A link between Notch and progesterone maintains the functionality of the rat corpus luteum

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Abstract

In this study, we investigated the interaction between the Notch pathway and progesterone to maintain the functionality of the corpus luteum (CL). When Notch signaling is activated, the γ-secretase complex releases the active intracellular domains (NICD) of their receptors, which exert survival effects. We designed studies to analyze whether the in vitro inhibition of Notch affects progesterone production, steroidogenic regulators, apoptotic parameters, and signaling transduction pathways in the cultures of CL isolated from pregnant and superovulated rats. We detected a decrease in progesterone production when corpora lutea (CL) were incubated with N-(N-(3,5-difluorophenacetyl-L-alanyl))-S-phenylglycine t-butyl ester (DAPT), a γ-secretase inhibitor. This effect could be in part due to the decrease detected in the CL protein levels of P450scc because STAR and 3β-hydroxysteroid dehydrogenase were not affected by Notch inhibition. Besides, the addition of aminoglutethimide to the CL culture medium decreased NICD of NOTCH1. We observed an increase in the expression of active CASPASE3 (CASP3) after inhibition by Notch, which was reversed by the presence of progesterone. The BAX:BCLXL ratio was increased in CL treated with DAPT and the presence of progesterone reversed this effect. In addition, phosphorylation of AKT was inhibited in CL treated with DAPT, but had no effect on ERK activation. To demonstrate that the action of DAPT is specifically related with the inhibition of Notch, CLs were incubated with DLL4 antibody and a decrease in progesterone production was detected. These results suggest the existence of a novel link between progesterone and the Notch signaling pathway to maintain the functionality of the CL.

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Introduction

The corpus luteum (CL) is a transient endocrine gland whose main function is to secrete the steroid hormone progesterone essential for implantation of the blastocyst and maintenance of pregnancy in mammals (Bowen-Shauver & Gibori 2004, Stouffer 2004, Stocco et al. 2007). One important step in luteal steroidogenic biosynthesis is the enzymatic conversion of cholesterol to pregnenolone catalyzed by the cytochrome P450scc enzyme; however, before this conversion, the active delivery of cholesterol to the inner mitocondrial membrane is carried out by the protein STAR (reviewed in Stocco et al. (2007)). Although the development and differentiation of a structurally and functionally mature CL depend mainly on the activation of the luteinizing hormone (LH) receptor, they also depend on other factors such as receptors, transcription factors, and signaling proteins (Stouffer 2004, Stocco et al. 2007). In addition, if pregnancy does not occur or when the CL is no longer required for the maintenance of pregnancy, the CL ceases to produce progesterone and regresses in a process called luteolysis (Bowen-Shauver & Gibori 2004, Stouffer 2004, Stocco et al. 2007).

The Notch system is an evolutionary conserved pathway involved in cell fate decisions, including proliferation, differentiation, and apoptosis. In mammals, the Notch family of proteins consists of four receptors (NOTCH1–4) and five ligands (JAGGED1–2, DELTA-like 1, 3, and 4 (DLL4)) expressed on the cell surface. When Notch signaling is initiated, the receptors expose a cleavage site in the extracellular domain to the metalloproteinase TACE and, following this cleavage, Notch undergoes another cleavage mediated by the presenilin–γ-secretase complex. This results in the release of the active intracellular domain (NICD), which translocates to the nucleus (Kopan & Ilagan 2009) and exerts pleiotropic effects by initiating a transcriptional cascade (Ranganathan et al. 2011).

Notch proteins and ligands have been localized in granulosa, luteal, and vascular cells of the rodent ovary (Johnson et al. 2001, Vorontchikhina et al. 2005, Jovanovic et al. 2013). In addition, corpora lutea (CL) from marmosets treated with a neutralizing antibody...
against DLL4 during the periovulatory period exhibit increased vascular density, but smaller size, with involution of luteal cells, increased cell death, and suppressed plasma progesterone concentrations (Fraser et al. 2012). Recently, Jovanovic et al. (2013) have demonstrated that the in vivo inhibition of the Notch signaling pathway in mice impairs folliculogenesis and induces the disruption of gonadotropin-stimulated angiogenesis. We have previously demonstrated that Notch1, Notch4 and DLL4 are expressed in small and large luteal cells of CL from pregnant rats and have shown evidences that Notch signaling promotes both luteal cell viability and steroidogenesis. In addition, our results suggest that the luteolytic hormone PGF2α might act, in part, by reducing the expression of some components of the Notch system (Hernandez et al. 2011).

On the other hand, several studies have demonstrated that progesterone can locally stimulate its own secretion and protect the CL from cell death (Stocco et al. 2007). In rat granulosa and luteal cells, Progesterone has an autocrine action on steroidogenesis and protects cells from apoptosis. In addition, it has been suggested that the effects are exerted through a progesterone receptor localized on the luteal cell membrane (Telleria et al. 1999).

The phosphotidylinositol-3 kinase (PI3K)/AKT/ERK1/2 interaction mediates relevant pathways involved in the promotion of cell survival or apoptosis inhibition (Gerber et al. 1998, Thakker et al. 1999), whereas the protein products of the Bcl2 family genes have also been described as apoptotic regulatory factors (Korsmeyer 1992, Boise et al. 1993). Follicle-stimulating hormone (FSH) and LH mediate luteinization by inducing a complex pattern of gene expression in ovarian cells that is regulated by the coordinate input from different signaling cascades such as the cAMP/protein kinase A, PI3K/AKT, and ERK1/2 cascades (Hunzicker-Dunn & Maizels 2006, Fan et al. 2008). In luteal cells, the luteolytic hormone PGF2α also regulates the ERK1/2 pathway (Chen et al. 1998). Moreover, depending on the balance between pro- and antiapoptotic proteins, the initiator CASPASE9 is activated and several effector caspases such as CASPASE3 (CASP3) or CASPASE7 are sequentially activated and promote apoptosis in various systems (Budihardjo et al. 1999). In previous studies, we reported the expression and activation of proapoptotic caspase-mediated pathways during both spontaneous luteolysis in pregnancy and natural cycles, and PGF2α-induced luteolysis (Pellufo et al. 2006, Hernandez et al. 2009). In addition, different reports have demonstrated the interaction between the Notch signaling and PI3K/AKT pathways in cancer cells (Meurette et al. 2009, Wang et al. 2011). In this context, we have recently demonstrated that Notch induces granulosa cell tumor proliferation, decreases apoptosis-mediated cell death, and might be interacting with the PI3K/AKT signaling pathway (Irusta et al. 2013). Yet, the cellular mechanisms by which progesterone exerts its local effects and whether progesterone interacts with the Notch system in CL survival remain incompletely understood. We thus hypothesized that there is a link between the Notch signaling pathway and progesterone, which exerts a regulatory mechanism to maintain the functionality of the CL. Therefore, we designed studies to analyze whether the in vitro inhibition of Notch signaling affects progesterone production, steroidogenic regulators, apoptotic parameters, and signaling transduction pathways in cultures of CL isolated from pregnant and superovulated rats.

**Materials and methods**

**Animal models**

**Pregnant rats**

Adult female Sprague–Dawley rats (body weight 200–250 g, 8-weeks-old) were housed at room temperature (21–23 °C) with a 12 h light:12 h darkness photo period in an air-conditioned environment. The rats had ad libitum access to food and water. The animals showing three consecutive 4-day cycles were used for the experiment and cycling stages were determined daily by vaginal cytology. Proestrous females were caged with fertile males overnight, separated the next morning, and vaginal smears analyzed for the presence of spermatozoa. The day spermatozoa were detected was considered day 1 of pregnancy. The animals were killed by CO2 aspiration and ovaries were collected on day 16 of pregnancy. In this experimental model (CL obtained from pregnant rats), key experiments were carried out: studies to elucidate the relationship between the Notch pathway and progesterone production in cultured CL and the role of AKT and ERK signaling pathways in Notch CL function.

**Superovulated rats**

Due to the limitations to obtain a large number of CL from pregnant rats, additional experiments were carried out in the CL of superovulated rats. For this purpose, 21–23-day-old immature female Sprague–Dawley rats housed in the same conditions as that of pregnant rats were injected subcutaneously with equine CG (eCG; 25 IU/rat) followed by human chorionic gonadotropin (hCG; 25 IU/rat) 48 h later. The treatment with eCG plus hCG causes a considerable (tenfold) increase in ovarian weight due to the stimulation and subsequent transformation of ovarian follicles into CL. The animals were killed by CO2 aspiration 4 days after hCG administration. To validate this experimental model, similar experiments to those carried out in CL of pregnant rats were repeated in CL of superovulated rats. In addition, steroidogenic regulator protein levels, apoptotic parameters, and specificity of Notch inhibition with DAPT using antibody against DLL4 were analyzed in CL cultures of superovulated rats. The experimental protocols were approved by the Animal Experimentation Committee of the Instituto de Biología y Medicina Experimental (IByME, Buenos Aires, Argentina) (PHS–NIH Approval Statement of Compliance no. A5072–01).
**CL culture**

The ovaries were removed and cleaned of adhering tissue in culture medium and CL were isolated by ovarian microdissection as previously described (Andreu et al. 1998, Hernandez et al. 2009).

For the inhibition of the Notch pathway, N-((3,5-difluorophenacetyl)narly)-S-phenylglycine t-butyl ester (DAPT, Sigma–Aldrich), a chemical component that inhibits the activity of the γ-secretase complex, was used. This inhibitor has been extensively used for experimental studies of Notch signaling, both in vitro and in vivo (Gordon et al. 2008).

Progesterone production was inhibited with aminoglutethimide (AG, Sigma–Aldrich), which blocks the conversion of cholesterol to pregnenolone by inhibiting the enzyme P450scc (Brueggemeier et al. 2005). When CLs were incubated in the absence of inhibitors, 0.05% of vehicle solution (DMSO) was added to the medium.

Previous experiments of the time course and DAPT dose-response assessments were carried out to determine optimal incubation conditions (data not shown). Taking these results into account, four CL/well of superovulated rats were incubated for 1 or 4 h in 0.35 ml of DMEM:F12 containing bicarbonate and 0.5% BSA at 37°C with 0.25 mM DAPT, 0.15 mM AG, 1.6 µM progesterone, or each inhibitor in the presence of progesterone. For each experiment, four ovaries from different rats were used to dissect CLs that were randomly distributed in the different wells (four wells/treatment). The four CLs from each well were pooled for western blotting assays. Each experiment was made in duplicate; in the case of pregnant rats, two CLs/well of superovulated rats were incubated for 1 or 4 h in 0.35 ml of DMEM:F12 containing bicarbonate and 0.5% BSA at 37°C with 20 mM DAPT, 0.15 mM AG, 1.6 µM progesterone, or each inhibitor in the presence of progesterone.

Inhibitors and all the parameters measured were expressed as a fold-change relative to the control. After incubations, the supernatants from each well were frozen for progesterone determination by RIA. The CLs were then processed for immunohistochemistry (IHC).

**Incubation with neutralizing antibody against DLL4**

Given that the γ-secretase complex has more than one substrate, Notch activation was also inhibited by incubating five CLs/0.35 ml with DLL4 neutralizing antibody (0.5, 2, and 5 µg/ml) and normal goat IgG as a control (0.5 µg/ml) for 4 h. After incubation, production of progesterone was measured in the culture medium by RIA.

**RIA for progesterone**

Progesterone was measured as described previously (Irusta et al. 2003) using specific antibodies supplied by Dr G D Niswender (Animal Reproduction and Biotechnology Laboratory, Colorado State University, Fort Collins, CO, USA). Under these conditions, the intra-assay and inter-assay coefficients of variations were 8.0 and 14.2% respectively. The detection limit of the RIA was 25 pg.

**Western blot analysis**

For western blotting analysis, the CLs were resuspended in 250 µl of lysis buffer (20 mM Tris–HCl pH 8, 137 mM NaCl, 1% Nonidet P-40, and 10% glycerol) supplemented with protease inhibitors (0.5 mM phenylmethylsulfonyl fluoride, 0.025 mM N-CBZ-L-phenylalanine chloromethyl ketone, 0.025 mM N-p-tosyl-lysine chloromethyl ketone, and 0.025 mM L-1-tosylamide-2-phenyl-ethylchloromethyl ketone) and phosphatase inhibitors (25 mM sodium fluoride, 0.2 mM sodium orthovanadate, and 10 mM b-glycerophosphate) and homogenized using an Ultra-Turrax (IKA-Werke GmbH & Co., Staufen, Germany) homogenizer. The samples were centrifuged at 4°C for 10 min at 10 000 g and the resulting pellets were discarded. Protein concentration in the supernatant was measured by the Bradford assay. After boiling for 5 min, 20 µg protein were applied to a SDS–polyacrylamide gel (12–15%) and electrophoresis was carried out at 25 mA for 1.5 h. The resolved proteins were transferred onto nitrocellulose or PVDF membranes for 2 h. The blot was preincubated in a blocking

### Table 1 Antibodies used for immunohistochemistry and western blotting analysis.

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<th>Peptide target</th>
<th>Manufacturer, catalog no.</th>
<th>Species raised in</th>
<th>Dilution</th>
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<td>β-ACTIN</td>
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<tr>
<td>3B-HSD</td>
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<td>Goat</td>
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<tr>
<td>STAR</td>
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<td>Rabbit</td>
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<td>Dr Anita Payne. Stanford University Medical Center, Stanford, CA, USA</td>
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<td>1:200</td>
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<tr>
<td>Biotinylated anti-rabbit IgG</td>
<td>Vectastain ABC system; Vector Laboratories</td>
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buffer (5% nonfat milk, 0.05% Tween-20 in 20 mM TBS pH 8.0) for 1 h at room temperature, and then incubated with appropriate primary antibodies (Table 1) in 0.05% Tween-20 in 20 mM TBS of pH 8.0 overnight at 4°C. The blots were then incubated with anti-rabbit or anti-mouse secondary antibodies conjugated with HRP (Table 1) and finally detected by chemiluminescence and autoradiography using X-ray film. Protein loading was normalized by reprobing the same blots with antibody against β-ACTIN or GAPDH (Table 1). Protein expression was quantified by densitometric analysis using Scion Image Software for Windows (Scion Corporation, Worman’s Mill, CT, USA).

**Immunohistochemistry**

Corpora lutea were deparaffinized in xylene and rehydrated by graduated ethanol washes. Endogenous peroxidase activity was blocked with hydrogen peroxide in PBS, and nonspecific binding was blocked with 2% BSA for 20 min at room temperature. The sections were incubated with anti-cleaved CASP3 antibody overnight at 4°C. After washing, the slides were incubated with biotinylated anti-rabbit IgG (Table 1) and after 30 min with avidin-biotinylated HRP complex (Vectastain ABC system; Vector Laboratories, Burlingame, CA, USA) for 30 min. Protein expression was visualized using diaminobenzidine staining. The negative controls were obtained in the absence of primary antibody. The reaction was stopped using distilled water, stained with hematoxylin, and dehydrated before mounting with mounting medium (Canada Balsam Synthetic; Biopack, Santa Barbara, CA, USA). To perform this study, four sections from each CL were analyzed (four CL/treatment) and stained cells were counted in the whole section.

The images were digitized using a camera (Nikon, Melville, NY, USA) mounted on a conventional light microscope (Nikon). Finally, the images were converted to a TIFF format (bilevel scale) for their analysis. The percentage of luteal cells were processed using Image J (Image Processing and Analysis in Java; National Institutes of Health, Bethesda, MD, USA; Rasband 2007). An apoptosis index (cleaved CASP3-positive cells expressed as a percentage of the total number of cells) was calculated for each section.

**Statistical analysis**

Statistical analysis was carried out using GraphPad Prism Software, Inc. San Diego, CA, USA. All experiments were carried out at least three times and the conditions were performed in quadruplicates.

One-way ANOVA following Newman–Keuls as post-test was used to analyze the experiments carried out in superovulated rats. Repeated measures ANOVA followed by Newman–Keuls as a post-test was used to analyze the experiments carried out in pregnant rats. The experiments were analyzed with paired Student’s t-test when two variables were involved.

Data are expressed as means ± S.E.M. of pooled results obtained from different independent experiments. The representative gels are shown in the figures. The values of *P*<0.05 were considered significant.

### Results

**Relationship between the Notch pathway and progesterone synthesis in cultured corpora lutea of pregnant rats**

Treatment with DAPT caused a 52.0% decrease on the cleaved (active) form of NOTCH1 (NICD) when compared with vehicle treatment (control). Surprisingly, AG also was able to produce a 40.0% decrease on the active form of NOTCH1. However, the presence of both inhibitors did not significantly change the effect obtained using each inhibitor separately (35.0% decrease relative to control (Fig. 1A).

Regarding the effect of the inhibitors on progesterone production measured in the culture medium, AG caused a significant decrease in progesterone production (70.8%), as expected, whereas DAPT caused a lower but significant decrease (45.7%) (Fig. 1B). Nevertheless, the presence of both inhibitors in the culture medium caused a progesterone decrease similar to that obtained with AG alone (68.9%).

**In vitro effect of Notch inhibition on progesterone production and steroidogenic regulators in corpora lutea of superovulated rats**

Corpora lutea were isolated from the ovaries of rats treated with gonadotropins and incubated with AG or DAPT for 1 or 4 h. In a conditioned medium of CL cultured for 1 h, AG significantly decreased progesterone production, but DAPT showed only a tendency to decrease (control: 319.50±49.01; AG: 51.75±10.06; DAPT: 256.50±17.53 ng/ml) (Fig. 2A). Similar to the

![Figure 1](image-url)
results obtained in CLs of pregnant rats, both treatments significantly decreased progesterone production after 4 h of culture (control: 427.80 ± 21.98; AG: 36.67 ± 2.63; DAPT: 217.5 ± 20.03 ng/ml) (Fig. 2B).

Progesterone production was also inhibited on incubation of CL from superovulated rats with DLL4 antibody for 4 h. In this experiment, progesterone production was significantly decreased in the culture medium (IgG: 482.8 ± 37.5; DLL4 antibody (5 μg/ml): 297.1 ± 37.6 ng/ml). Similar results were observed with lower DLL4 antibody concentrations (Fig. 2C).

To determine whether some members of the progesterone synthesis pathway are regulated by Notch, the expression of P450scc, STAR and 3β-hydroxysteroid dehydrogenase (3β-HSD) was determined by western blotting analysis. We found a significant decrease in the CL protein levels of P450scc after 4 h culture with DAPT. The coincubation with progesterone was able to reverse the content of this enzyme even to levels higher than those of the control (Fig. 2D). In addition, only progesterone was able to change the levels of STAR. In fact, the incubation with progesterone for 4 h caused a 20% increase in the STAR CL protein levels with respect to control values. Interestingly, the presence of DAPT in the culture medium reversed this effect (Fig. 2E). These experiments were repeated after 1 h of incubation and consistently with progesterone results at this time, no changes were observed in the levels of these proteins (data not shown).

Involvement of Notch signaling and progesterone in apoptotic parameters in the corpora lutea of superovulated rats

To identify whether the relationship between Notch and progesterone signaling influences the survival of luteal cells of superovulated rats, we cultured CLs with DAPT, DAPT in the presence of progesterone or progesterone

![Figure 2](https://i.imgur.com/12345678.png)

**Figure 2** Levels of progesterone and steroidogenic enzymes in the culture medium and CL of superovulated rats respectively. (A) Progesterone in culture medium of CL cultured for 1 h with AG or DAPT (a vs b, P < 0.01). (B) Progesterone in culture medium of CL cultured for 4 h with AG or DAPT (a vs b and c, P < 0.001). (C) Progesterone in culture medium of CL cultured for 4 h with different concentrations of DLL4 Ab (a vs b, P < 0.01). (D) P450scc protein content in the CL of superovulated rats cultured for 4 h (a vs b, P < 0.05; a vs c, P < 0.05; b vs c, P < 0.001). (E) STAR protein content in the CL of superovulated rats cultured for 4 h (a vs b, P < 0.01). (F) 3β-HSD protein content in CL from superovulated rats cultured for 4 h. Values are expressed as mean ± s.e.m. of progesterone in the culture medium (n = 4) or as arbitrary units ± s.e.m. normalized to β-ACTIN or GAPDH (n = 4). Groups with different letters over the error bars (a, b, and c) represent significant differences.

Link between Notch and progesterone in CL function

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alone. After 4 h of culture, we analyzed active CASP3 expression by IHC in CL sections incubated under the mentioned conditions. The luteal cells exhibited high staining for active CASP3 in the DAPT group (Fig. 3Ab). In contrast, the luteal cells of the control group (Fig. 3Aa) showed a low immunoreactivity for this protein. Active CASP3 staining was more evident in the nuclei of the CL sections, in coincidence with the fact that, once activated, active CASP3 translocate to the nucleus (Irusta et al. 2007, Parborell et al. 2008). Interestingly, the presence of progesterone in the culture medium not only reversed the increase in the immunoreactivity for active CASP3 observed with DAPT but also significantly decreased active CASP3 with respect to the control values (Fig. 3Ac and d). In addition, according to the antiapoptotic action described in rodent luteal cells, progesterone was able to decrease active CASP3 content in CLs cultured with this hormone (Fig. 3Ad). Figure 3B shows the quantification of these data obtained by IHC (control: 65.68±2.10%; DAPT: 70.69±0.90%; DAPT+progesterone: 59.88±0.90%; progesterone: 60.83±1.49%; P<0.05; n=4).

In light of these results, we examined the luteal content of the proapoptotic protein BAX and the antiapoptotic protein BCLXL, two known regulators of ovarian apoptosis (Flaws et al. 1995, Tilly et al. 1995). Although DAPT treatment did not increase BAX protein content (Fig. 4A), it significantly decreased the levels of BCLXL relative to control levels (Fig. 4B). Consequently, the BAX:BCLXL ratio was significantly increased in CLs treated with DAPT compared with the control ratio (Fig. 4C). The coincubation with DAPT and progesterone reversed the values of BCLXL and BAX:BCLXL ratio to control levels (Fig. 4B and C). Incubation of CL with progesterone alone was not able to reverse the BAX or BCLXL levels to those obtained in the control group (Fig. 4A, B and C).

Participation of AKT and ERK signaling pathways in the survival role of Notch in the corpora lutea of superovulated rats

To determine whether Notch is involved in the phosphorylation of the AKT protein, we carried out a western blotting analysis of the phosphorylated form of AKT (pAKT) in CL. Preliminary results using 1 or 4 h of incubation showed significant differences only after 1 h of incubation with the different stimulus, suggesting that basal activation by phosphorylation is a rapid event probably independent of protein synthesis. For this reason, our next experiments were designed for 1 h incubation. In this condition, DAPT significantly decreased AKT phosphorylation. The coincubation with DAPT and progesterone restored pAKT levels to the basal values (control), but no effect was observed in the presence of progesterone alone in the culture medium (control: 0.78±0.13; DAPT: 0.63±0.05; DAPT+progesterone: 0.56±0.04; progesterone: 0.58±0.03; control vs DAPT: P<0.05; n=3) (Fig. 5A).

In addition, ERK phosphorylation was studied by western blotting analysis of phosphoERK (pERK) from CL incubated in the same conditions described for the measurement of pAKT. No significant differences were observed in pERK levels among groups (Fig. 5B).
Link between Notch and progesterone in CL function

Optical density is expressed as arbitrary units 

significant differences (Groups with different letters over the error bars (a and b) represent shown in the lower panel. (B) Densitometric quantification of BCLXL in CL. Optical density is expressed as arbitrary units 

Superovulated rats. (A) Densitometric quantification of BAX in CL. 

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Discussion

This study was designed to determine a possible interaction between the Notch signaling pathway and progesterone to maintain the functionality of the CL. We describe for the first time that the inhibition of Notch signaling in rat CL cultures decreases progesterone production, in part through the regulation of the enzyme P450scc. In addition, Notch inhibition caused an increase in apoptotic parameters and a decrease in AKT phosphorylation, whereas progesterone inhibition decreased the NICD active Notch levels.

It is well known that LH is essential for the stimulation and maintenance of progesterone production by the CL; however, several autocrine and paracrine factors regulate the function of luteal cells (Stocco et al. 2007). Notch signaling plays a critical role in many developmental processes, influencing differentiation, proliferation and apoptosis, key mechanisms that regulate the dynamics and function of the CL (Artavanis-Tsakonas et al. 1999, Bolos et al. 2007). We have previously demonstrated both that notch pathway components are present in the CL of pregnant rats and that the mRNA expression of Notch1, Notch4, and Dll4 decreases during PGF2α-induced luteolysis. In addition, the in vivo intrabursal administration of DAPT to pregnant rats decreases progesterone levels and increases luteal levels of active CASP3 and the proapoptotic/antiapoptotic protein ratio (Hernandez et al. 2011). In this context, Fraser et al. (2012) described that the administration of a DLL4 neutralizing antibody to marmosets affects early-luteal angiogenesis and subsequent luteal function. Other researchers also demonstrated that the blockade of the
Notch signaling pathway with the administration of an inhibitor of the γ-secretase complex or DLL4 blocking antibody alters follicular development and induces a disruption of the VEGF-dependent luteal angiogenesis (Garcia-Pascual et al. 2013, Jovanovic et al. 2013). The present data demonstrate a decrease in progesterone production when CLs obtained from pregnant or superovulated rats were incubated with DAPT, a γ-secretase inhibitor. This effect could be in part due to the decrease detected in the CL protein levels of P450scc, because the enzymatic conversion of cholesterol to pregnenolone, catalyzed by this enzyme, is considered as one of the rate-limiting steps in progesterone biosynthesis in steroidogenic tissues (Lieberman et al. 1984, Waterman & Simpson 1985). On the other hand, other steroidogenic regulators as the STAR, a protein able to regulate the delivery of cholesterol to the mitochondrial (Stocco & Clark 1996) and 3β-HSD, the enzyme located in the smooth endoplasmic reticulum involved in progesterone synthesis from pregnenolone (Peng et al. 2002), were not affected by Notch inhibition. However, changes in the expression of the enzyme 20α-HSD, that catabolizes progesterone into the inactive progesterone and 20α-DHP cannot be rule out. Coincident with a previous report (Rekawiecki et al. 2005), the presence of progesterone in the culture medium caused an increase in CL STAR protein expression. It is worth noting that the inhibition of Notch overrides this effect, suggesting an influence of the Notch pathway on the progesterone autocrine CL regulation. Overall, our results suggest that Notch signaling is a novel mechanism that is able to regulate luteal steroidogenesis.

Interestingly, the addition of AG, a progesterone synthesis inhibitor, to the pregnant CL culture medium decreased the active NICD of NOTCH1. This result is in agreement to that obtained in primate endometrium, where progesterone increases the intracellular transcriptionally competent NOTCH1 (Afshar et al. 2012). In that work, the authors suggested that hCG and progesterone synergize to activate NOTCH1, which in turn induces alpha smooth muscle actin and inhibits stromal cell apoptosis. Further experiments are needed to elucidate the mechanism of action of progesterone on the Notch pathway in rat CL.

In addition, to demonstrate in our experimental model that the action of DAPT is specifically related with the inhibition of the Notch pathway, we blocked Notch action with an antibody against DLL4, the Notch ligand with a well-described luteotropic role (Hernandez et al. 2011, Fraser et al. 2012, Garcia-Pascual et al. 2013). This experiment showed a decrease in luteal progesterone production, confirming that the Notch system is involved in luteal function.

Progesterone plays a protective role against apoptosis in the CL of rodents (Stocco et al. 2007). In addition, this hormone is a potent survival factor for the pregnant rat CL, an effect that occurs in the absence of classic intracellular progesterone receptors (Goyeneche et al. 2003). In this context, Peluso et al. (2005) established that progesterone receptor membrane component 1 (PGRMC1) mediates the anti-apoptotic effects of progesterone observed in rat granulosa cells (Peluso et al. 2005), rat luteal cells (Peluso et al. 2005), human granulosa/luteal cells (Engmann et al. 2006), and spontaneously immortalized granulosa cells. In addition, progesterone activates a PGRMC1-dependent mechanism that promotes human granulosa/luteal cell survival but not progesterone secretion (Peluso et al. 2009). In the present work, we report an increase in the expression of active CASP3 and in the BAX:BCLXL ratio when Notch is inhibited in CL cultured with DAPT, an effect reversed by the presence of progesterone in the culture medium. To elucidate whether the cells are able to recover from apoptosis, a proliferation marker, proliferating cell nuclear antigen (PCNA), was measured by IHC in the CL cultured under the different conditions. DAPT treatment significantly decreased the percentage of positively stained nuclei and this effect was reversed by progesterone (data not shown). These results suggest that there is a direct link between the Notch system and progesterone, which upregulates the survival of luteal cells.

Different reports have demonstrated the interaction between Notch signaling and PI3K/AKT pathways. In breast epithelial cancer cells, Notch signaling induces an autocrine signaling loop that activates AKT and is necessary for Notch-induced protection against apoptosis (Meurette et al. 2009). More recently, Wang et al. (2011) have reported that in prostate cancer cells, the downregulation of NOTCH1 leads to the inhibition of cell growth mechanistically linked with the downregulation of AKT, suggesting that this protein is a downstream target of Notch1 signaling. In addition, in a previous work we have demonstrated that phosphorylation of AKT is repressed in a granulosa cell line (KGN) cultured with a Notch inhibitor (Irusta et al. 2013). In this study, we showed that phosphorylation of AKT was inhibited in CL treated with DAPT and that this effect was reversed with coincubation with progesterone. In this regard, it has been described that, in addition to transcriptional effects, progesterone activates the SRC/ERK1/2 and PI3K/AKT pathways in breast cancer and endometrial stroma cells (Ballare et al. 2006, Lee & Kim 2014). Our results suggest a similar mechanism in luteal cells, strengthening the hypothesis that an association exists between the antiapoptotic action of progesterone and Notch1/PI3K/AKT signaling. Nevertheless, further experiments are needed to deeply investigate this relationship.

In summary, the results of this study provide the first evidence that there is a crosstalk between the Notch system and progesterone, which upregulates the survival of luteal cells. One mechanism of Notch action is the increase in P450scc synthesis and, in turn, progesterone...
could regulate the NICD active Notch fragment. Our results demonstrate that Notch induces luteal progesterone in vitro production through P450scc activation and decreases apoptosis-mediated cell death. Also, the Notch/PI3K/AKT signaling pathway might be interacting with progesterone, intensifying the survival role of this hormone in luteal cells.

Declaration of interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

Funding

This study was supported by Universidad de Buenos Aires (UBA 20020090300061), CONICET (PIP 1223) and ANPCYT (PICT 2010-0248).

References


Stocco DM & Clark BJ 1996 Regulation of the acute production of steroids in steroidogenic cells. Endocrine Reviews 17 221–244.


Received 28 August 2014
First decision 22 September 2014
Revised manuscript received 9 October 2014
Accepted 14 October 2014