

PI3K/AKT/mTOR pathway promotes progesterin resistance in endometrial cancer cells by inhibition of autophagy

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Abstract: Endometrial cancer (EC) is now one of the most common malignant tumors in young women. In all, 90% of young patients with EC have a high expression of progesterone receptor, can be treated with progesterin, and have very good prognosis. However, some of the young EC patients are resistant to progesterin, the mechanism of which is unclear. To illuminate the mechanism by which endometrial cells acquire progesterin resistance, we treated Ishikawa cells by slowly increasing dosage of progesterin and established a progesterin-resistant cell subline. We show here that progesterone resistant cells acquire increased proliferation rate and interestingly decreased autophagy. To uncover the mechanism by which cells increase proliferation and bypass autophagy, we found higher activation of phosphatidylinositol 3-kinase/AKT/mTOR signaling pathway was necessary to this malignant acquirement by RNAi technique. Further, we elucidated that activation of mTOR was sufficient and necessary for progesterin resistance. RAD001, an inhibitor of mTOR, decreased phosphorylation of mTOR and inhibited proliferation of progesterin-resistant cancer cells by promoting autophagy. Thus, our results indicated that mTOR can be a target to treat the progesterin-resistant EC.

Keywords: progesterone receptor, RAD001, proliferation, Ishikawa, phosphorylation

Introduction

Progestins, such as medroxyprogesterone acetate (MPA), were commonly used in young early endometrial adenocarcinoma patients as conservative endocrine treatment.¹⁻³ But according to clinical data, >30% of young endometrial cancer (EC) patients did not respond to progesterin because of de novo or acquired progesterin resistance during progesterin treatment, despite the different drugs or regimens used.⁴⁻⁷ The mechanism by which cancer cells acquire resistance is still unclear.

Phosphatidylinositol 3-kinase (PI3K)/AKT/mTOR pathway is central to the control of cell transcription, translation, migration, metabolism, proliferation, and survival.^{8,9} Aberrant hyperactivation of PI3K/AKT/mTOR pathway is one of the most common tumor-related signaling pathways that can be detected in a variety of tumor types, such as breast cancer, colorectal cancer, endometrial carcinoma, lung cancer, and glioblastoma, mainly including PIK3CA mutation, PTEN loss, and AKT1 mutation. In addition, KRAS mutation and BRAF mutation from the MAPK pathway can also result in PI3K/AKT/mTOR pathway activation.¹⁰⁻¹⁵ A previous study showed that progesterin might activate PI3K/AKT signaling pathway independent of progesterone receptor (PR) in breast cancer.¹⁶

Autophagy is a catabolic degradation process in which cellular proteins and organelles are engulfed by double-membrane autophagosomes and degraded in

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lysosomes. Autophagy has emerged as a critical pathway in tumor development and cancer therapy.¹⁷ Previous studies showed that several cytokines and sex steroids can regulate autophagy in different cancers.^{18–20}

Here we show that activation of the PI3K/AKT pathway would result in activation of mTOR and promote cell proliferation by inhibiting autophagy. Inhibition of PI3K/AKT/mTOR pathway could reverse the progestin resistance in EC.

Materials and methods

Plasmid construction and transient transfection

The complete mTOR coding sequence was amplified by polymerase chain reaction (PCR) using primers 5'-GAT CGC TAG CAT GCT TGG AAC CGG ACC-3' (forward) and 5'-GAT CGC GGC CGC TTA CCA GAA AGG GCA CCA GCC-3' (reverse). The PCR product was purified and cloned into pcDNA3.1 vector using NheI/NotI. The selected clone was fully sequenced in order to verify that no mutations were introduced by PCR. The mTOR RNAi sequence is 5'-AAG CCA TCC AGA TTG ATA CCT-3'. The AKT1 RNAi sequence is 5'-AAG CAC CGC GTG ACC ATG AAC-3'. Scramble sequence is 5'-CAA GAT GAA GAG CAC CAA A-3'. For transfection, the day before transfection, cells were seeded in six-well plates and grown overnight until the cells had reached 90%–95% confluence. Transient transfections were performed using Lipofectamine 2000 (Thermo Fisher Scientific, Waltham, MA, USA) according to the manufacturer's protocol.

Cell culture

Human endometrial carcinoma cell line, Ishikawa cells (European Collection of Cell Cultures; Porton Down, Salisbury, Wiltshire, UK), were grown in Dulbecco's Modified Eagle's Medium (Thermo Fisher Scientific) supplemented with 10% fetal bovine serum (Thermo Fisher Scientific). Cells were maintained at 37°C under an atmosphere of 5% CO₂. All research experiments were approved by the Department of Gynecology, Affiliated Hospital of Qingdao Medical College, Qingdao University Ethics Committee.

Establishment of progestin-resistant EC cell lines

Induction of progestin-resistant EC cell line was described previously.²¹ Briefly, Ishikawa cells were maintained in Dulbecco's Modified Eagle's Medium supplemented with 10% fetal bovine serum, and MPA (Sigma-Aldrich Co., St Louis, MO, USA) was added for 6 months. The concentration of MPA was increased twofold every month until it reached 10 µM.

The medium containing MPA was changed every 3 days. Cells were passaged when the surviving cells grew to 90% confluent. This method produced a subline refractory to the growth-suppressive effects of MPA, which was considered to consist of progestin-resistant Ishikawa cells, and was thereafter maintained in 10 µM MPA.

Western blot

Western blot analysis was performed as previously described.²² Cells were lysed in hot 1× sodium dodecyl sulfate sample buffer, and 30 µg samples were loaded into each lane of 4%–12% polyacrylamide gels. The proteins were separated by electrophoresis, and the proteins in the gels were transferred onto nitrocellulose membranes (Pall; Port Washington, NY, USA). The membrane was blocked with 5% nonfat milk for 1 hour at room temperature and then incubated with antibodies against PR (3176; Cell Signaling Technology, Danvers, MA, USA), pAKT (Ser473; 4058; Cell Signaling Technology), AKT (4685; Cell Signaling Technology), phosphor-mTOR (Ser2448; 5536; Cell Signaling Technology), mTOR (2972; Cell Signaling Technology), LC3B (2775; Cell Signaling Technology), ATG3 (3415; Cell Signaling Technology), ATG5 (8540; Cell Signaling Technology), KRAS (ab137739; Abcam, Cambridge, UK); PTEN (ab170941; Abcam), EIG121 (ab156275; Abcam), P62 (ab91526; Abcam), Beclin-1 (ab114071; Abcam), and β-actin (sc-47778; Santa Cruz Biotechnology Inc., Dallas, TX, USA) for 16 hours at 4°C. Then, the specific horseradish peroxidase-conjugated rabbit anti-mouse or rabbit anti-mouse IgG was added to the membrane and incubated for 1 hour at room temperature. Detection by the chemiluminescence reaction was carried out using the enhanced chemiluminescence (ECL) kit (Pierce; Rockford, IL, USA).

Cell proliferation assay

Cells were seeded in 24-well plates at low density (2×10⁴ cells) and allowed to attach overnight. Then cells were cultured for indicated times. Twenty microliters of 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT; 5 mg/mL; Sigma-Aldrich Co.) was added into each well at 0 hours, 24 hours, 48 hours, 72 hours, and 96 hours, and the cells were incubated for a further 4 hours. The absorbance was recorded at 570 nm with a 96-well plate reader after the addition of dimethyl sulfoxide.

Statistical analysis

Data were analyzed by using SPSS statistical package (Version 16; SPSS Inc., Chicago, IL, USA). Independent two group's analyses used Student's *t*-test. *P* < 0.05 was considered statistically significant.

Results

Progesterin-resistant cells show increased cell growth and decreased autophagy

The progesterin-resistant cell (PRC) subline was established by long-term MPA treatment.¹² We then characterized the PRCs by examining cell growth and cell viability. The MTT results showed that MPA significantly inhibited the proliferation of parental but not PRCs (Figure 1A). Previous studies²¹ showed lower expression of PR in PRCs. We also found lower expression of PR in our system (Figure 1B). We showed that MPA promoted autophagy of parental cells, but not in PRCs, by Western blot for autophagy markers (Figure 1C). This result indicates that continuous progesterin treatment could lead to PR downregulation and activation of other pathways to promote cell growth and inhibit cell autophagy in EC cells.

Progesterin activates the PI3K/AKT/mTOR pathway in progesterin-resistant EC cells

Abnormal activation of PI3K/AKT pathway is one of the most common tumor-related signaling abnormalities that regulated cell proliferation and viability in a variety of tumors.^{12–14} To illustrate if PI3K/AKT pathway was activated by progesterin, we examined the phosphorylation of AKT1 on Ser473 in response to MPA treatment in progesterin-resistant EC cells. MPA treatment resulted in reduced phosphorylation of AKT1 in parental Ishikawa cells, but interestingly, the phosphorylation of AKT1 increased in the PRCs (Figure 2A). We also showed that the expression of PTEN is decreased, whereas the expression of KRAS is increased in the PRCs, which is consistent with a previous study.²³

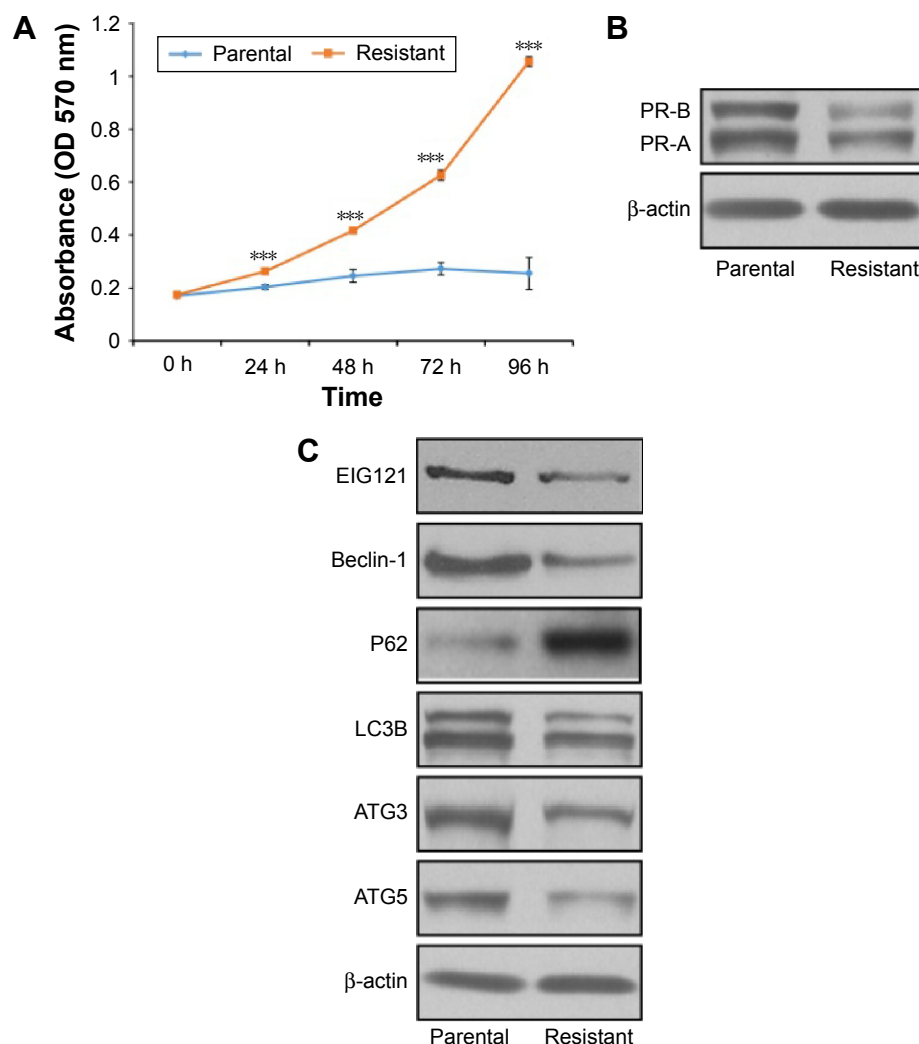


Figure 1 Progesterin-resistant cells show increased cell growth and decreased autophagy.

Notes: (A) The cell growth curves of Ishikawa parental- and progesterin-resistant cells are shown by MTT assay. Data are expressed as the mean results from three independent experiments. *** $P < 0.001$. (B) Western blot showed expression of PR. (C) Western blot showed expression of autophagy markers EIG121, Beclin-1, P62, LC3B, ATG3, and ATG5 and the expression of β -actin as internal control.

Abbreviations: MTT, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide; PR, progesterone receptor; PR-A, progesterone receptor isoform A; PR-B, progesterone isoform B; OD, optical density; h, hours.

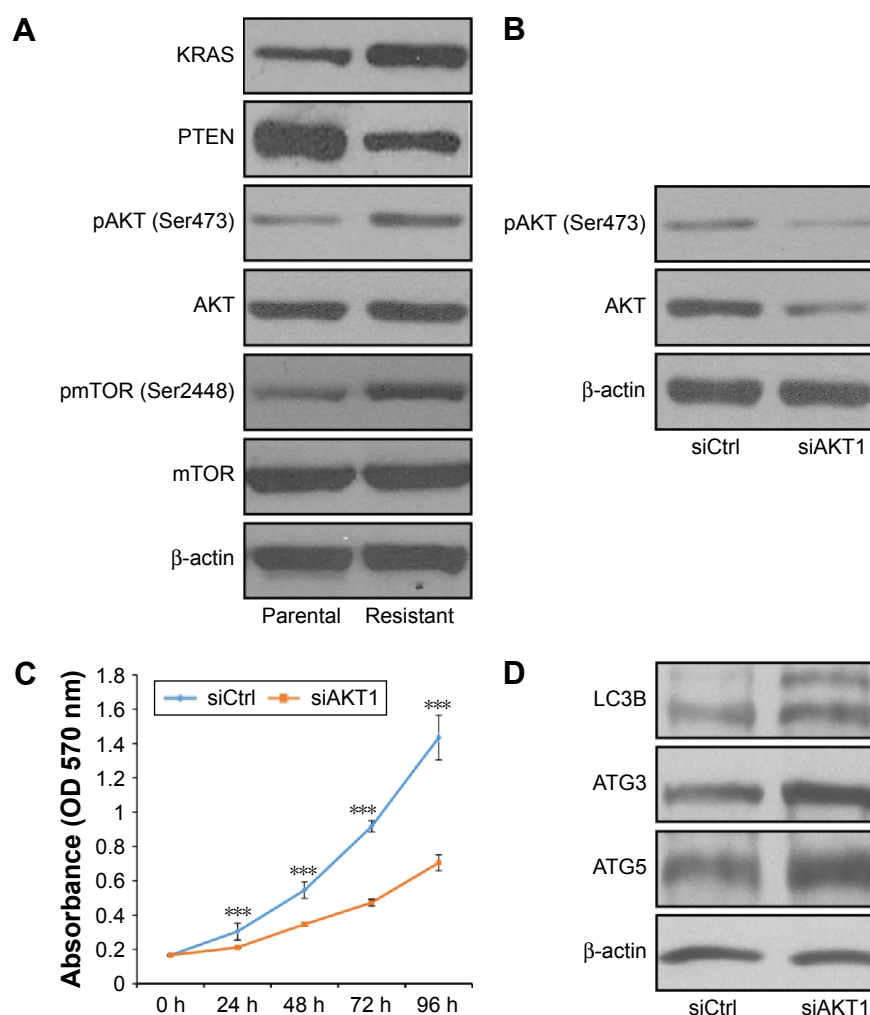


Figure 2 Progestin activates the PI3K/AKT/mTOR pathway in progestin-resistant endometrial cancer cells.

Notes: (A) Western blot assay was used to characterize the activation of PI3K/AKT/mTOR pathway. (B) Western blot showed expression of AKT1 in control and AKT1-knockdown cells. (C) The cell growth curves of control and AKT1 knockdown resistant cells are shown by MTT assay. Data are expressed as the mean numbers of independent triplicate experiments. $***P < 0.001$. (D) Western blot showed expression of autophagy markers LC3B, ATG3 and ATG5 and the expression of β -actin as internal control.

Abbreviations: PI3K, phosphatidylinositol 3-kinase; AKT, protein kinase B; mTOR, mechanistic target of rapamycin; MTT, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide; OD, optical density; Ctrl, control; h, hours; pAKT, phosphor-AKT; pmTOR, phosphor-mTOR; siAKT1, short interfering RNA targeting AKT1; siCtrl, short interfering RNA control with scrambled sequence.

It is well known that the PI3K/AKT/mTOR pathway plays a critical role in cell growth and viability; hence, we examined the activation status of mTOR. The result showed that the phosphorylation of mTOR on Ser 2448 is increased in PRCs compared with progestin-sensitive cells (Figure 2A).

PI3K/AKT/mTOR signaling pathway promotes cell growth in EC cells by diminishing autophagy

To address whether PI3K/AKT activation is necessary for the progestin resistance, we reduced AKT1 expression in PRCs using siRNA. The siRNA successfully decreased AKT1 expression and phosphorylation of AKT1 in the cells (Figure 2B). We showed decreased cell growth (Figure 2C) and increased autophagy in AKT1-knockdown cells (Figure 2D).

To address whether mTOR is involved in the progestin resistance, we then decreased mTOR expression in PRCs using siRNA (Figure 3A). The expression of PR showed no significance after knockdown of mTOR in PRCs (Figure 3A), which showed that PR might not be involved. Upon elimination of mTOR, cell growth decreased (Figure 3B) and expression of autophagy markers increased dramatically (Figure 3C). Further, we wondered whether mTOR activity is sufficient to promote progestin resistance in Ishikawa cells; hence, we rescued the expression of mTOR with mutation at the siRNA-recognized site in PRCs. We then found restored phosphorylation of mTOR (Figure 3D). MTT assay showed restored proliferation of PRCs (Figure 3E); Western blot against autophagy markers showed decreased expression of LC3B, ATG3, and ATG5 (Figure 3F).

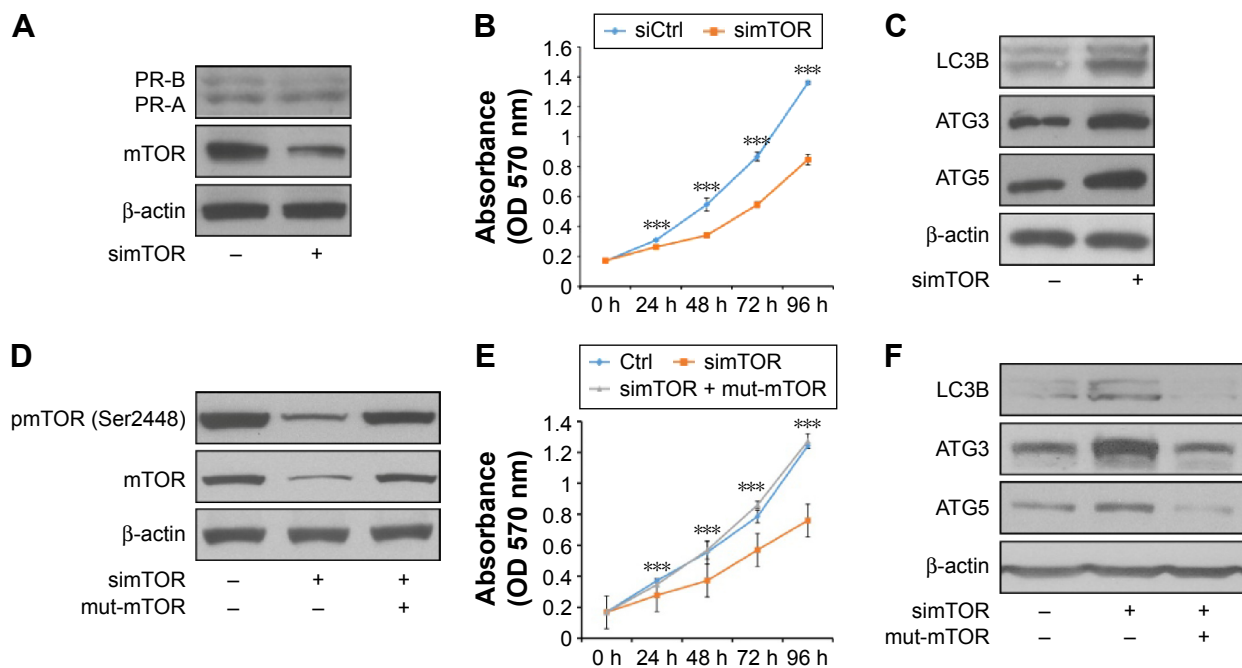


Figure 3 Phosphorylation of mTOR is sufficient and necessary for cell growth in endometrial cancer cells by regulating autophagy.

Notes: (A) Western blot showed expression of PR and mTOR in control and mTOR-knockdown cells. (B) The cell growth curves of control and mTOR-knockdown cells are shown by MTT assay. Data are expressed as the mean numbers of independent triplicate experiments. $***P < 0.001$. (C) Western blot showed expression of autophagy markers LC3B, ATG3, and ATG5 and the expression of β -actin as internal control. (D) Western blot showed expression and phosphorylation of mTOR after restoration of mutant mTOR. (E) The cell growth curves are shown by MTT assay. Data are expressed as the mean numbers of independent triplicate experiments. $***P < 0.001$. (F) Western blot showed expression of autophagy markers LC3B, ATG3, and ATG5 and the expression of β -actin as internal control.

Abbreviations: mTOR, mechanistic target of rapamycin; PR, progesterone receptor; MTT, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide; OD, optical density; Ctrl, control; h, hours; pmTOR, phosphor-mTOR; siCtrl, short interfering RNA control with scrambled sequence; mut, mutant; simTOR, short interfering RNA targeting mTOR.

These results confirmed that progesterin activated PI3K/AKT/mTOR pathway, and PI3K/AKT/mTOR pathway is both sufficient and necessary for the progesterin resistance of EC cells.

RAD001 inhibits proliferation in progesterin-resistant EC cells by inducing autophagy

RAD001 (Everolimus) is an inhibitor of mTOR and was approved for the treatment of advanced renal cell carcinoma, advanced breast cancer, and pancreatic neuroendocrine tumors.^{24,25} To assess whether RAD001 can inhibit cell growth and promote autophagy in EC cells, we treated progesterin-resistant Ishikawa cells with RAD001. The phosphorylation of mTOR by Western blot analysis is shown in Figure 4A. RAD001 significantly inhibited phosphorylation of mTOR, and the expression of LC3B, ATG3, and ATG5 was all increased after RAD001 treatment (Figure 4A). MTT results showed decreased cell growth after RAD001 treatment (Figure 4B). These results demonstrate that RAD001 treatment could inhibit proliferation of progesterin-resistant EC cells by inducing autophagy.

Discussion

Progesterin plays a very critical role in EC therapy by inhibiting cell proliferation and inducing autophagy by binding of the nuclear receptor PR. But clinically, MPA treatment stimulated the proliferation of PRCs with low expression of PR. These studies indicate that the proliferation promotion ability of progesterin on PRCs might take advantage of a non-transcriptional pathway other than the PR pathway.

It has been shown that AKT hyperactivation could induce endocrine resistance in breast cancer and non-small-cell lung cancer.¹⁰⁻¹⁵ We also showed AKT hyperphosphorylation in PRCs with MPA treatment (Figures 2 and 3). But AKT phosphorylation was not due to PR mediation because the PRCs showed very low or no expression of PR (Figure 1B). Knockdown of AKT in MPA-treated PRCs inhibited AKT phosphorylation and inhibited cell growth. Interestingly, inhibition of activity of AKT induced autophagy. Further, we studied the detailed mechanism by which PI3K/AKT regulates progesterin resistance, and we found that mTOR signaling pathway is critical to promote cell growth and inhibit autophagy in progesterin-resistant Ishikawa cells. According to these results, we proposed that PRCs that do not have or

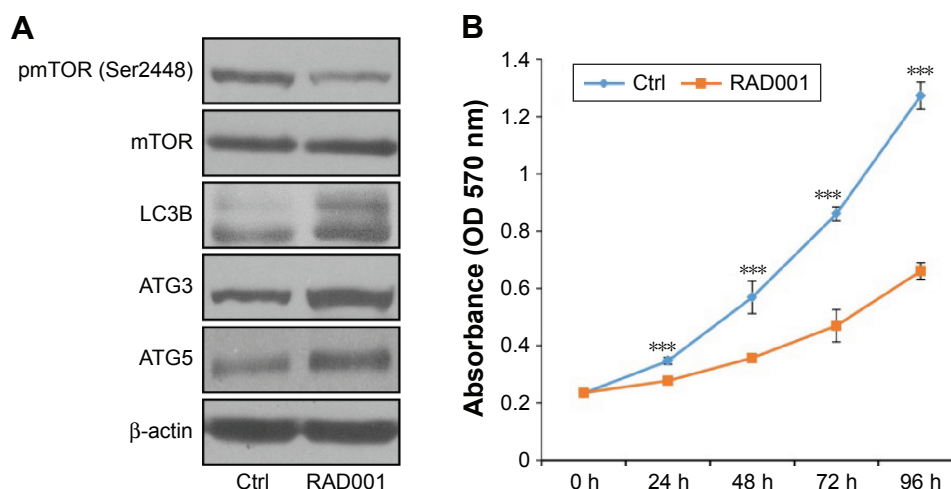


Figure 4 RAD001 inhibits proliferation in progestin-resistant endometrial cancer cells by inducing autophagy.

Notes: (A) Western blot showed phosphorylation of mTOR and expression of autophagy markers with or without RAD001 treatment. (B) The cell growth curves with or without RAD001 treatment are shown by MTT assay. Data are expressed as the mean numbers of independent triplicate experiments. *** $P < 0.001$.

Abbreviations: mTOR, mechanistic target of rapamycin; MTT, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide; Ctrl, control; OD, optical density; h, hours.

have low PR expression possibly have other hyperactivated signaling and blockade of PI3K/AKT/mTOR pathway could recover progestin resistance in EC. We also showed that combination treatment of progestin and mTOR inhibitor RAD001 can resensitize PRCs to progestin treatment.

To summarize, here we suggest that long-term progestin treatment causes progestin resistance by activating PI3K/AKT/mTOR signaling pathway. In addition, hyperactivation of PI3K/AKT/mTOR signaling pathway inhibits autophagy of PRCs. Blockade of PI3K/AKT/mTOR pathway promotes autophagy and sensitizes PRCs to progestin.

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Disclosure

The authors report no conflicts of interest in this work.

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