Selective modulation of the prostaglandin F2α pathway markedly impacts on endometriosis progression in a xenograft mouse model

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Submitted on July 14, 2015; resubmitted on September 21, 2015; accepted on October 9, 2015

STUDY HYPOTHESIS: Selective activation or blockade of the prostaglandin (PG) F2α receptor (FP receptor) affects ectopic endometrial tissue growth and endometriosis development.

STUDY FINDING: FP receptor antagonists might represent a promising approach for the treatment of peritoneal endometriosis.

WHAT IS KNOWN ALREADY: Eutopic and ectopic endometrium from women with endometriosis exhibit higher expression of key enzymes involved in the PGF2α biosynthetic pathway. It has also been shown that the PGF2α-FP receptor interaction induces angiogenesis in human endometrial adenocarcinoma.

STUDY DESIGN, SAMPLES/MATERIALS, METHODS: For this study, a mouse model of endometriosis was developed by inoculating human endometrial biopsies into the peritoneal cavity of nude mouse (n = 15). Mice were treated with AL8810 (FP receptor antagonist), Fluprostenol (FP receptor agonist) or PBS. Endometriosis-like lesions were collected and analysed for set of markers for angiogenesis, tissue remodelling, apoptosis, cell proliferation and capillary formation using qPCR and immunohistochemistry.

MAIN RESULTS AND THE ROLE OF CHANCE: We found that selective inhibition of the FP receptor with a specific antagonist, AL8810, led to a significant decline in the number (P < 0.01) and size of endometriosis-like lesions (P < 0.001), down-regulated the expression of key mediators of tissue remodelling (MMP9, P < 0.05) and angiogenesis (VEGF, P < 0.01) and up-regulated the pro-apoptotic factor (Bax, P < 0.01) as compared with controls. Immunohistochemical analyses further showed a marked decrease in cell proliferation and capillary formation in endometrial implants from AL8810-treated mice, as determined by proliferating cell nuclear antigen (PCNA) and von Willebrand factor (vWF) immunostaining, respectively. Moreover, Fluprostenol, a selective FP receptor agonist, showed the opposite effects.

LIMITATIONS, REASONS FOR CAUTION: We carried out this study in nude mice, which have low levels of endogenous estrogens which may affect the lesion growth. Caution is required when interpreting these results to women.

WIDER IMPLICATIONS OF THE FINDINGS: This study extends the role of PG signalling in endometriosis pathogenesis and points towards the possible relevance of selective FP receptor antagonism as a targeted treatment for endometriosis.

LARGE SCALE DATA: Not Applicable.

STUDY FUNDING AND COMPETING INTEREST(S): This work was supported by grant MOP-123259 to the late Dr Ali Akoum from the Canadian Institutes for Health Research. The authors have no conflict of interest.

Key words: endometriosis / prostaglandins / PGF2α / FP receptor / AL8810 / Fluprostenol
Introduction

Endometriosis is a chronic inflammatory disease affecting 6–10% of reproductive-age women. It is characterized by the presence of functional endometrial tissue outside the uterine cavity and is associated with pelvic pain, dysmenorrhea and infertility (Giudice, 2010; Macer and Taylor, 2012). The most accepted explanation of the extra-uterine localization of endometrial tissue is mainly based on the common occurrence of retrograde menstruation, where menstrual endometrial tissue is disseminated into the peritoneal cavity via the Fallopian tubes and is capable of implanting and developing into endometriosis lesions (Sampson, 1927). Although the full range of mechanisms responsible for the development of endometriosis lesions remain to be clarified, a number of recent GWAS studies have highlighted genetic risk factors that may contribute to life-time risk (Rahmioglu et al., 2014).

Prostaglandins (PGs) are well-known regulators of signalling within the female reproductive tract and their roles in ovarian function, embryo implantation and menstruation are well described (Sales and Jabbour, 2003; Vilella et al., 2013). PGs have also been implicated in endometrial pathologies such as endometriosis and endometrial cancer (Jabbour and Sales, 2004). In the female reproductive tract, the E and F series of prostanoids are synthesized from arachidonic acid via a series of oxidation steps involving cyclooxygenase (COX-1, -2) enzymes and the PG E and F synthases, respectively (Narumiya and FitzGerald, 2001). Notably the aldo-keto reductases AKR-1C3 and AKR-1B1, which have PGF synthase activities, have also been localized to the human endometrium (Fortier et al., 2008). After biosynthesis, PGF2α is transported out of the cell by means of a carrier-mediated process where it exerts autocrine/paracrine functions through a G protein receptor (GPCR)-mediated interaction (Chan et al., 1998). The GPCR that binds human PGF2α, the FP receptor, has been cloned, and its activation leads to coupling of the G protein Gq, activation of phospholipase C (PLC) and release of inositol triphosphate (IP3) and diacylglycerol (Abramovitz et al., 1994).

Endometriosis is a neuroinflammatory disorder associated with pain and infertility. It has been suggested that altered endometrial functions contribute both to the aetiology of the disorder and development of infertility (Taylor et al., 1999; Macer and Taylor, 2012). Notably ectopic, extra-uterine endometrial tissue found in lesions retains certain hallmark features of eutopic endometrium including a dependence on estrogens for continued growth (Hudelist et al., 2007). This observation has led to the adoption of hormonal suppression as a widely used medical therapy, however this can result in development of unacceptable side effects including a pseudo-menopause (due to a hypo-estrogenic environment) or pseudo-pregnancy (due to a progesterin-dominant environment) (Bulun, 2009). Although hormonal manipulations are often used as first-line therapy as well as after surgery to prevent recurrence of symptoms, their long-term use is associated with loss of bone density, low mood and increased risk for uterine and ovarian cancers (Swiersz, 2002; Vercellini et al., 2014). Recurrence rates are 50–60% within a year after cessation of hormone therapy (Guo and Olive, 2007; Kyama et al., 2008) and there is therefore an urgent need to identify non-steroidal therapeutic targets for the treatment of endometriosis.

Our recent findings suggested a significant deregulation of PGF2α bio-synthesis and action in women with endometriosis at multiple levels (Rakhila et al., 2013). These included an over-expression of COX2, the inducible rate limiting enzyme in PG synthesis, in eutopic and ectopic endometrium of women with endometriosis and an up-regulation of AKR-1C1 in endometriosis lesions (Rakhila et al., 2013). In addition, PGF2α-FP receptor interaction has recently been shown to induce angiogenesis in human endometrial adenocarcinoma (Sales et al., 2005). The present study was therefore designed to investigate, using a heterologous mouse model of endometriosis, the impact of treatment with selective FP receptor modulators on ectopic endometrial tissue growth and endometriosis development. Our data suggest that treatment with FP receptor antagonists might represent a promising approach for the treatment of peritoneal endometriosis.

Materials and Methods

Human tissue resource

Endometrial biopsies (n = 3/patient) were obtained from five patients undergoing surgical explorative laparoscopy or hysterectomy for benign conditions (confirmed as not having endometriosis and not receiving anti-inflammatory or hormonal medication for at least 3 months before surgery). These patients signed an informed consent for a research protocol approved by Saint-François d’Assise Hospital ethics committee on human research (Laval University, Quebec, Canada).

Animal handling and treatment

For this study, fifteen 6- to 8-week-old female athymic Nude-Foxn1nu mice (Harlan Laboratories, Indianapolis, IN, USA) were used. The protocol was approved by the committee of animal protection of Laval University and in vivo experiments were performed according to the Canadian committee of animal’s protection (CPA) rules. Mice were housed under laminar-flow filtered hoods in rooms maintained at 28°C with a 12:12 h light-dark cycle. Housing materials, food and water were sterilized before use. A schematic illustration of the experimental design is shown in Fig. 1A. Human endometrial tissue samples collected were placed in cold sterile PBS and dissected into small pieces (∼1 mm³) and labelled with 8 × 10⁻⁶ M carboxyfluorescein diacetate, succinimidyl ester (CFDA-SE, Invitrogen, Burlington, ON, Canada) diluted in PBS for 20 min at room temperature. Tissue fragments were washed twice in PBS and labelling was confirmed by fluorescence stereomicroscopy (Carl Zeis, Germany) equipped with a fluorescein isothiocyanate (FITC) filter to detect the fluorescence of CFDA SE at ex465/em535.

For induction of endometriosis mice, were given buprenorphine (1.68 g per mouse) by intradermal injection for analgesia, then anaesthetized with a mixture of oxygen (1:5:1) and isoflurane (3–4%) (Abbot Laboratories, Saint-Laurent, Quebec, Canada). A small (1 cm) cutaneous and peritoneal incision was made in a sterile environment, and 0.1 ml of PBS containing 13 CFDA-SE labelled endometrial tissue fragments were injected into the peritoneal cavity using a micropipette (Essentially, biopsy from 1 patient was chopped into 39 fragments). The incision was closed with Coated NB (polyglactin 910) sutures (Ethicon Johnson & Johnson, Markham, ON, Canada) for the cutaneous tissue and CFDA-SE labelled endometrial tissue fragments were injected into the peritoneal cavity using a micropipette (Essentially, biopsy from 1 patient was chopped into 39 fragments). The incision was closed with Coated NB (polyglactin 910) sutures (Ethicon Johnson & Johnson, Markham, ON, Canada) for the peritoneal tissue and MiRkon autoclip 9 mm (Clay Adam Brand, Sparks, MD, USA) for the cutaneous tissue. The mice did not receive any exogenous supply of estrogen and they were monitored daily for comfort, survival, and weight for 12 days after initial surgery. To manipulate FP receptors, the mice were treated with the FP agonist AL8810 ([SZ,13E]-9S,11,15R)-9,15-dihydroxy-11-fluoro-15-(2-indanyl)-16,17,18,19,20-pentanor-5,13-prostadienoic acid) (Cayman Chemical Company, Ann Arbor, MI, USA) (Griffin et al., 1999) or the FP receptor agonist Fluprostenol (Cayman Chemical Company) (Jin et al., 2006). On Day 12 mice were injected intra-peritoneally with AL8810 (5 mg/kg), Fluprostenol (0.15 mg/kg) (Jin et al., 2006; Glushakov et al., 2013) or PBS as a vehicle control. Additional daily
Figure 1 (A) Schematic illustration of the experiment design. Human endometrial tissue was inoculated into the peritoneal cavity of mice (n = 15; 13 fragments/mouse from one patient) using a micropipette and left for 12 days before starting treatment. On Days 12–19 AL8810, Fluprostenol or vehicle (PBS) was injected i.p. once a day (n = 5/group). (B) Representative images captured at time of cull from mice treated with AL8810, Fluprostenol or vehicle. Note presence of endometriotic lesions under bright field (arrows) and human tissue origin confirmed under fluorescence.
recovered and processed for RNA or histology as detailed below. The area of lesion was measured using ImageJ software by multiplying the maximum and minimum diameter of the lesion.

**RNA extraction and qRT–PCR**

Endometriosis lesions were dissected under fluorescence stereomicroscopy from the surrounding tissue and RNA was extracted with Trizol reagent (Invitrogen) according to the manufacturer’s instructions. The total RNA concentration was measured by using a NanoDrop spectrophotometer and then RNA was reverse transcribed using random hexamers. qRT–PCR was performed using an ABI 7000 Thermal Cycler (Applied Biosystems, Foster City, CA, USA). Each PCR reaction contained 2 μl of reverse transcriptase product, 0.5 μl of primer (final concentration, 0.1 μM), 12.5 μl of SYBR Green PCR Master Mix (Invitrogen) containing TaqDNA polymerase buffer, deoxynucleotide triphosphate mix, SYBR green I, MgCl₂, and TaqDNA polymerase. Primers were designed with Primer Premier 5 software to cross intron-exon boundaries, and specificity to human tissue was verified with Basic Local Alignment Search Tool (BLAST) (Table I). Samples were tested in duplicate, and, for each reaction, negative controls without RNA or reverse transcriptase, RNA from mouse tissue (negative control) and RNA from endometrial tissue (positive control) were added.

**Histology and immunohistochemistry**

Lesions were removed carefully and fixed in 10% formalin and then embedded into paraffin. Cryosections (5 μm) of paraffin embedded tissue sections were rehydrated and stained with haematoxylin and eosin. For immunostaining, endometriotic lesions were mounted on poly-l-lysine-coated microscope glass slides and immunostained as described previously (Rakhila et al., 2013). The primary antibodies used were anti-vWF (Dako, Burlington, ON, Canada) (A0082, 1:100) and anti-PCNA (Dallas, TX, USA) (sc-25280, 1:100). Tissue sections incubated without the primary antibody were included as negative controls. Secondary antibodies used were HRP-conjugated goat anti-mouse IgG Jackson (115-035-146) (1:2000 dilution in PBS/BSA/Tween) for PCNA and a biotin-conjugated goat anti-rabbit IgG (E0432, Dako) (1:2000 dilution in PBS/BSA/Tween) for vWF. Microphotographs were captured using the Image Pro Express program (Meyer Instrument, Houston, TX, USA).

**Statistical analysis**

Data related to the number and volume of lesions followed a nonparametric distribution and were analysed using Mann–Whitney U-test. Data related to the weight of mice and qRT–PCR followed a Gaussian distribution and were analysed using ANOVA and Bonferroni test (GraphPad Software, San Diego, CA, USA). Differences were considered as statistically significant using \( P < 0.05 \).

**Results**

**AL8810 and Fluprostenol treatments engender opposite effects on ectopic endometrial tissue growth**

The animals exposed to either AL8810 or Fluprostenol showed no signs of any discomfort or weight loss. The engraftment rate was similar in all control mice (5–6 implants survived out of 13 fragments) and was not patient dependent. At the time of lesion recovery endometriotic-like implants were found scattered throughout the abdominal cavity of the mice. Initial examination revealed that lesions were smaller in AL8810-treated mice compared with those in Fluprostenol and vehicle-treated mice (Fig. 1B). Histological evaluation of harvested lesions showed endometrial tissue composed of epithelial glands and compact stroma (Fig. 2A). In mice treated with AL8810, endometriotic tissue implants were small cystic structures with degenerating endometrial glands and scattered stromal cells, whereas in mice treated with Fluprostenol, endometrial tissue closely adhered to the host tissue and exhibited many well-defined, secretory and active endometrial glands and compact stroma. Mice treated with AL8810 developed fewer lesions and the lesions detected were smaller, compared with Fluprostenol-treated mice or control mice, which clearly had larger, more and well defined endometriotic lesions. Statistical analyses showed that the mean number and size of endometriotic lesions were significantly decreased in AL8810-treated mice, compared with vehicle-treated control mice (\( P < 0.001 \) and \( P < 0.01 \) respectively), but they were significantly increased in

<table>
<thead>
<tr>
<th>Gene</th>
<th>Forward primer (5’-3’)</th>
<th>Reverse primer(5’-3’)</th>
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<tr>
<td>Cox-1</td>
<td>GACCCGGCTCTCATCTCATAG</td>
<td>TTGGAACCTGGACACGGAACA</td>
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<tr>
<td>Cox-2</td>
<td>TCCCTTGGGTGTCAAAGGTAA</td>
<td>AAAACTGATGCTGGAAATGCTG</td>
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<td>mPGES-1</td>
<td>GAGTGCACCTTCTGCTTTC</td>
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<td>mPGES-2</td>
<td>CTATCAGCAGCAATGCCTAA</td>
<td>CACGCCACGCGCATA</td>
</tr>
<tr>
<td>cPGES-</td>
<td>AGCCTGCTTCTGCAAAGTGG</td>
<td>TCCCTGAGAACACTGAATG</td>
</tr>
<tr>
<td>AKR-1C3</td>
<td>TTATTTGGGATTTGGCAACCTA</td>
<td>CAACACTGCTCTCATTATTGAT</td>
</tr>
<tr>
<td>AKR-1B1</td>
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<td>CAACAAGGCGACGCCACCTC</td>
</tr>
<tr>
<td>15-PGDH</td>
<td>AAGCACAATGGAGGTAAGG</td>
<td>CCAACTATGCACTGTTGTA</td>
</tr>
<tr>
<td>MMP-9</td>
<td>TTGACAGGCGGAAGTGG</td>
<td>CCAACAGGAGGAGCCAGG</td>
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<td>TIMP-1</td>
<td>GAGAAGGGAAGGCGACTCTGGAAC</td>
<td>AAACCTATATCTCTTCTAGC</td>
</tr>
<tr>
<td>VEGF</td>
<td>GCTTACCTCCACATGCCA</td>
<td>CACCACTCCGTATGATTCTG</td>
</tr>
<tr>
<td>Bax</td>
<td>TCAACTGGGGGGGCTTGTC</td>
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<td>Bcl-2</td>
<td>GCCACACGCCCATCCAGCC</td>
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Fluprostenol-treated mice ($P < 0.01$ and $P < 0.001$ respectively) (Fig. 2B). Endometriosis lesions were found at several sites, including the peritoneum, intestines, peritoneal fat, liver and kidney. However, in AL8810-treated mice lesion development was limited only to the peritoneal fat.

**Expression of PGE2 and PGF2α biosynthetic and catabolic enzymes are altered by AL8810 and Fluprostenol treatments**

In lesions recovered from AL8810-treated mice, concentrations of COX2 mRNA were reduced compared with lesions from control mice ($P < 0.05$). Treatment with Fluprostenol significantly increased COX2 mRNA concentrations as compared with vehicle control ($P < 0.01$) (Fig. 3A). Concentrations of COX-1 mRNA was not altered by either treatment (Fig. 3B). The expression of the PGF2α biosynthetic enzyme AKR-1C3 was significantly decreased in lesions from AL8810-treated mice ($P < 0.01$), but was significantly increased following Fluprostenol treatment ($P < 0.01$) (Fig. 3C). However, the expression of AKR-1B1 did not show any significant changes in response to AL8810 or Fluprostenol (Fig. 3D). Analysis of specific PGE2 biosynthetic enzymes showed that mPGES-1 and mPGES-2 were down-regulated in lesions from AL8810-treated mice, but up-regulated in those from Fluprostenol-treated mice as compared with controls ($P < 0.05$, $P < 0.001$) (Fig. 3E and F). Concentrations of 15-PGDH mRNA, the catabolic enzyme of PGE2 and PGF2α, were significantly up-regulated in lesions from AL8810-treated mice ($P < 0.001$), but significantly down-regulated in lesions from Fluprostenol-treated mice ($P < 0.01$) as compared with controls (Fig. 3H).
AL8810 and Fluprostenol modulate the expression of tissue remodelling and angiogenic factors

We next assessed the expression levels of MMP-9, an important tissue-remodelling factor that is up-regulated in active endometriotic lesions in women (Weigel et al., 2012) and a mediator of PGF2α signalling pathway (Sales et al., 2005). Treatment of mice with AL8810 showed significantly down-regulated MMP-9 mRNA concentrations as compared with control (P < 0.05). In contrast, Fluprostenol treatment up-regulated MMP-9 compared with AL8810 (P < 0.01) (Fig. 4A). Our data further showed that AL8810 treatment, up-regulated mRNA concentrations of TIMP-1, a natural tissue inhibitor of MMP-9 (Brew and Nagase, 2010) as compared with vehicle control (P < 0.01), whereas
Fluprostenol treatment caused a down-regulation of TIMP-1 mRNA levels ($P < 0.01$) (Fig. 4B). We next assessed the expression of VEGF, a major angiogenic factor, that is up-regulated in human endometriosis lesions (Donnez et al., 1998). Data displayed in Fig. 4C showed that VEGF mRNA levels were significantly reduced in lesions from mice treated with AL8810 compared with vehicle-treated control mice ($P < 0.01$), but significantly increased in mice treated with Fluprostenol ($P < 0.05$).

### AL8810 and Fluprostenol alter the expression of survival/apoptotic factors in endometriotic lesions

As shown in Fig. 5, the mRNA expression level of Bax, a pro-apoptotic factor, was up-regulated in endometriosis-like lesions from AL8810-treated mice ($P < 0.01$), but was down-regulated in lesions from Fluprostenol-treated mice ($P < 0.001$) as compared with lesions from vehicle-treated control mice.

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**Figure 4** Real-time PCR analysis of the expression of MMP9 (A), TIMP1 (B) and VEGF (C) in endometriotic lesions. Lesions were harvested from mice treated with vehicle (control), AL8810 or Fluprostenol. mRNA levels were normalized to that of the house-keeping gene GAPDH. Results were from five control mice, five mice treated with AL8810 and five mice treated with Fluprostenol. Data are mean ± SEM. * $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$, respectively.

**Figure 5** Real-time PCR analysis of the expression of Bax (A) and Bcl-2 (B) in endometriotic lesions. Lesions were harvested from mice treated with vehicle (control), AL8810 or Fluprostenol. mRNA levels were normalized to that of the house-keeping gene GAPDH. Results were from five control mice, five mice treated with AL8810 and five mice treated with Fluprostenol. Data are mean ± SEM. * $P < 0.05$ and ** $P < 0.01$ respectively.
control mice treated with vehicle (Fig. 5A). Conversely, treatment with AL8810 showed a down-regulation of mRNA levels of the anti-apoptotic factor Bcl-2, while it was up-regulated in mice treated with Fluprostenol compared with AL8810 mice ($P < 0.05$) (Fig. 5B).

**Immunohistochemical analysis of proliferation and blood capillary formation**

Due to the limited number of endometriotic lesions from AL8810-treated mice, it was not possible to test every protein, so we focused on a few key processes. Immunolocalisation of PCNA, a marker of cell survival and proliferation (Yu *et al.*, 1991; Weigel *et al.*, 2012), showed that numbers of PCNA positive cells were decreased in AL8810-treated lesions but increased in Fluprostenol-treated lesions compared with controls (Fig. 6). We also immunolocalised vWF (Von Willebrand Factor), an endothelial cell marker (Zanetta *et al.*, 2000), and found that the density of microvessels was increased in lesions from Fluprostenol-treated mice, while it was difficult to detect vWF-positive cells in lesions from AL8810-treated mice (Fig. 7).

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**Figure 6** Representative immunohistochemical staining of PCNA in endometriotic lesions from Vehicle, AL8810 or Fluprostenol treated mice. Sections from proliferative phase of human endometrium were used as a positive control and the same sections incubated without the primary antibody were used as negative control for immunostaining; scale bar = 20 μm.
Discussion

In our study, we used a heterologous model of endometriosis to investigate the effect of in vivo manipulation of an FP-selective agonist (AL8810) and an FP-selective antagonist (Fluprostenol) on lesion size and the concentrations of key mRNAs within the human tissue. In control and Fluprostenol treated mice, the engraftment of lesions was found to occur throughout the peritoneal cavity attached to the intestine, kidney, liver and peritoneal wall while the lesions found in AL8810-treated mice were mainly found in peritoneal fat. Our data showed that AL8810 resulted in a marked diminution of the size and number of endometriosis-like lesions and significant changes in the mRNA expression of major molecular mediators of angiogenesis, tissue remodelling, apoptosis and PG biosynthesis, as well as inhibitory effects on markers of cell proliferation and development of microvessels in endometriotic implants. In contrast, Fluprostenol, had significant but opposite effects on these pathways and instead favoured cell proliferation, angiogenesis and the growth of endometrial implants.

Cumulative evidence supports a significant role for PGs in the pathophysiology of endometriosis. Our previous data showed distinct

Figure 7 Representative immunohistochemical staining of vWF in endometriotic lesions from, Vehicle, AL8810 or Fluprostenol treated mice. Sections from human endometrium were used as a positive control and the same sections incubated without the primary antibody were used as negative control for immunostaining; scale bar = 20 µm.
expression patterns of PG biosynthetic enzymes in ectopic and eutopic endometrial tissues of women with endometriosis and a marked increase in the expression levels of the rate-limiting COX2 and the specific terminal synthases for PGE2 (mPGES-1, mPGES-2 and cPGES) and PGF2α (AKR-1C3) in endometriotic lesions (Rakhila et al., 2013). This is consistent with findings from other studies (Ota et al., 2001; Matsuzaki et al., 2004; Sun et al., 2004), supporting an increase in local production of PGs in endometriosis tissue deposits. Elevated levels of PGE2 and PGF2α are also found in the peritoneal fluid of women with endometriosis (Dawood et al., 1984). Although well recognized as major mediators of pain and inflammation, PGs have also been shown to exert a wide array of biological functions and to possess direct and indirect growth-promoting, angiogenic and tissue remodelling effects (Ricciotti and Fitzgerald, 2011). Based on our evidence and that of other studies, we hypothesized that selective blockade of cell receptivity to PGs may represent an interesting treatment avenue for endometriosis. PGE2 has four known cognate receptors, namely EP1, EP2, EP3 and EP4, and recent studies have shown that targeting EP2 and EP4 may inhibit the growth and survival of human endometriotic cell in vitro (Lebovic et al., 2013). PGF2α has only one known cognate receptor, the F-series prostanoid (FP). Therefore, it is tempting to speculate that specific inhibition of PGF2α signalling via its specific receptor is more achievable as a potential therapeutic option.

Extensive cell proliferation, tissue remodelling and angiogenesis and aberrant apoptosis occur at the ectopic sites where endometrial tissue deposits develop into endometriotic lesions. In this study, AL8810 down-regulated the expression of Bcl-2, which would have favoured cell survival, and concomitantly up-regulated the expression of Bax, a key pro-apoptosis regulatory protein (Basu and Haldar, 1998). Meanwhile, the FP agonist Fluprostenol displayed opposite effects both on Bcl-2 and Bax expression. Taken together our data suggests that blocking PGF2α would favour cell death and endometriotic lesion regression. The finding of an increased expression of PCNA, a marker of cell proliferation (Yu et al., 1991), in the Fluprostenol-treated mice and a decreased expression of this marker in AL8800-treated animals is consistent with these data and suggests a plausible impact of FP antagonism on cell proliferation.

Recently, a novel pro-angiogenic role for PGF2α has been described in endometrial adenocarcinoma (Sales et al., 2005). This PG has been shown to activate inositol-1,4,5-triphosphate in autocrine and paracrine manners and thereby initiate ERK signalling via the activation of MMPs, transphosphorylation of epidermal growth factor receptor (EGFR) and release of VEGF, which promotes angiogenesis by acting on adjacent endothelial cells (Sales et al., 2004). The involvement of MMPs and VEGF in the growth and neovascularisation of endometriotic lesions is well documented. These molecules show an up-regulated expression locally in endometriotic lesions and peritoneal macrophages as well as in the uterine eutopic endometrial tissue. Their levels are also elevated in the peritoneal fluid of women with endometriosis (Donnez et al., 1998; Chung et al., 2002; Collette et al., 2006). Our study showed that specific blockade of PGF2α signalling using a specific antagonist of its receptor decreased the expression of VEGF and MMP-9 in endometriotic lesions. Beyond its well-known proteolytic activity, MMP-9 is endowed with a variety of biological functions. This gelatinase is involved in extracellular matrix remodelling in the early angiogenic phase of vascular bud and sprout formation (van Hinsbergh and Koolwijk, 2008) and plays an important role in tumourigenesis and tissue invasion (Hua et al., 2011).

MMP-9 shows an increased expression in both ectopic and eutopic endometrial tissues of women with endometriosis, according to our and other previous studies, acts as a potent mediator of inflammation (Bellehumeur et al., 2005) and may contribute to endometriosis progression and dissemination (Chung et al., 2002; Collette et al., 2006). Interestingly, treatment with AL8810 resulted in a parallel up-regulation of TIMP-1, a natural tissue inhibitor for MMP-9 (Brew and Nagase, 2010), which suggests the induction of a disequilibrium that may promote endometrial tissue invasion and growth within the host peritoneal tissue and the development of new blood vessels. In keeping with these findings, immunohistochemical analyses revealed that AL8810 effectively attenuated angiogenesis in endometriotic lesions, as indicated by a marked reduction in vWF-positive microvessels, and that Fluprostenol stimulated cell proliferation and capillary ingrowth.

In this study, we demonstrated that specific blockade of PGF2α-FP receptor signalling acted both upstream by inhibiting the expression of the rate-limiting enzyme COX2 and downstream by down-regulating the expression of the specific terminal synthases of PGF2α (AKR-1C3) and PGE2 (mPGES-1, mPGES-2 and cPGES). Furthermore, this was paralleled by a significant increase in the PG catabolic enzyme 15-PGDH, thereby suggesting a catabolic shift that we propose leads to a diminution of PG levels. Interestingly, selective activation of cell signalling using a specific FP receptor agonist led to opposite effects on the PGF2α and PGE2 biosynthesis pathways. Our data suggest that PGF2α-FP receptor signalling influences the biosynthesis of PGE2 and points to a mutual regulatory mechanism between PGF2α and PGE2. This is consistent with previous cell signalling studies showing reciprocal crosstalk between the FP receptor and PGE2 receptor EP2 in endometrial cells (Sales et al., 2008; Abera et al., 2010) and some evidence that PGF2α and PGE2 can both activate the FP receptor. Our findings further suggest that the PGF2α-FP receptor signalling promotes ectopic endometrial tissue growth and make plausible the involvement of PGF2α signalling.

One limitation of our model is that the success rate for implant survival was not high. One explanation could be that nude mice have lower levels of endogenous estrogen. It is also important to note that nude mice do not have T or B cells but they do possess NK cells and macrophages (Budzynski and Radzikowski, 1994) that can exhibit a partial immune response to clear foreign tissue.

Most current medical treatments of endometriosis inhibit the pro-proliferative impact of estrogens on ectopic lesions via suppression of ovarian steroidogenesis using oral contraceptives, aromatase inhibitors or gonadotrophin releasing hormone analogues. Although use of COX-2 inhibitors could be beneficial, their clinical application is of concern because of reported cardiovascular and gastro-intestinal side effects (Howes, 2007). Given the promising data obtained using our well validated mouse model, we speculate that selective inhibition of the action of PGF2α may represent an alternative targeted treatment for endometriosis.

Acknowledgements

The authors wish to thank Drs Karine Girard, Mathieu Leboeuf, Madeleine Lemyre and Marleen Daris for patient evaluation and for providing endometrial biopsies, and Dr Mahera Al-Akoum and Nathalie Bourcier for technical assistance. S.F.A. is grateful to Professor Philippa Saunders and Dr Erin Greaves for critical evaluation of the paper and assistance with revisions.


**Authors’ roles**

A.A. and S.F.A. designed the study. S.F.A. carried out the experiments and generated the data. A.A. supervised the experiments and data analysis and reviewed the first draft of the manuscript. S.F.A. and A.W.H. wrote the final manuscript.

**Funding**

This work was supported by grant MOP-123259 to the late Dr Ali Akoum from the Canadian Institutes for Health Research. The data analysis and preparation of this manuscript were supported by MRC Centre Grant G1002033.

**Conflict of interest**

None declared.

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