Estrogen-dependent up-regulation of TRPA1 and TRPV1 receptor proteins in the rat endometrium

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Abstract

Transient receptor potential ankyrin 1 (TRPA1) and vanilloid 1 (TRPV1) receptors expressed predominantly in sensory nerves are activated by inflammatory stimuli and mediate inflammation and pain. Although they have been shown in the human endometrium, their regulation and function are unknown. Therefore, we investigated their estrogen- and progesterone-dependent alterations in the rat endometrium in comparison with the estrogen-regulated inflammatory cytokine macrophage migration inhibitory factor (MIF). Four-week-old (sexually immature) and four-month-old (sexually mature) female rats were treated with the non-selective estrogen receptor (ER) agonist diethylstilboestrol (DES), progesterone and their combination, or ovariectomized. RT-PCR and immunohistochemistry were performed to determine mRNA and protein expression levels respectively. Channel function was investigated with ratiometric [Ca²⁺]ᵢ measurement in cultured primary rat endometrial cells. Both TRP receptors and MIF were detected in the endometrium at mRNA and protein levels, and their localizations were similar. Immunostaining was observed in the immature epithelium, while stromal, glandular and epithelial positivity were observed in adults. Functionally active TRP receptor proteins were shown in endometrial cells by activation-induced calcium influx. In adults, Trpa1 and Trpv1 mRNA levels were significantly up-regulated after DES treatment. TRPA1 increased after every treatment, but TRPV1 remained unchanged following the combined treatment and ovariectomy. In immature rats, DES treatment resulted in increased mRNA expression of both channels and elevated TRPV1 immunopositivity. MIF expression changed in parallel with TRPA1/TRPV1 in most cases. DES up-regulated Trpa1, Trpv1 and Mif mRNA levels in endometrial cell cultures, but 17β-oestradiol having ERα-selective potency increased only the expression of Trpv1. We provide the first evidence for TRPA1/TRPV1 expression and their estrogen-induced up-regulation in the rat endometrium in correlation with the MIF.

Keywords
- transient receptor potential ankyrin 1 and vanilloid 1
- macrophage migration inhibitory factor
- rat endometrium
- estrogen
- progesterone
- mRNA expression
- immunohistochemistry
- fluorescent calcium imaging
Introduction

Transient receptor potential ankyrin 1 (TRPA1) and vanilloid 1 (TRPV1) are non-selective cation channels predominantly localized in capsaicin-sensitive peptidergic sensory neurons and mediate pain and inflammation (Szallasi et al. 2007). TRPV1 or ‘capsaicin receptor’ is activated by noxious heat (>43°C), protons (pH>5.5), bradykinin, lipoxygenase products and anandamide produced during inflammation and tissue injury. TRPV1 is also expressed in the CNS (Szolcsányi 1988, Mezey et al. 2000) and in several non-neuronal cells in the skin, kidneys, lungs, testis, pancreas, spleen, cornea and uterus (Rocha et al. 2011, Liu et al. 2012, Song et al. 2012). Although the physiological/pathophysiological relevance of non-neuronal TRP is unknown, a cross-talk has been proposed between non-neuronal and neuronal TRP channels (Denda et al. 2010, Assas et al. 2014). Activation of non-neuronal TRPV1 in various cells results in mediator release with both physiological and pathological functions (Fernandes et al. 2012): activation of epidermal TRPV1 increases IL8 and prostaglandin E₂ (Southall et al. 2003), while TRPA1 induces IL1α and IL1β release (Nilius & Szallasi 2014).

TRPA1 is also activated by various chemical and physical stimuli, such as noxious cold (<17°C), allyl-isothiocyanate and cinnamaldehyde, as well as endogenous ligands including hydrogen peroxide, formaldehyde, methylglyoxal and acrolein produced during inflammation and tissue damage (Nagata 2007). The pathophysiological relevance of TRPA1 has been shown in inflammatory diseases of the respiratory, cardiovascular and gastrointestinal tracts. Similarly to TRPV1, functional TRPA1 was also described in enterochromaffin cells, synoviocytes, fibroblasts, melanocytes, pancreatic β-cells, epidermal keratinocytes, intestinal epithelial cells and macrophages, as well as human endometrial cells besides sensory neurons (Fernandes et al. 2012, Greaves et al. 2014).

Macrophage migration inhibitory factor (MIF) was originally identified as a T-cell-derived lymphokine (David 1966); it regulates immune responses and pain, but its specific receptor has not yet been identified. It is constitutively expressed by macrophages and T cells (Nishihiira 2000), neurons (Bacher et al. 1998), vascular endothelial cells and smooth muscle cells (Lin et al. 2000). A hormonal cycle-dependent expression of MIF was described in the human endometrium, which was elevated during the late proliferative and early secretory phases predominantly driven by estrogen (Yang et al. 2000, Kats et al. 2005, Akoum et al. 2006). MIF is also involved in human ectopic endometrial cell proliferation (Yang et al. 2000), and has been proposed a biomarker of endometriosis (Akoum et al. 2006). The two estrogen receptor (ER) subtypes ERα and ERβ respond similarly to some ligands, but there are also several receptor-specific activators and responses. These receptors are located in the nucleus and regulate the transcription of specific target genes by binding to associated DNA regulatory sequences. In the uterus, ERα is present similarly to the mammary gland, ovary and bone. By contrast, ERβ is found mainly in the prostate, bladder, ovary, colon, adipose tissue and the immune system. Both subtypes are markedly expressed in the cardiovascular and CNSs (Paterni et al. 2014). The synthetic compound diethylstilboestrol (DES) is a non-selective agonist, while 17β-oestradiol has an ERβ-selective agonist potency (Barkhem et al. 1998).

TRP channels have recently been described in the human endometrium, accompanied with estrogen/progestone-induced decidualization, where the TRP canonical 1 (TRPC1) channel has been shown to be up-regulated in vitro (Kumar et al. 2014). A member of the TRPV subfamily, TRPV6, is also present in the luminal and glandular epithelia of the human, rat, mouse and pig endometrium. TRPV6 has a cycle-dependent expression pattern in the mouse and human endometrium, and the maximal amount of Trpv6 mRNA was detected during the proliferative phase, or oestrus in the presence of high estrogen levels (Kumar et al. 2014).

Although TRPV1 and TRPA1 have been shown in the human eutopic and ectopic endometrium, their regulation and functional importance are not known (Wu et al. 2010, Liu et al. 2012, Song et al. 2012). Furthermore, there are no data regarding the link between ER activation and the expression of TRP channels and MIF in the normal endometrium related to different hormone levels. Animal models are important to precisely investigate their alterations during sexual maturation, the influence of estrogen/gestagen actions and ER-dependent mechanisms. Therefore, we aimed to describe the expression of TRPV1 and TRPA1 in the rat endometrium at mRNA and protein levels, as well as their hormone-dependent changes in correlation with the MIF.

Materials and methods
Ethics

All experimental procedures were carried out according to the 1998/XXVIII Act of the Hungarian Parliament on...
Animal Protection and Consideration Decree of Scientific Procedures of Animal Experiments (243/1988) and complied with the recommendations of the International Association for the Study of Pain. All experiments were approved by the Ethics Committee on Animal Research of Pécs University according to the Ethical Codex of Animal Experiments (licence: BA02/2000-11/2011).

Animals and treatments

Four-week-old and four-month-old female Wistar rats were bred and kept in the Laboratory Animal House of the Department of Pharmacology and Pharmacotherapy, University of Pécs. They were kept with a ratio of 12 h light:12 h darkness at 24–25 °C and had access to food and water ad libitum. Rats of both ages were implanted with s.c. bee wax pellets containing the synthetic estrogen analogue DES (100 μg, ~2 μg daily release), or were administered daily 2 mg s.c. progesterone (Sigma–Aldrich) dissolved in sesame oil for three consecutive days (n = 5/group) (Garai & Clark 1992). When given in combination, progesterone administration started 2 days after DES pellet implantation. In a separate group of mature rats (n = 5), ovariectomy was performed in order to investigate the effect of reduced endogenous hormone production. Samples were taken 10 days after completing the treatments; solvent-treated/sham-operated animals of the same age were used as controls.

Tissue preparation and analysis

Animals were killed under deep anaesthesia (sodium thiopental, 50 mg/kg i.p.; Sandoz, Kundl, Austria) and the uterus horns were harvested. The endometrium was scraped from the myometrium: one part was placed in RNA-Later solution (Sigma–Aldrich) and stored at −80 °C; the other one was fixed in 4% (v/v) paraformaldehyde, embedded in paraffin and sectioned for immunohistochemical analysis.

RNA extraction and quantitative real-time PCR

Total RNA was extracted using TRI Reagent (Molecular Research Centre, Inc., Cincinnati, OH, USA) and the Direct-Zol RNA isolation kit, and then treated with DNase I (both supplied by Zymo Research, Irvine, CA, USA) to remove genomic DNA. RNA was measured with a NanoDrop ND-1000 Spectrophotometer (NanoDrop Technologies, Inc., Wilmington, DE, USA). First-strand cDNA synthesis was carried out with 1 μg of total RNA/sample using the RevertAid H Minus First Strand cDNA Synthesis Kit (Thermo Scientific, Waltham, MA, USA) with oligo(dT)18 primers. Relative gene expression ratios were measured with Stratagene MX3000P QPCR System (Agilent Technologies, Santa Clara, CA, USA), using peptidyl-prolyl cis–trans isomerase A (Ppia) as the reference gene. Each reaction contained 2 μl of cDNA, 10 μl Luminaris Color HiGreen Low ROX qPCR Master Mix (Thermo Scientific), 0.3 μM primer and 6.8 μl water. The following primer pairs were used to amplify the target loci: Trpa1 (sense): 5-AGTGCGAAATGTGGAGCGATA-3 and (antisense): 5-TC CCGTCGATTCAGCAATG-3; Trpv1 (sense): 5-AATAC ACCATCGCTCTGT-3 and (antisense): 5-CAATGTCGA GTGCTGTCTGG-3; Mif (sense): 5-CACCATGCGCTA TGTTACTGTAACA-3 and (antisense): 5-GCCCGG CTCAGCAGGTGGAACCCTT-3 (Sun et al. 2005); inducible nitric oxide synthase (iNOS (Nos2)) (sense): 5-CAAGATGGCCCTGGAGAC-3 and (antisense): 5-TGATGCGATCTACAGCTCC-3; interleukin 1 beta (Il1b) (sense): 5-CCATTAGCTTGCCCTTGGGAG-3 and (antisense): 5-CAATCCACGAGTCACAGGAG-3; Ppia (sense): 5-GCAGAAAGTTCCAAGACAGC-3 and (antisense): 5-CCATTAGGCGTGTTGAAGTC-3. Amplification was carried out under the following conditions: 95 °C (10 min), followed by 40 cycles of 95 °C (15 s), 60 °C (45 s) and 72 °C (45 s). Measurements included a dissociation curve analysis to verify amplification specificity. Reactions were carried out in triplicate; relative expression ratios were calculated using MxPro QPCR Software (Agilent Technologies) with ΔΔCt method, using samples of untreated animals as a calibrator. Primer efficiencies were taken into account when calculating gene expression ratios (Pfaffl 2001).

Immunohistochemistry

Paraformaldehyde-fixed, paraffin-embedded samples were deparaffinized, rehydrated and incubated in acidic citrate buffer (pH 6) in a microwave oven for antigen recovery, and then treated with 3% hydrogen peroxide to quench endogenous peroxidase activity. After washing, the sections were incubated in normal blocking solution and treated with rabbit polyclonal anti-TRPV1 (Neuromics, Edina, MN, USA), anti-TRPA1 (Abcam, Cambridge, UK) and anti-MIF (Life Technologies) antibodies at a 1:1000 dilution. Incubation was performed with the EnVision system anti-rabbit secondary antibody conjugated with HRP (DakoCytomation, Carpinteria, CA, USA) and the reaction was visualized using 3,3-diaminobenzidine tetrachloride containing 0.01% hydrogen peroxide.
Primary cultures of rat endometrial cells

Primary endometrial cell cultures were prepared in order to test the functionality of TRPV1 and TRPA1 receptors by detecting agonist-evoked Ca\(^{2+}\) influx responses, as well as to determine their ER activation-induced expression regulations and correlation with the MIF. Four-week-old Wistar rats were decapitated under ether anaesthesia. Uteri were placed and cut into small strips in sterile incomplete Hank’s balanced salt solution (HBSS, Ca\(^{2+}\) and Mg\(^{2+}\) free, pH 7.4) containing 1 M HEPES, 2% antibiotic–antimyocotic solution and 1 M sodium hydroxide. Samples were placed in 10 ml HBSS containing 0.1% collagenase and 0.005% DNasel and incubated at 37 °C for 30 min, and the dispersed cells were digested with 0.01% trypsin and 0.005% DNasel at 37 °C for 5 min. Pellets were washed three times with HBSS and cultured in enriched DMEM (high glucose) containing 10% fetal bovine serum, 2% antibiotic–antimyocotic solution and 0.004% kanamycin (Kornyey et al. 2001). All chemicals were purchased from Sigma–Aldrich. Cells were pre-incubated for 18 h with the physiological concentration of 200 pM 17β-oestradiol (Herbison 2009) having relative selectivity to ER\(z\), and the same concentration of the non-selective ER\(z\) and ER\(\beta\) receptor agonist DES was used in our in vivo experiment (Barkhem et al. 1998).

After the calcium imaging measurements, cells were isolated from the plate by trypsin–EDTA diluted in incomplete HBSS, centrifuged at 700 g for 5 min, and then the pellet was resuspended in 600 μl RNA-Later solution (Sigma–Aldrich). Total RNA was isolated with TRI Reagent the same way as from the endometrial tissues. After DNase I digestion, the first-strand cDNA synthesis was performed from 5 ng of total RNA using the High-Capacity cDNA Reverse Transcription Kit (Applied Biosystems).

To evaluate the effects of chronic DES pretreatment in our in vitro cell culture, test the functionality of the TRP...
receptors, and find a direct link between the MIF cytokine and TRPA1/TRPV1, we made primary endometrial cell cultures from DES-pretreated (100 μg, w/≈2 μg daily release) and placebo-pretreated 4-month-old rats for 10 days (bee wax pellet without active ingredient). Sub-confluent phase of the cultured endometrial cells was treated for 24 h with 1 μg MIF/μl, 330 nM capsaicin and 3.3 mM formalin respectively and the relative gene expression ratios of Trpa1, Trpv1, iNOS and Il1b were measured by qPCR.

**Ratiometric technique of [Ca²⁺]ᵢ measurement**

Sub-confluent phase of the cultured endometrial cells was determined with phase-contrast microscopy on day 7. Uterine cells were digested with trypsin and placed in lysine-covered 24-well plates before the intracellular calcium ([Ca²⁺]ᵢ) measurement. Cultures were stained with the fluorescent Ca²⁺ indicator dye fura-2-AM, as described in detail previously (Szoke et al. 2010). [Ca²⁺]ᵢ measurement was done in extracellular solution (ECS) by fluorescence microscopy: ECS and the test solutions were given via separate tubes and rapid solution changes were controlled by the fast-step perfusion system. Fluorescence images were taken after illuminating the cells alternately at 340 and 380 nm light generated by a monochromator. The emitted light >510 nm was measured with Axon Imaging Workbench 2.1 (AIW) software. The fluorescence ratio F340/F380 was monitored (rate 1 Hz) continuously for up to 5 min and R values were generated by the AIW software. Baseline fluorescence was read from the period of recordings taken before exposing the cells to the TRPV1 agonist capsaicin (330 nM) or the TRPA1 agonist formalin (3.3 mM).

**Statistical analysis**

Values are expressed as mean ± S.E.M. of n = 5/group. For evaluating gene expression, analysis was performed by one-way ANOVA followed by Dunnett’s multiple comparison test. For the analysis of the semi-quantitative scoring of the immunohistochemical results, the non-parametric Kruskal–Wallis test with Dunn’s post-test was used. P ≤ 0.05 was considered statistically significant.

![Representative photographs of TRPA1 receptor-immunopositive areas in the rat endometrium. Immunostaining of (A) the untreated group compared with (B) DES-implanted, (C) progesterone-treated, (D) DES- and progesterone-treated and (E) ovariectomized groups, and (F) semi-quantitative scoring of TRPA1 immunopositivity in 4-month-old animals. Box plots with the whiskers represent the medians ± 25–75 percentiles of the score values (Kruskal–Wallis with Dunn’s post-test: *P < 0.05, **P < 0.005). Magnification: 200 ×. A full colour version of this figure is available at http://dx.doi.org/10.1530/JME-15-0184.](image-url)
Results

*Trpa1, Trpv1 and Mif* mRNA are expressed in the rat endometrium and up-regulated following estrogen treatment

To quantify the expression of TRPA, TRPV1 and MIF in the endometrium, we measured their relative mRNA levels by qPCR compared with the housekeeping gene *Ppia* showing the most stable expression in the uterus independently of age (Rajat et al. 2013; Supplementary Figure 1, see section on supplementary data given at the end of this article).

Relative *Trpa1* mRNA expression was significantly higher by about 8- and 2.5-fold in the endometrium of DES-treated rats compared with the untreated ones both in the sexually mature (4-month-old; Fig. 1A) and immature (4-week-old; Fig. 1D) groups. When progesterone was administered in combination with DES, this elevation was absent, and progesterone alone did not induce *Trpa1* mRNA increase in either age group (Fig. 1A and D). Although there was an increasing tendency after ovariectomy in mature rats, *Trpa1* mRNA levels did not significantly change compared with the intact controls (fold change 1.21).

Similarly to *Trpa1*, the relative expression of *Trpv1* also showed eight- and fivefold increases in response to DES treatment in the sexually mature (Fig. 1B) and immature (Fig. 1E) rats respectively. After combining DES with progesterone or administering progesterone by itself, no significant change was observed in *Trpv1* expression in either the young or older rats, and ovariectomy in the mature group did not significantly alter the expression levels in comparison with the intact (Fig. 1B and E) or sham-operated group (fold change 1.09).

DES induced a small, but significant 1.5- and 2.5-fold *Mif* up-regulation in the mature (Fig. 1C) and immature (Fig. 1F) rats respectively. This elevation was absent when progesterone was added to DES, and progesterone in either age group or ovariectomy in the sexually matured animals did not significantly change the expression of *Mif* mRNA (Fig. 1C and F; sham-operated 1.19-fold).

**TRPA1, TRPV1 and MIF proteins are localized in rat endometrial cells and up-regulated by hormones**

In the control endometrium of sexually mature rats, there is a weak to moderate TRPA1 staining of the surface epithelium and glands, with scattered, weak staining of stromal cells close to the surface (Fig. 2A). Similar pattern and staining intensity was observed in the immature endometrium (Fig. 3A). The mature endometrium displayed weak TRPV1 labelling restricted mostly to the epithelium (Fig. 4A). The immature endometrium showed...
no or minimal staining in the epithelial structures and no staining in the endometrial stroma (Fig. 5A). MIF showed moderate to strong staining in the endometrial glands and surface epithelium, while mild positivity was detectable in the stromal cells of both age groups (Figs 6A and 7A).

In sexually mature rats, all hormone treatments and ovariectomy equally elicited significantly increased intensity of TRPA1 immunopositivity in the epithelial layer and the glands (Fig. 2). In immature animals, DES treatment induced a considerable immunopositivity increase in the epithelium, while progesterone by itself and in combination with DES resulted in elevated positivity in the stroma near the epithelial layer when compared with the control group. However, only the combination treatment resulted in a statistically significant immunostaining intensity increase (Fig. 3).

In adult rats, TRPV1 immunopositivity was observed in the stroma and the glands with weak expression in the epithelium. DES and progesterone treatment caused significantly elevated immunopositivity in all areas; the combination resulted in a similar tendency, but ovariectomy did not alter the staining intensity (Fig. 4). In young animals, TRPV1 positivity significantly increased after DES and progesterone treatment in the stroma and the glands, while the epithelium showed weak expression (Fig. 5).

Weak MIF expression detected in the epithelial layer and the stroma in control adult rats was more intensive after all the treatments, but only progesterone administration resulted in a significant increase focally in the epithelium (Fig. 6). In immature animals, the weak MIF immunopositivity detected in the epithelium and the surrounding stroma increased in all cases, but reached the level of statistical significance after progesterone and combination treatments (Fig. 7). The endometrial thickness was measured in all the experimental groups in five different sections of each animal and then averaged. There were no significant differences in any treatment groups, although the variations of the results were greater in sexually premature animals (Supplementary Figure 2, see section on supplementary data given at the end of this article). Negative control slides where the primary antibodies were not applied showed lack of immunostaining (Supplementary Figure 3).

**Functional TRPA1 and TRPV1 receptors are expressed on cultured primary rat endometrial cells**

Both the TRPA1 agonist formalin (3.3 mM) and the TRPV1 activator capsaicin (330 nM) evoked a rapid Ca$^{2+}$ influx into the endometrial cells, providing functional...
evidence for the presence of functional receptor proteins. Capsaicin caused a rapid, transient Ca$^{2+}$ influx in the cytosol of epithelial cells as detected by the magnitude of the fluorescence response. The percentage of capsaicin-responsive cells was 10.84% (4 out of 37), and then after a 2 min wash period, the responses were reproducible. Formalin administration caused Ca$^{2+}$ influx, which developed after 30–60 s latency. The percentage of cells responding to formaldehyde was 13.5% (5 out of 37) (Fig. 8A and B). Original responses to the repetitive stimuli by capsaicin and formaldehyde are shown in Fig. 8C and D.

DES up-regulates Trpa1, Trpv1 and Mif mRNA in the primary cultures of rat endometrial cells

Pre-incubation of the primary rat endometrial cell cultures for 18 h with 200 pM of the non-selective ER$\alpha$/ER$\beta$ agonist synthetic compound DES used in our in vivo experiments induced 10-, 17- and 5-fold up-regulation of Trpa1, Trpv1 and Mif mRNA respectively. Meanwhile, 17$\beta$-oestradiol having ER$\alpha$-selective agonist potency evoked a remarkable increase (about fivefold) only in the expression of Trpv1 (Fig. 8E, F and G).

However, the intensity of the fluorescent calcium signals in the endometrial cells and the number of responsive cells to the TRPV1 agonist capsaicin or the TRPA1 agonist formalin was not altered after the pre-incubation with either DES or 17$\beta$-oestradiol (data not shown).

Chronic in vivo DES pre-treatment modulates MIF-induced Trpa1 and Trpv1 expression, as well as their activation-evoked iNOS and Il1b gene expression in endometrial cells

In the primary cultures of rat endometrial cells, a 24-h incubation with 1 $\mu$g MIF/$\mu$l induced an approximately threefold up-regulation of Trpa1 mRNA, but chronic (10-day-long) in vivo DES pretreatment caused a significantly greater increase (tenfold). MIF alone did not alter the expression of Trpv1 mRNA levels, but after chronic DES pretreatment, it caused a significant 2.5-fold elevation in comparison with the placebo-treated animals. TRPA1 stimulation with 3.3 mM formalin did not influence its own expression in the cells derived from the placebo-pretreated rats, but induced a significant 2.5-fold up-regulation after chronic in vivo DES pretreatment.
TRPV1 activation with 330 nM capsaicin resulted in a 30-fold increase of Trpv1 mRNA in the cells obtained from the placebo-pretreated animals, but a significantly greater increase (40-fold) in the endometrial cell cultures of the DES pretreated ones (Fig. 9A).

In endometrial cells obtained from the chronically DES-pretreated rats, TRPA1 (but not TRPV1) activation-induced iNOS mRNA up-regulation was significantly decreased, but both TRPV1 and TRPA1 stimulation-evoked Il1b mRNA increases were significantly reduced when compared with placebo pretreatment (Fig. 9B).

**Discussion**

The endometrium undergoes continuous dynamic changes, such as proliferation, differentiation, regeneration and disintegration, in response to fluctuating estrogen and progesterone levels modulated by peptide hormones, growth factors and cytokines produced locally by various cell types (von Wolff et al. 2000, Srisuparp et al. 2001). The well-established morphological and functional changes during the different phases of the hormonal cycle result from complex gene transcription alterations responsible for divergent molecular pathways, which are not yet fully understood.

The present study reports Trpa1 mRNA expression in the rat endometrium, and hormone-dependent up-regulation of TRPA1 and TRPV1 in correlation with the inflammatory cytokine MIF in both sexually immature and mature animals. The estrogen-induced TRPA1, TRPV1 and MIF increase suggests their potential roles in normal endometrial functions during the reproductive cycle, which might also be extrapolated to pathological conditions with pain and inflammation (Suzuki et al. 1996, Akoum et al. 2006, Liu et al. 2012).

We describe an estrogen-specific up-regulation of Trpa1/Trpv1 mRNA in the endometrium and also provide evidence for the functionality of these receptor proteins in cultured primary endometrial cells. Specific TRPA1/TRPV1 activation provoked an up-regulation of respective receptor mRNA in endometrial cell cultures. This can be a further evidence for receptor functionality, but a compensatory reaction to receptor desensitization cannot be excluded (Bito et al. 1998, Czikora et al. 2013). MIF administration also increased Trpa1/Trpv1 mRNA levels. Specific up-regulation of Trpv1 transcripts in isolated human leukocytes has been described in response to elevated serum MIF levels in a case study (Bachio et al. 2011), but we demonstrate the first functional evidence of MIF–TRP signalling augmented by the chronic estrogen
Specific TRPA1/TRPV1 stimulation resulted in the elevated levels of iNOS and Il1b mRNA, pointing to functional relevance of endometrial TRP channels. These mediators play roles in the local control of the endometrium during the normal hormonal cycle, e.g. vasodilation (NO) and pro-inflammatory responses during ovulation, pregnancy or inhibition of decidualization (IL1B) (Telfer et al. 1997, Mizuno et al. 1999, Wira et al. 2010). Moreover, both are released from ectopic endometrial cells upon TRPA1/TRPV1 activation (Greaves et al. 2014). Il1b and iNOS transcripts were down-regulated after TRPA1/TRPV1 activation in the cells obtained form the DES-pretreated animals. Transcriptional responses after prolonged effects of DES can reflect an estrogen-driven signalling and underlying gene expression patterns: MIF levels are cycle-dependent in the human endometrium (Kats et al. 2005), Il1b is down-regulated (Wira et al. 2010), while iNOS is regulated by estrogen action in a complex manner (Han et al. 2005).

TRPV1 mediates NO and IL1B release in human endometriosis (Hucho & Levine 2007, Liu et al. 2012). Stimulation of TRPV1 in rat C fibres is dependent on the oestrous cycle favouring oestradiol (Peng et al. 2008), and oestradiol may contribute to pain through TRPV1 regulation in the hippocampus (Wu et al. 2010). It exerts classical (slow, genomic) effects on Trpv transcription (Hoenderop et al. 2005) and can also directly or indirectly stimulate the TRPV1 receptor (Kumar et al. 2014). In contrast to mRNA, progesterone also increased TRPA1 and TRPV1 protein expression levels in the endometrium, possibly due to sensory neural expression, local translational/protein degradation differences or mRNA contribution of different cell types. Progesterone is also well known to mediate β2-adrenergic receptor transcription (Vivat et al. 1992) and eventually might have an indirect effect on TRPV1 signalling, but no direct modulation has been described so far (Kumar et al. 2014).

Ovariectomy resulted in increasing Trpa1/Trpv1 and Mif mRNA expression tendencies, and significant TRPA1 protein up-regulation in the endometrium. Reduced estrogen effects (e.g. after ovariectomy) up-regulate or stimulate TRPV1 and increase pain/hyperalgesia (Idris et al. 2010, Wu et al. 2010, Rossi et al. 2014). According to a well-proven explanation, high estrogen levels determine a female phenotype of signalling pathways downstream of the β2 adrenergic receptor, such as attenuated protein kinase A and Ca activities (Hucho & Levine 2007). Ovariectomy alleviates suppression of these
TRPV1 and MIF expression (Kastin et al. 2014). Ovariectomy also increases non-neuronal cell expression of TRPV1 and TRPA1 in the rat endometrium before and after the application of the TRPV1 agonist capsaicin (330 nM). Original recordings showing the responses induced by repetitive capsaicin and the TRPA1 agonist formalin (3.3 mM) stimuli. Relative gene expression of (E) Trpa1, (F) Trpv1 and (G) Mif mRNA after an 18-h administration of DES and 17β-oestradiol (n=4/group).

We demonstrated that MIF transcription is regulated by DES in the rat endometrium in parallel with Trpa1/Trpv1 mRNA levels. Its expression is mediated by estrogen levels, while ovariectomy also increases MIF expression. Beside its functions in innate immunity, MIF is a potent angiogenic, anti-apoptotic, proliferative and tissue remodelling factor (Calandra & Roger 2003) partly by acting on the CD74 receptor (Leng et al. 2003). It is expressed cycle-dependently in human endometrial epithelial and stromal compartments (Kats et al. 2005).

In order to assess the involvement of ERα and ERβ in the estrogen-driven up-regulation of these molecules, the protein kinases that are known to activate or sensitize TRPV1 (Goswami et al. 2011). This was described in neurons where reduced estrogen levels provoke pain/hyperalgesia (Idris et al. 2010, Wu et al. 2010, Rossi et al. 2014). Ovariectomy also increases non-neuronal TRPV1 and MIF expression (Kastin et al. 1992, Oshima et al. 2006, Emmerson et al. 2009, Idris et al. 2010, Wu et al. 2010, Kahnamoei 2012, Rossi et al. 2014). Endometrial cells express the β2 adrenergic receptor (Onatsouka et al. 2004, Bruzzone et al. 2005); therefore, it is reasonable to explain our ovariectomy-evoked results by this noradrenaline-dependent system.

Figure 8
(A and B) Representative transmitted light pseudocolour images of a rat endometrial cell before and after the application of the TRPV1 agonist capsaicin (330 nM). Original recordings showing the responses induced by (C) repetitive capsaicin and (D) the TRPA1 agonist formalin (3.3 mM) stimuli. Relative gene expression of (E) Trpa1, (F) Trpv1 and (G) Mif mRNA after an 18-h administration of DES and 17β-oestradiol (n=4/group).

Figure 9
Relative mRNA expression of (A) Trpa1 and (B) Trpv1 receptors, as well as (C) iNOS and (D) Il1b in the primary endometrial cell cultures derived from chronically DES-pretreated or placebo-pretreated rats in response to (A and B) 1 μg MIF/ml, (A, C and D) TRPA1 activation by 3.3 mM formalin or (B, C and D) TRPV1 stimulation by 330 nM capsaicin (n=4/group).

Fold changes represent respective mRNA levels normalized to the Ppaia as a housekeeping gene following the ΔΔCT method. Each column shows the ratio of relative gene expression (mean±s.e.m.; one-way ANOVA with Dunnett’s multiple comparison test: **P<0.005, ***P<0.0001). A full colour version of this figure is available at http://dx.doi.org/10.1530/JME-15-0184.
primary rat endometrial cell cultures were pre-incubated with the non-selective ERα/ERβ agonist synthetic compound DES in comparison with 17β-oestradiol having ERα-selective agonist potency. DES up-regulated Trpa1, Trpv1 and Mif mRNA in this in vitro system, similarly to our whole tissue results following the in vivo treatment. Meanwhile, only Trpv1 transcription increased in response to 17β-oestradiol, suggesting that ERβ might also play a role in the regulation of TRPA1, TRPV1 and MIF. Despite the marked up-regulation of these molecules, fluorescent calcium signal intensity and number of endometrial cells responsive to TRPV1/TRPA1 activation were not altered after pre-incubation with either DES or 17β-oestradiol. This might be due to intracellular calcium signals being regulated by several different mechanisms including the contribution of intracellular stores; therefore, this technique is less suited for quantitative analysis. Moreover, another possible explanation is that TRP receptors in the endometrium may play a role in signal transduction pathways similarly to Na+/K+−ATPase that is involved in the assembly of multiple protein complexes transmitting signals to different intracellular compartments (Xie & Cai 2003). Further studies are needed to determine this issue and draw a conclusion on the mechanism.

Based on literature data obtained in keratinocytes, synoviocytes, endometriosis cells and placenta (Cella et al. 2008, Fernandes et al. 2012, Liu et al. 2012, Nilius & Szallasi 2014, Wu et al. 2015), IL1A and IL1B, NO, prostaglandin E2, substance P, IL8 and matrix metalloproteinase-1 release can be proposed from endometrial cells upon TRPA1/TRPV1 activation/sensitization by estrogen. Beside their involvement in pain/inflammation, these mediators play physiological roles in reproductive, reparative and inflammatory-like processes of the normal endometrium (Curry & Osteen 2003, Goff 2004, Thippeswamy 2006, Wira et al. 2010).

Endometrial TRPA1 and TRPV1 receptors have an estrogen-regulated expression pattern similar to dorsal root ganglion primary sensory neurons innervating the area and also other cell types (Hoenderop et al. 2005, Greaves et al. 2014). This indicates that they might play a role in estrogen-evoked signal generation and transmission in conditions with altered sex hormone levels. Similarly to other TRP or cation channels of the endometrium (Ruan et al. 2014, Singh et al. 2015), TRPA1/TRPV1 may mediate homeostatic and barrier functions, Ca²⁺ signalling, cell proliferation/differentiation, endometrial receptivity, embryo implantation and sensory-immune interactions (Fernandes et al. 2012). Non-neuronal TRPV1 can also be activated by the endocannabinoid anandamide in the rat reproductive system (Cella et al. 2008, Scotchie et al. 2014).

These results are consistent with increased TRPA1 and TRPV1 expression in rat and human endometriosis demonstrated by our laboratory (unpublished results) and literature data (Hucho & Levine 2007, Ilie & Ilie 2013, Graham et al. 2015). Increased estrogen synthesis in endometriosis lesions makes those results comparable to these data. Furthermore, the TRP agonist endocannabinoids regulate the migration of endometrial stromal cells (Gentilini et al. 2010). TRPA1/TRPV1 in non-neural cells (stromal, glandular and epithelial cells) might have estrogen-mediated normal sensory, secretory and consequent inflammation-generating and pain-transmitting roles under pathological conditions. Although not investigated by the present study, non-neural TRP channels may amplify pain/inflammatory signals under pathological conditions as described in keratinocytes (Pang et al. 2015) and synoviocytes (Wu et al. 2015).

The present results provide the first evidence that i) functional non-neuronal TRPA1 and TRPV1 receptor proteins are expressed in the rat endometrium, ii) their expressions are regulated by estrogen and positively correlate with the oestrus cycle-dependent regulatory factor MIF, iii) MIF significantly increases TRPA1 and TRPV1 expression and iv) chronic estrogen action increases TRPA1/TRPV1 activation-induced iNOS and Il1b mRNA up-regulation being involved in endometrial homeostasis.
References


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