosis mediated by inhibition of AKT (27). The levels of BIRC3 were decreased in Wnt7acre−/− Mig-6−/− mice while the high levels of BIRC3 were not altered in P4+/+ Mig-6−/− mice after P4 treatment (Fig. 6). It suggested that the induction of BIRC3 by P4 plays a role in the resistance to P4 therapy observed in some women with endometrial carcinoma (27). Our results support the function of BIRC3 in the resistance of P4 therapy. It is sufficient to function as a tumor suppressor or mediator of PR-P4 signaling, although expression of Mig-6 in Wnt7acre−/− mice is lower than control mice after P4 treatment. Our results suggest that activated stromal Mig-6 can regulate proliferation and apoptosis via regulation of ERα activity in the epithelium, and that epithelial Mig-6 is a critical tumor suppressor involved in P4-mediated protection against the development of endometrial cancer. These results suggest that epithelial Mig-6 is critical for a tumor suppressor function in endometrial cancer.

In conclusion, our results show the role of epithelial Mig-6 in steroid hormone regulation and endometrial cancer. Ablation of epithelial Mig-6 in the murine uterus resulted in development of endometrial hyperplasia and P4 treatment prevented the occurrence of the endometrial hyperplastic phenotype, which occurs via Mig-6 regulation of ERE activity (Table 1). The Wnt7acre−/− Mig-6−/− model is useful for studying new targets during cancer progression and can be exploited therapeutically to identify new therapies for the prevention and treatment of endometrial cancer. Determining the role of Mig-6 in stromal–epithelial crosstalk will be critical in understanding the role of steroid hormone signaling in endometrial function and dysfunction associated with infertility and endometriosis as well as in developing therapy for both of these common uterine diseases.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Authors’ Contributions

Conception and design: T.H. Kim, J-W. Jeong


Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): D-K. Lee, R.R. Behringer, J-W. Jeong

Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): T.H. Kim, B.J. Ku, R.R. Broadus, J-W. Jeong

Writing, review, and/or revision of the manuscript: T.H. Kim, D-K. Lee, R.R. Behringer, J. Lydon, B.J. Ku, A.S. McCampbell, R.R. Broadus, J-W. Jeong

Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): S-N. Cho, J-W. Jeong

Study supervision: B.J. Ku, J-W. Jeong

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Grant Support

This work was financially supported by NIH R01HD057873, the American Cancer Society Research Scholar Grant RSG-12-084-01-TRG, and World Class University program (R31-10056) through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology (J-W. Jeong), NIH HD30284 and SPORE in Uterine Cancer CA098258 (R.R. Broadus), and the National Cancer Institute CA099299 Training Program in the Molecular Genetics of Cancer (G.D. Orvis).

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Table 1. The comparison between whole uterine and epithelial-specific Mig-6 ablation

<table>
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Abbreviation: KO, knockout.

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References


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Cancer Res  Published OnlineFirst June 27, 2013.

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Access the most recent version of this article at:
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