

# ER $\beta$ -dependent effects on uterine endothelial cells are cell specific and mediated via Sp I

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Submitted on October 28, 2012; resubmitted on April 16, 2013; accepted on April 24, 2013

**STUDY QUESTION:** What are the *in vitro* effects of estrogen receptor  $\beta$  (ER $\beta$ ) activation on the function of endothelial cells (ECs) from different vascular beds: human endometrial ECs (HEECs; endometrium), uterine myometrial microvascular ECs (UtMVECs; myometrium) and human umbilical vein ECs (HUVECs)?

**SUMMARY ANSWER:** Studies conducted *in vitro* demonstrate that the ER $\beta$  agonist 2,3-bis(4-hydroxy-phenyl)-propionitrile (DPN) has EC type-specific effects on patterns of gene expression and network formation. Identification of a key role for the transcription factor Sp I in ER $\beta$ -dependent signaling in uterine ECs offers new insights into cell-specific molecular mechanisms of estrogen action in the human uterus.

**WHAT IS KNOWN ALREADY:** Estrogens, acting via ERs (ER $\alpha$  and ER $\beta$ ), have important, body-wide impacts on the vasculature. The human uterus is an estrogen target organ, the endometrial lining of which exhibits physiological, cyclical angiogenesis. In fixed tissue sections, human endometrial ECs are immunopositive for ER $\beta$ .

**STUDY DESIGN, SIZE, DURATION:** Cells were treated with a vehicle control or the ER $\beta$  agonist, DPN, for 2 h or 24 h ( $n = 5$ ) followed by gene expression analysis. Functional assays were analyzed after a 16 h incubation with ligand ( $n = 5$ ).

**PARTICIPANT/MATERIALS, SETTING, METHODS:** Analysis of DPN-treated ECs using Taqman gene array cards focused on genes involved in angiogenesis and inflammation identified cell type-specific ER $\beta$ -dependent changes in gene expression, with validation using qPCR and immunohistochemistry. Molecular mechanisms involved in ER $\beta$  signaling were investigated using bioinformatics, reporter assays, immunoprecipitation, siRNA and a specific inhibitor blocking Sp I-binding sites. The endometrium and myometrium from women with regular menses were used to validate the protein expression of candidate genes.

**MAIN RESULTS AND THE ROLE OF CHANCE:** HEECs and UtMVECs were ER $\beta$ +/ER $\alpha$ -. Treatment of ECs with DPN had opposite effects on network formation: a decrease in network formation in HEECs ( $P \leq 0.001$ ) but an increase in UtMVECs ( $P \leq 0.05$ ). Genomic analysis identified opposite changes in ER $\beta$  target gene expression with only three common transcripts (*HEY1*, *ICAM1*, *CASP1*) in all three ECs; a unique profile was observed for each. An important role for Sp I was identified, consistent with the regulation of ER $\beta$  target genes via association with the transcription factor ('tethered' mechanism).

**LIMITATIONS, REASONS FOR CAUTION:** The study was mainly carried out *in vitro* using ECs of which one type was immortalized. Although the analysis of the protein expression of candidate genes was carried out using intact tissue samples from patients, investigations into *in vivo* angiogenesis were not carried out.

**WIDER IMPLICATIONS OF THE FINDINGS:** These results have implications for our understanding of the mechanisms responsible for ER $\beta$ -dependent changes in EC gene expression in hormone-dependent disorders.

**STUDY FUNDING/COMPETING INTEREST(S):** The study was funded by a Medical Research Council Programme Grant. E.G. is the recipient of an MRC Career Development Fellowship. The authors have nothing to disclose.

**Key words:** uterus / estrogen / endothelial / angiogenesis / Sp I

## Introduction

Estrogens have body-wide effects and are essential regulators of reproductive function in part by modulating key processes such as angiogenesis and inflammation (Smith, 2001; Jabbour *et al.*, 2009). Endothelial cells (ECs) that line the interior surface of blood vessels are believed to be direct targets for estrogen action. Notably, both positive and negative effects of estrogenic ligands (natural and synthetic) on vascular function have been reported. These include comparisons between the incidence of vascular disease in men and women (Farhat *et al.*, 1996; Vitale *et al.*, 2010), in women before and after the menopause (McCrohon *et al.*, 2000) and in women taking hormone replacement therapy (Yang and Reckelhoff, 2011). Angiogenesis is tightly regulated during development and in adulthood. In adults, physiological angiogenesis is a feature of reproductive tissues subject to cyclical remodeling in response to sex steroids (Jabbour *et al.*, 2006) and is an essential component of normal wound healing (Bao *et al.*, 2009). In contrast, aberrant angiogenesis is associated with disorders of the reproductive system (Smith, 2001) and with tumour growth and metastasis (Weis and Cheresh, 2011).

The human uterus contains two distinct tissue layers, the outer muscular myometrium and the inner multi-cellular endometrium. In a normal non-pregnant woman, both layers are exposed to cyclical variations in circulating concentrations of estrogens arising from ovarian activity (Abraham, 1974). The inner/luminal layer of the endometrium is shed at the time of menses and regeneration, followed by growth of new blood vessels, which is an essential feature of the estrogen-dominated proliferative phase (Nayak and Brenner, 2002). There have been conflicting reports of the impact of estrogenic ligands on endometrial angiogenesis (Girling and Rogers, 2005). The limited number of studies that have been carried out on purified cell populations suggest that estrogens may stimulate angiogenic activity of both endometrial (Kayisli *et al.*, 2004) and myometrial ECs (Zaitseva *et al.*, 2004), although the study on myometrial ECs included cells isolated from women with fibroids, a patient group in which endometrial function may be disturbed (Sunkara *et al.*, 2010).

In the uterus as in other tissues, estrogen action is mediated by receptors acting as ligand-activated nuclear transcription factors or as part of membrane-associated signaling cascades (Heldring *et al.*, 2007). Estrogen-dependent changes in gene expression can be mediated by binding of estrogen receptors (ERs) to DNA either directly via classical mechanisms at estrogen response elements (EREs), or through tethered (non-classical) associations with other transcription factors (e.g. Sp1, Jun/Fos), involving half EREs and GC-rich or AP-1 regions, respectively (O'Lone *et al.*, 2004). Human ERs are the products of two genes *ESR1* and *ESR2* that encode the ER $\alpha$  and ER $\beta$  proteins, respectively. These ER subtypes exhibit differential temporal and spatial expression patterns within reproductive tissues and these profiles have impacts on tissue function (Gibson and Saunders, 2012). ER $\alpha$  and ER $\beta$  have a similar arrangement of domains including a highly conserved DNA-binding domain and a ligand-binding domain (LBD; Matthews and Gustafsson, 2003). The LBD of both receptors has been crystallized and differences in the size/shape of the ligand-binding pocket have led to the development of synthetic subtype-selective ER agonists, examples include 4,4',4''-(4-propyl-(1H)-pyrazole-1,3,5-tryl)trisphenol (PPT, ER $\alpha$  selective) and 2,3-bis(4-hydroxy-phenyl)-propionitrile (DPN,

ER $\beta$  selective; Sun *et al.*, 2003). Ligand binding induces a conformational change in the receptor, unique to the ligand–receptor combination. The resultant 3D structure determines which co-regulatory proteins are bound to the complex; this can play an important role in determining whether target gene expression is augmented or abrogated (Nilsson and Gustafsson, 2010). Additionally, a number of anti-estrogens that block receptor activation have been developed, e.g. the anti-estrogen ICI 182780 (Fulvestrant), which functions as an estrogen receptor down-regulator, it binds ER $\alpha$  and ER $\beta$  with high affinity, blocks receptor dimerization and accelerates receptor degradation (Hermenegildo and Cano, 2000).

Studies on the relative contributions of ER $\alpha$  and ER $\beta$  to body-wide impacts of estrogens have revealed that ER $\alpha$  plays a key role in the regulation of cell proliferation and stromal–epithelial interactions and that co-expression of ER $\beta$  in ER $\alpha$ -positive cells can alter the pattern of gene expression (Gustafsson, 2003; Hewitt *et al.*, 2005).

Studies have shown that ECs behave in a vascular bed specific manner in response to locally derived signals (Rocha and Adams, 2009). This implies that studies conducted on EC function must be carried out on cells derived from the vascular bed of interest. As estrogen also exhibits tissue selective effects, the commonly used human umbilical vein EC (HUVEC) model could potentially be inappropriate to model uterine EC function. To date, there is little evidence as to the function of ER $\beta$  when it is the sole ER subtype present in cells. We have previously reported that endometrial ECs are ER $\beta$ + / ER $\alpha$ - (Critchley *et al.*, 2001) suggesting estrogen-dependent effects on their function are ER $\beta$  mediated.

The aim of the current study was to investigate the functional consequence of ligand-dependent ER $\beta$  activation in ECs from different compartments of the human uterus.

## Materials and Methods

### Cells and tissues

Three EC lines were used in the current study. The human endometrial ECs (HEECs; gifted from Yale University) were originally isolated from human endometrial microvessels using *Ulex europaeus* lectin (Schatz *et al.*, 2000). These cells were subsequently telomerase immortalized and a comparison between the primary and immortalized cells demonstrated that they retained an identical phenotype including the expression of CD31, von Willebrand's factor and the Tie-2 receptors (Schatz *et al.*, 2000; Krikun *et al.*, 2005a). Primary uterine myometrial microvascular ECs (UtMVECs) were obtained from Lonza (Walkersville, USA); these cells are guaranteed through 15 population doublings and sold as CD31 / 105 and von Willebrand Factor VIII positive. HUVECs (gifted from T. Ramaesh, University of Edinburgh) are commercially available primary ECs that are widely used for cell-based research into factors regulating EC function. HUVECs were included in the current study as a control (non-uterine) EC. All ECs were maintained in endothelial growth media (EGM-2) (Lonza) supplemented with 10% fetal calf serum (FCS) in flasks coated with attachment factor (Gibco, Paisley, UK). Ishikawa cells (endometrial adenocarcinoma cell line; European collection of cell cultures (UK) were maintained in Dulbecco's modified eagle's medium (Gibco) supplemented with 10% FCS, 2 mmol/l, L-Glutamine, antibiotics and non-essential amino acids. Cells were cultured at 37°C with 5% CO<sub>2</sub>; at least 24 h prior to experiments, medium was changed to phenol red-free media with 10% charcoal stripped FCS. Cells were stimulated with 10<sup>-8</sup> M 17 $\beta$ -estradiol (E2; Sigma, UK), the ER $\alpha$ -selective agonist PPT

(Tocris, Bristol, UK) or the ER $\beta$ -selective agonist DPN (Tocris) alone or in combination with the anti-estrogen Fulvestrant—ICI 182 780 (ICI;  $10^{-7}$  M; Tocris) dissolved in dimethylsulphoxide (DMSO). Full-thickness uterine biopsy material used for immunohistochemistry (IHC) was obtained as previously described (Critchley et al., 2001).

## Immunodetection

Immunocytochemistry was carried out on cells grown on chamber slides. Cells were fixed in ice-cold methanol for 10 min and then permeabilized in a blocking solution containing 0.2% IGEPAL (Sigma-Aldrich). Non-specific binding sites were blocked with a species-specific blocking solution [1:5 part normal serum in Tris-buffered saline (TBS)/5% bovine serum albumin (BSA)] for 30 min. Endogenous streptavidin and biotin were blocked using a kit available from Vector Laboratories. Primary antibodies were diluted in blocking solution (Supplementary data, Table S3) and incubated overnight at 4°C. Biotinylated secondary antibodies (1:500) were diluted in 5% BSA in TBS and incubated at room temperature (RT). A streptavidin–HRP conjugate (1:1000; Sigma-Aldrich) was diluted in TBS and used for incubation at RT for 30 min followed by visualization with ImmPACT™ DAB peroxidase substrate (Vector Laboratories). Cells were counterstained, dehydrated, cleared in xylene and mounted in Pertex.

IHC was carried out on paraffin-embedded full-thickness uterine sections. Sections were dewaxed in xylene and rehydrated to water. Citrate antigen retrieval was performed followed by endogenous peroxidase block with 3% H<sub>2</sub>O<sub>2</sub> in methanol. Streptavidin–biotin block (Vector Laboratories) was carried out followed by species-specific block and incubation with primary antibody overnight. Secondary antibody detection and counterstaining were performed as above. For full-thickness sections, tiling was carried out using Axiovision for Axiovert (Carl Zeiss). Dual immunofluorescence on paraffin-embedded full-thickness uterine sections was achieved by dewaxing and rehydrating sections as before, then the antigen retrieval and peroxidase block were performed followed by species-specific block. All washes were carried out in PBS for fluorescent methods. Primary antibody was diluted in blocking solution and incubated overnight at 4°C. A secondary F(ab) polyclonal antibody to IgG (HRP) was diluted in blocking solution and incubated on sections for 30 min at RT. All subsequent washes included a single wash with PBS containing 0.05% Tween and then a wash in PBS. Antibody detection was carried out using a TSA™ system kit labelled with either Cy3 (red) or fluorescein (green; Perkin Elmer, Inc.) diluted 1:50 for 10 min. For the detection of the second protein of interest, sections were microwaved for 2.5 min in boiling citrate buffer, an additional species-specific block was carried out and the second primary antibody was applied overnight at 4°C. The secondary antibody was detected as before with the appropriate TSA system and sections were counterstained with DAPI (1:500) for 10 min. Slides were mounted in Permafluor (Thermo Fisher Scientific) and imaged using an LSM710 confocal microscope and AxioCam camera (Carl Zeiss, Inc.).

ER proteins were detected using a mouse monoclonal raised against a peptide present at the C-terminus of full-length wild-type ER $\beta$  (ER $\beta$ 1; Serotec, Kidlington, UK) but absent from splice variants of human ER $\beta$  (ER $\beta$ 2, ER $\beta$ 5; Critchley et al., 2002) and a mouse monoclonal specific for ER $\alpha$  (Vector, Peterborough, UK). CD31 protein was detected using a mouse monoclonal anti-CD31 (Dako, Cambridgeshire, UK). Candidate proteins were detected using a rabbit polyclonal anti-IFN $\beta$ 1 (Epitomics, CA, USA) and a rabbit monoclonal ICAM1 (Abcam, Cambridge, UK). More details on antibody dilutions are available in Supplementary data, Table S3.

## RNA extraction and cDNA synthesis

Total RNA was extracted at 2 or 24 h post-stimulation with ligand using the RNeasy kit (QIAGEN, Crawley, UK) and cDNA was synthesized using

SuperScript®VILO™ (Invitrogen, Paisley, UK) with a starting template concentration of ~100 ng RNA.

## Quantitative real-time PCR

Taqman array cards (TACs) for angiogenesis and inflammation gene signatures (Applied Biosystems, CA, USA) were analyzed according to the manufacturer's instructions using Taqman® Universal PCR mastermix (Applied Biosystems). Additional real-time PCR reactions were performed using the Roche Universal ProbeLibrary (Roche Applied Science, West Sussex, UK) and Express qPCR Supermix (Invitrogen). qPCR was performed on a 7900 Fast Real-Time PCR machine with 18S as the endogenous control. Primer sequences can be provided on request. Bioinformatics analysis was carried out using Metacore™ (GeneGo.Com).

## Western blot analysis

Nuclear protein was prepared using a Nuclear Extract Kit (Active Motif, CA, USA) separated on a NuPAGE® Bis-Tris Gel (Invitrogen), transferred onto polyvinylidene fluoride (PVDF) membranes (Millipore) and probed with the following antibodies: mouse polyclonal anti-ER $\beta$  (Santa Cruz Biotechnology, CA, USA), mouse monoclonal anti-ER $\alpha$  (Vector), mouse monoclonal anti-Sp1 (Abcam), rabbit polyclonal anti-Lamin  $\beta$ 1 (Abcam) or mouse monoclonal anti-Lamin  $\beta$ 1 (Abcam). For secondary detection, goat anti-mouse IgG (Alexa fluor IR 680, Invitrogen Molecular Probes) and goat anti-rabbit IgG (IR Dye 800 CW, LI-COR, NE, USA) were used at 1:10 000 dilution. Antibody binding was visualized using infra-red imaging on an Odyssey imaging system (LI-COR).

## Network formation assay

ECs were plated at 25 000 cells per insert into transwells coated with phenol red-free growth factor reduced Matrigel (BD Biosciences, Oxford, UK). Where appropriate, the pure anti-estrogen Fulvestrant/Faslodex® (ICI) was added into the upper chamber of media 1 h before the addition of ligands. All ligands were added to the bottom chambers and cells were incubated for 16 h at 37°C with 5% CO<sub>2</sub>. To block binding of Sp1 to GC regions, we used Mithramycin A (50 nM; Sigma). Cells were fixed in ice-cold methanol for 20 min and briefly stained with haematoxylin. The formation of networks was visualized using an Axiovert microscope (Carl Zeiss, Germany), where three independent fields of vision were captured at  $\times 5$  magnification for each well. Network formation was quantified using ImageJ (NIH.gov) software, with images converted to binary and the area of networks analyzed using the 'count particles' option. Results were verified by counting the number of closed polygons. The mean number of polygons per well was calculated, followed by the mean for each treatment. The fold change compared with the vehicle control was plotted.

## Immunoprecipitation

Total cell protein was extracted from HEECs treated with DMSO or DPN ( $10^{-8}$  M) for 24 h. Immunoprecipitations were performed using Dynabeads protein G (Life Technologies) following the manufacturer's instructions with anti-ER $\beta$  (Abcam) or rabbit IgG (Dako) as the control. Antibodies were cross linked to the Dynabeads using BS3 (Thermo Fisher Scientific) and samples incubated with the cross-linked complex overnight at 4°C. The input and immunoprecipitated proteins were resolved by SDS–PAGE electrophoresis and transferred onto PVDF membranes. Complexes containing Sp1 were detected by incubating membranes with mouse anti-Sp1 (Abcam) at 1:300 dilution and analyzed using the LICOR system as described above.

## siRNA knockdown

ECs were transfected with a non-specific siRNA (negative) or a synthetic siRNA directed to ER $\beta$  or Sp1 (Ambion, Paisley, UK) at a final concentration

of 5 nM using HiPerFect transfection reagent (QIAGEN). At 48 h after transfection, cells were treated with ligand and harvested at 2 or 24 h post-treatment. Depletion was confirmed by qPCR.

## Proliferation assay

ECs were plated into 96-well plates at 3000 cells/well and allowed to adhere overnight. Cell medium was replaced with EGM-2 1% charcoal stripped FCS for 3 h, followed by addition of ligands. Treatments were replaced three times during the 72 h culture period. To assess proliferation, medium was removed and replaced with a 1:5 ratio of CellTiter96Aqueous One Solution Proliferation Reagent (Promega) and EGM-2 1%. After a 3 h incubation, the formation of formazan was recorded by measuring the absorbance at 490 nm.

## Luciferase reporter assays

Cells were plated at  $1 \times 10^5$  per well into 24-well plates and left to adhere overnight; for each luciferase experiment, a corresponding control plate was set up allowing the analysis of protein levels for normalization. Cells were infected with an adenoviral 3 $\times$  ERE luciferase construct (in house development) with a multiplicity of infection of 50, with 6  $\mu$ g/ml Polybrene (Sigma). For the adenoviral system, 24 h after incubation, cells were stimulated with ligands ( $10^{-8}$  M). Whole cell lysates were harvested 24 h after the addition of ligand with Glo Lysis buffer (Promega). Lysates were transferred to luminometer plates and a 1:1 ratio of Bright-Glo reagent (Promega) was added. Luminescence was measured using a Fluostar OPTIMA plate-reader (BMG Labtech). Analysis of corresponding plates was analyzed for protein concentration using the DC protein assay (Bio-Rad), and reporter gene expression was corrected by protein levels.

## Statistical analysis

Statistical analysis was carried out using a one-way analysis of variance followed by a Neuman–Keuls post-comparison test or a two-tailed unpaired Student t-test. For qPCR data, statistical analysis was carried out on transformed data. \* $P < 0.05$ , \*\* $P < 0.01$  and \*\*\* $P < 0.001$ .

## Ethical approval

In brief, a full-thickness uterine biopsy material was collected from women undergoing hysterectomy. Written informed consent was provided by all subjects and ethical approval for tissue collection was granted by the Lothian research ethics committee. Patients had regular menstrual cycles and were not taking exogenous hormones.

## Results

### Uterine ECs express ER $\beta$ but not ER $\alpha$

To extend and confirm our previous observations, we used dual fluorescent IHC to co-stain full-thickness uterine samples for ER $\beta$  and the EC marker CD31. ER $\beta$  and CD31 were co-localized in ECs within the endometrium and myometrium at all stages of the menstrual cycle (Fig. 1A and B). Myometrial ECs appeared immunonegative for ER $\alpha$  even when closely adjacent cells were CD31+ (Fig. 1C and D; [Supplementary data, Fig. S1A](#)). Eight patient samples were analyzed in detail (four proliferative stage and four secretory stage), all vessels were examined in each section of the myometrium and no CD31-positive cells were found to express ER $\alpha$ . ER $\beta$ + ECs were readily detectable in all uterine layers ([Supplementary data, Fig. S1B](#)). Cells derived from microvascular beds of the human endometrium (HEECs; [Schatz et al., 2000](#); [Krikun et al., 2005a,b](#)), myometrium (UtMVECs) and HUVECs were

characterized to confirm their EC phenotype ([Supplementary data, Fig. S2](#)). All EC models were ER $\beta$ + / ER $\alpha$ - at the level of mRNA (Fig. 1E) and protein (Fig. 1F). Ishikawa cells were used as an ER $\alpha$  expressing control to validate our antibodies and primers. These comprehensive profiling studies confirmed that uterine ECs recapitulated the pattern of expression of ERs in their native vascular beds.

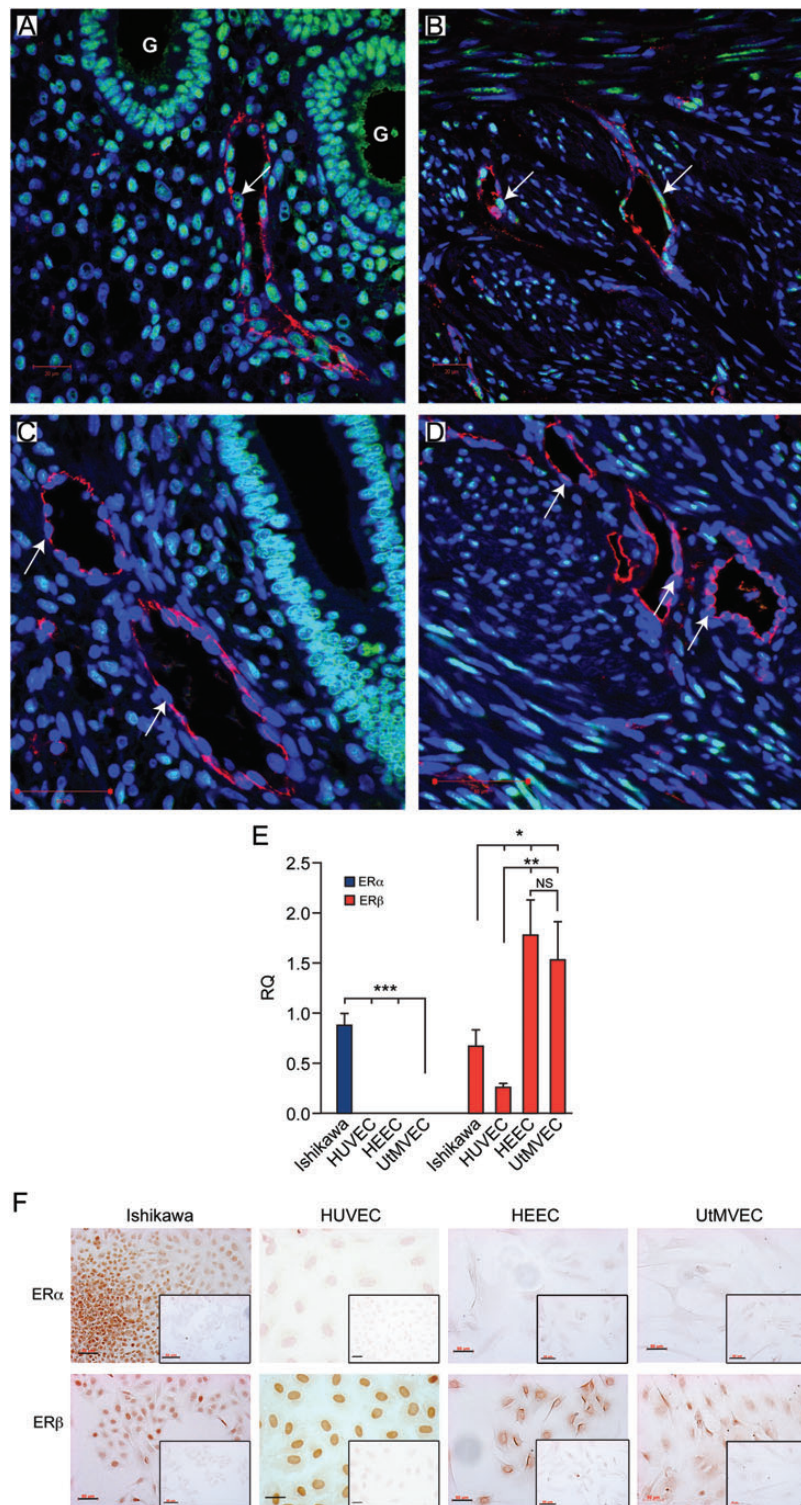
### A selective ER $\beta$ agonist has an endothelial subtype-specific impact on angiogenesis

An *in vitro* model of angiogenesis (the network formation assay) was used to compare the impacts of E2 and the ER $\beta$ -selective agonist DPN on endothelial function. These studies revealed striking opposite impacts of DPN on HEECs and UtMVECs with a significant decrease in the amount of networks formed by HEECs (Fig. 2A;  $n = 6$ ,  $P \leq 0.001$ ) and a significant increase in UtMVECs (Fig. 2B;  $n = 6$ ,  $P \leq 0.05$ ). In both, the effect was abrogated by the addition of the pure anti-estrogen Fulvestrant (ICI) and surprisingly the same concentration of E2 had no significant impact. In HUVECs, we found that E2 and DPN had no significant impact on network formation compared with the vehicle control; however, there was a significant decrease in network formation when cells were treated with ligand plus ICI (Fig. 2C;  $n = 6$ ,  $P \leq 0.01$  and  $P \leq 0.001$ ). In HEECs and HUVECs, treatment with DPN or E2 increased cell proliferation ([Supplementary data, Fig. S3A and C](#)); the changes observed in UtMVECs were not significant ([Supplementary data, Fig. S3B](#)).

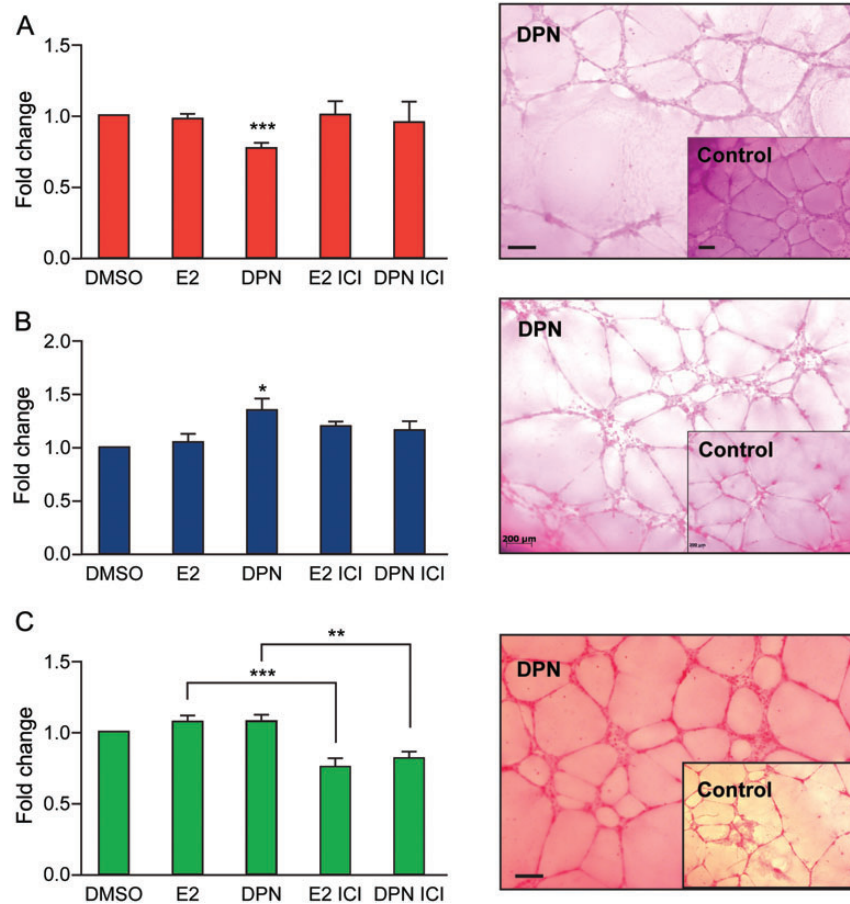
### The ER $\beta$ -selective agonist DPN induces specific patterns of gene expression in ECs derived from different vascular beds

Using targeted gene arrays, we compared changes in the expression of genes implicated in the regulation of angiogenesis and inflammation in response to treatment with DPN between uterine ECs and a widely used EC model (HUVECs). DPN was used in TAC studies because this subtype-selective ER agonist produced the most profound effect in the above functional studies. We used two time points (2 and 24 h) to encompass both an early and later response to ER $\beta$  activation in cells. Analysis of RNA recovered from cells incubated with or without ligand at both time points resulted in the identification of significant ( $> 1.5$ -fold) changes in 22 of 92 genes associated with angiogenesis (Fig. 3A;  $n = 3$ ) and in 14 of 92 genes associated with inflammation (Fig. 3B;  $n = 3$ ) as analyzed using TAC. The complete lists of differentially regulated genes in each cell type are given in [Supplementary data, Tables S1 and S2](#). Notably, there were very few ER $\beta$ -dependent genes common to more than one of the three cell lines and several of the shared ER $\beta$ -dependent genes identified were regulated in opposite directions in HEECs and UtMVECs ([Supplementary data, Table S1, Fig. 4](#)). Analysis of the angiogenesis gene set revealed that only the expression of *HEY1*, a transcriptional repressor part of the Notch signaling family was altered in response to DPN (24 h) in all three EC lines (Fig. 3A). Two other genes were regulated in HEECs and UtMVECs but not in HUVECs; these were interferon  $\beta$ -1 (*IFNB1*) and autotaxin/ectonucleotide pyrophosphatase/phosphodiesterase 2 (*ENPP2*). Analysis using the inflammation TAC array revealed two ER $\beta$ -dependent transcripts common to all three ECs: intercellular adhesion molecule 1 (*ICAM1*, CD54) and Caspase 1 (*CASP1*); these were significantly changed after 2 h in HEECs and 24 h in UtMVECs and HUVECs. We also observed





**Figure 1** ER $\beta$ , but not ER $\alpha$ , is expressed in ECs in both the endometrium and myometrium and *in vitro* models retain the original phenotype. (**A** and **B**) Dual immunofluorescent staining for ER $\beta$  (green) and CD31 (EC marker; red) was carried out on full-thickness uterine biopsies at different stages of the menstrual cycle. Co-localization was observed in vessels in the endometrium (A) and myometrium (B). Arrows indicate ECs. G, Gland. Scale bar is 20  $\mu$ m. (**C** and **D**) Dual immunofluorescent staining for ER $\alpha$  (green) and CD31 (red) carried out on full-thickness sections at different stages of the menstrual cycle. ECs were negative for ER $\alpha$  in the endometrium (C) and myometrium (D). Scale bar is 50  $\mu$ m. (**E**) mRNAs encoding wild-type ER $\beta$  (ER $\beta$ 1) and ER $\alpha$  were both detected in human adenocarcinoma cells (Ishikawa) but all three EC lines, HEECs, UtMVECs and HUVECs, only contained measurable concentrations of ER $\beta$  mRNAs. Values represent the mean  $\pm$  SEM analyzed in triplicate from three separate experiments. Results are normalized to Ishikawa cells, where one replicate was given the arbitrary value of 1. RQ, relative quantification (\* $P$  < 0.05, \*\*\* $P$  < 0.001). (**F**) Immunolocalization of ER $\alpha$  and ER $\beta$  I carried out on cell lines grown on chamber slides—note only Ishikawa cells were ER $\alpha$ +. ER $\beta$  was localized to cell nuclei in all cell types. Negative controls with primary antibody omitted are shown as insets. Bar = 50  $\mu$ m.



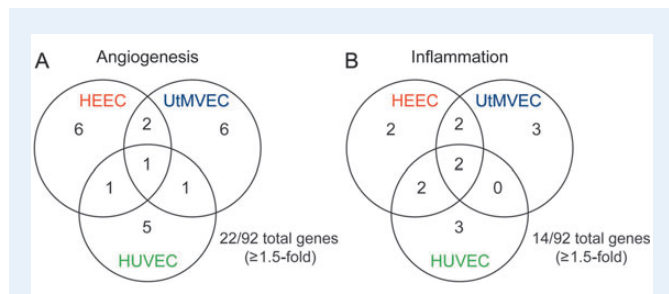
**Figure 2** ER $\beta$  activation has specific and opposing effects on endometrial and myometrial EC function. (A, B and C) Cells were plated onto growth factor reduced matrigel and incubated with E2 or DPN ( $10^{-8}$  M) in the presence or absence of the pure ER antagonist (ICI;  $10^{-7}$  M). The impact on network formation in HEECs (A), UtMVECs (B) and HUVECs (C) was analyzed after 16 h. Images show representative photos taken from wells treated with DPN (large images) or DMSO (inset) illustrating differences in the formation of networks. Scale bars are 200  $\mu$ m. Values represent the mean  $\pm$  SEM from five separate experiments (\* $P$ <0.05, \*\* $P$ <0.01, \*\*\* $P$ <0.001).

particular trends present within the data set. For example, genes associated with prostaglandin synthesis were regulated in all three ECs. Although this common pathway was found, common genes within the pathway were not (Supplementary data, Table S2). To summarize, only one gene associated with angiogenesis and two genes associated with inflammation were regulated by DPN in all three EC lines. Interestingly, we found that the pattern of expression of angiogenic genes correlated with our functional studies. For example, in HEECs, we observed an overall down-regulation in pro-angiogenic factors but an up-regulation in angiogenesis inhibitors (Supplementary data, Table S1). This correlated with our observed decrease in network formation in response to DPN. However, in the UtMVECs, we observed an up-regulation in pro-angiogenic factors and a down-regulation in inhibitors in response to DPN, correlating with an increase in network formation.

To complement and extend the data gathered using the TAC arrays, qRT-PCR validation experiments were carried out using additional cultures of all three EC lines treated with DPN alone, DPN plus ICI, E2 alone, E2 plus ICI or the ER $\alpha$ -selective agonist PPT ( $n = 5$ ; Fig. 4, Supplementary data S4 and S5). Changes in the expression of *HEY1* detected

using TAC in response to DPN were confirmed using qRT-PCR in HEECs (significantly reduced) and UtMVECs (significantly increased). In all cases, inclusion of ICI abrogated the change observed and inclusion of PPT had no impact consistent with the lack of expression of ER $\alpha$  in these cells (Supplementary data S4A). Treatment of cells with E2 induced the same changes as DPN in UtMVECs and HUVECs but were opposite (increased expression) in HEECs (Supplementary data S4A). qRT-PCR analysis of *IFNB1* expression confirmed TAC results in HEECs (significantly up-regulated by DPN or E2 at 24 h). In UtMVECs, validation confirmed significant down-regulation of *IFNB1* by E2 but not by DPN (Supplementary data S4B). In HUVECs, *IFNB1* was significantly up-regulated following incubation with DPN or E2 for 24 h (Fig. 4B, Supplementary data S4B); this had not initially been detected using the TAC array. We were, therefore, able to recapitulate results gained using TAC (angiogenesis) in additional experiments, with the exception of *IFNB1* in UtMVECs that was regulated by E2 alone and not DPN.

Confirmation of expression of *ICAM1* in HEECs, UtMVECs and HUVECs in response to E2 or DPN as detected by qRT-PCR revealed



**Figure 3** Incubation of ECs with DPN results in altered expression of distinct subsets of genes in ECs derived from different vascular beds. HEECs, UtMVECs and HUVECs were incubated with media containing vehicle alone (control, DMSO) or DPN ( $10^{-8}$  M in DMSO) for 2 or 24 h. A sample size of two from three separate experiments was generated for each time point and cell line; all samples were analyzed in parallel on TAC. Only genes that were subject to a statistically significant change following the treatment with DPN were reported. **(A)** Venn diagram representing ER $\beta$ -dependent genes associated with angiogenesis. **(B)** Venn diagram representing ER $\beta$ -dependent genes associated with inflammation. Diagrams represent the sum of all up- and down-regulated genes that showed statistically significant changes at 2 or 24 h post-stimulation. Full gene lists are supplied in [Supplementary data, Tables S1 and S2](#). TAC, TaqMan array cards.

additional time dependent but similar impacts of DPN and E2, no significant response to PPT and abrogation of responses in the presence of ICI (Fig. 4C, [Supplementary data Fig. S5A](#)). qRT-PCR analysis of *CASP1* in HEECs (by E2) and HUVECs (by E2 and DPN) revealed an up-regulation at 2 h in contrast to the down-regulation detected by TAC (inflammation; [Supplementary data Fig. S5A](#)); this may indicate that ER $\beta$ -dependent regulation of *CASP1* is not as robust as other candidates. Validation of *CASP1* mirrored the TAC results for UtMVECs.

To complement studies using anti-estrogen, depletion of ER $\beta$  mRNA using siRNA was carried out in HEECs ([Supplementary data Fig. S6A](#)); incubation of ER $\beta$ -depleted cells with DPN failed to induce the same significant changes in *HEY1* and *IFNB1* mRNAs seen in cells incubated with a control siRNA ([Supplementary data Fig. S6B and C](#)).

To extend investigations on the expression of *IFNB1* and *ICAM1*, IHC was performed on full-thickness uterine sections. Both proteins were detected in CD31+ ECs within the endometrium ([Supplementary data Fig. S7A and E; S7I and M](#)) and myometrium ([Supplementary data Fig. S7B and F; Fig. S7J and N](#)), during both phases of the cycle. Both proteins were co-expressed with ER $\beta$  in ECs as well as in other uterine cell types including epithelial cells (Fig. S7 labelled G).

### Bioinformatics identifies Sp1 as a key regulator of ER $\beta$ -mediated gene expression in ECs

Following the identification of ER $\beta$ -dependent changes in vascular function and associated changes in gene expression, additional studies were directed at understanding the molecular mechanisms by which ER $\beta$  induces changes in gene transcription in response to ligand activation. Endothelial and Ishikawa (control) cells were infected with an adenoviral construct containing a luciferase reporter gene under the control of a 3 $\times$ ERE promoter. In Ishikawa cells, reporter gene expression was induced by E2, DPN and PPT and abrogated by the inclusion of ICI

([Supplementary data Fig. S8A](#)). In contrast, there was no evidence of reporter gene activation in any of the ER $\beta$ + ECs (Fig. S8B–D). It has been proposed that ER $\beta$ -mediated transcription may involve ‘tethered’ mechanisms depending upon the recruitment of additional transcription factors; therefore, bioinformatic analysis of genes identified on the array cards was carried out. This revealed that 12 of 18 of the ER $\beta$ -dependent genes identified in HEECs, including *HEY1*, *ICAM1* and *ENPP2*, were associated with the transcription factor Sp1 (Fig. 5A). Western analysis confirmed the expression of Sp1 in all three ECs (Fig. 5B). Immunoprecipitation was performed on HEEC proteins using an anti-ER $\beta$  antibody with the detection of Sp1 in the complex confirmed following western blotting and probing the membrane with an anti-Sp1 antibody (Fig. 5C). This demonstrated that ER $\beta$  and Sp1 are bound together within HEECs regardless of the presence of ligand.

### Inhibition of Sp1-dependent activity abrogates ER $\beta$ -dependent changes in EC function and gene expression

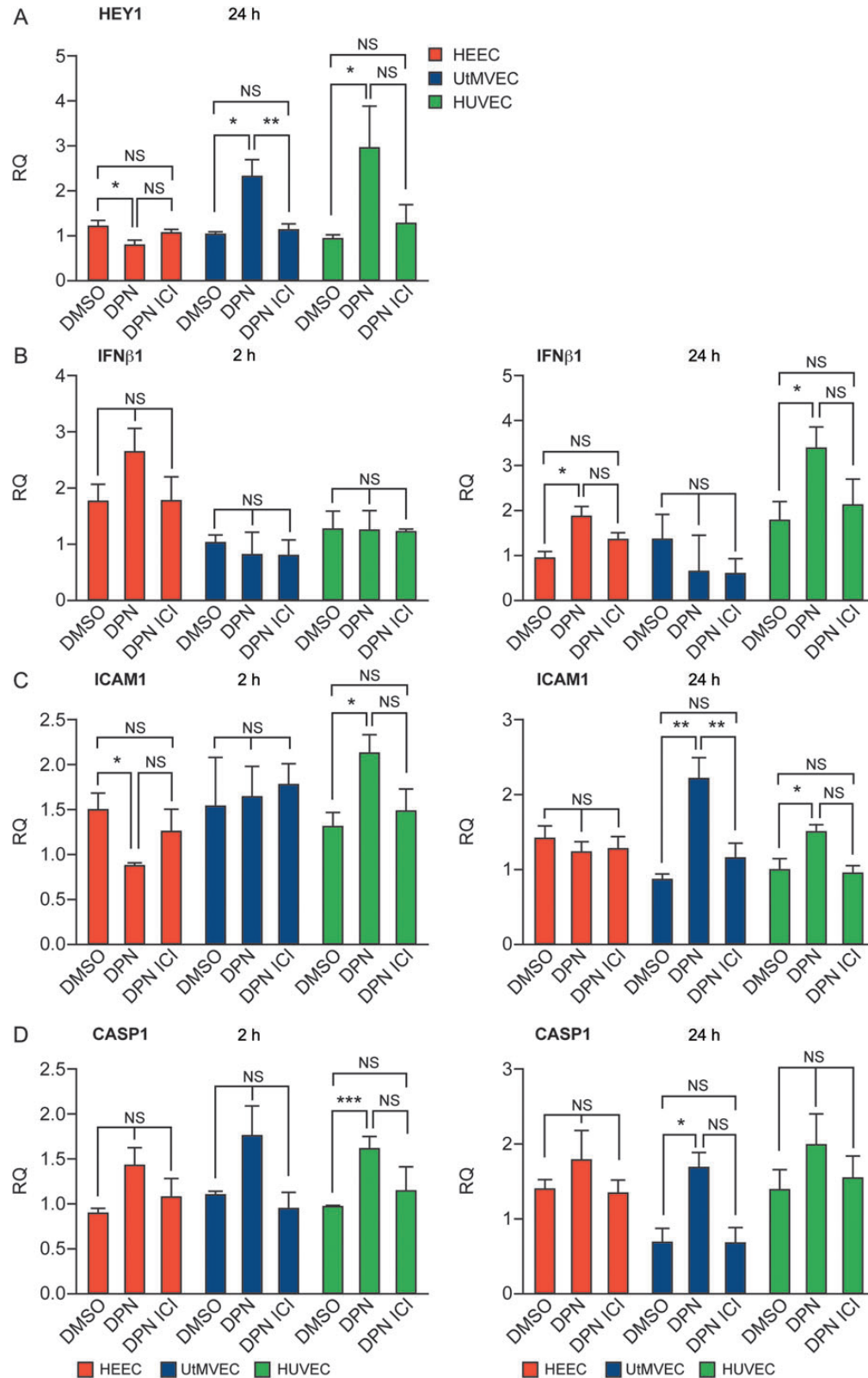
To investigate whether the ER $\beta$ -dependent changes in gene expression detected in EC were Sp1 dependent, we carried out siRNA knockdown experiments using HEECs. Partial knockdown of Sp1 mRNA was achieved using a Sp1-specific siRNA (Fig. 5D); the resulting reduction in the expression of Sp1 abrogated DPN-dependent changes in the expression of *HEY1* and *IFNB1* (Fig. 5E and F). To determine whether the ER $\beta$ -dependent decrease in network formation observed in HEECs was also Sp1 dependent, cells were treated with Mithramycin A, an anti-cancer drug that binds to GC-rich regions of chromatin and prevents binding of Sp transcription factors. Mithramycin A alone had no impact but the addition of Mithramycin A to cultures containing DPN rescued the cells from the ER $\beta$ -dependent decrease in network formation (Fig. 5G and H).

## Discussion

This study is a comparative analysis of the impact of ER $\beta$  activation, via the binding of an ER $\beta$  agonist (DPN), on EC function and associated gene expression changes in microvascular EC lines derived from different vascular beds of the human uterus (HEECs and UtMVECs) and ECs obtained from HUVECs. HUVECs were included in the current study as they are used extensively in studies on EC function.

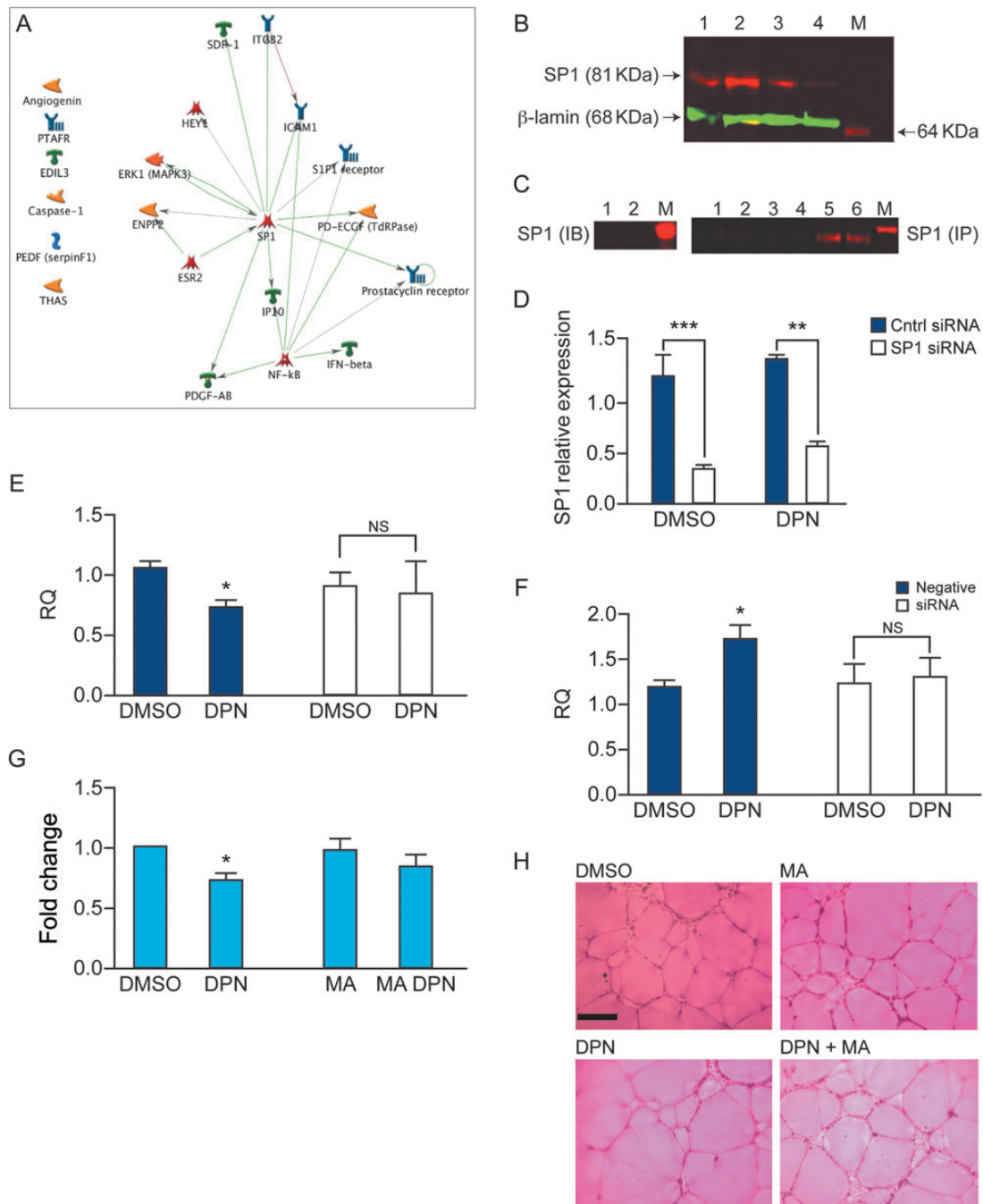
While the study does possess limitations because primary tissue was not used, we believe that our results demonstrate a number of novel findings. First, to our knowledge, this study is the first to directly compare ECs from the endometrium and myometrium and to indicate opposing properties for the two. This indicates that ER selective agonists may have distinct effects in different vascular beds, which may have implications for the therapeutic application of ER subtype-selective agonists in hormone responsive disorders characterized by aberrant angiogenesis. Secondly, our findings expand suggestions that ECs from different vascular beds exhibit unique phenotypes. Notably, we found little overlap in the expression of genes associated with angiogenesis and inflammation in the three ECs we analyzed, each of which demonstrated unique ER $\beta$ -dependent patterns of gene expression, suggesting that our cell models retain the phenotype of their vascular origin. These results also suggest that there may be no ‘ideal EC model’ in which to study ER $\beta$ -mediated changes in cell function and that assessment of the likely impacts of





**Figure 4** ERβ-dependent changes in gene expression are regulated in opposite directions in ECs derived from different vascular beds. qRT-PCR validation of TAC results was carried out using Roche Universal ProbeLibrary (Roche Applied Science) with Express qPCR Supermix (Invitrogen) on HEECs, UtMVECs and HUVECs, treated with the vehicle control (DMSO), DPN ( $10^{-8}$  M) or DPN plus the anti-estrogen Fulvestrant (ICI,  $10^{-7}$  M). Values represent the mean  $\pm$  SEM,  $n = 5$ . Results are normalized to the vehicle control where one replicate was given the arbitrary value of 1. RQ, relative quantification (\* $P < 0.05$ , \*\* $P < 0.01$ , \*\*\* $P < 0.001$ ). (A) *HEY1* 24 h (no impact at 2 h), (B) *IFNβ1*, 2 and 24 h, (C) *ICAM1*, 2 and 24 h and (D) *CASP1*, 2 and 24 h. TAC, TaqMan array cards.





**Figure 5** Sp1 is a regulator of ER $\beta$ -mediated gene expression and function in uterine ECs. **(A)** Bioinformatics analysis using Metacore<sup>TM</sup> revealed that 12 out of 18 ER $\beta$ -dependent genes identified in HECCs have known associations with the transcription factor Sp1. Metacore software utilizes some alternative gene names: S1P1 receptor (*ECGF*), PD-ECGF (platelet derived ECGF), prostacyclin receptor (*PTGIR*), IP10 (*CXCL10*), ESR2 (*ER $\beta$* ), ERK1 (*MAPK3*), THAS (*TBXAS1*), PEDF (*SERPINF1*), SDF1 (*CXCL12*). **(B)** Western blot analysis of nuclear extracts from all four cell lines using antibodies specific for Sp1 (81 kDa) and the endogenous control  $\beta$  lamin (68 kDa); lane 1, Ishikawa cells; lane 2, HUVEC; lane 3, HECC; lane 4, UtMVEC; M, Marker. **(C)** Sp1 was detected by immunoblotting (IB) with Sp1-specific mouse monoclonal antibody. HECCs treated with DMSO (lane 1) or  $10^{-8}$  M DPN (lane 2) for 24 h and after immunoprecipitation (IP) with an anti-ER $\beta$  rabbit polyclonal antibody in HECCs treated with DMSO (lane 5) or DPN (lane 6). No Sp1 was detected in HECCs immunoprecipitated with rabbit IgG (lane 3) or in the cross-linked IP sample (lane 4). **(D)** Knockdown of Sp1 in HECCs was achieved following transfection with a Sp1-specific siRNA (white bars) in the presence or absence of DPN for 24 h; control scrambled siRNA is shown with blue bars. qPCR analysis confirmed knockdown efficiency: 61% in DMSO-treated samples and 67% DPN-treated samples. **(E, F)** Knockdown of Sp1 (white bars) in HECCs abrogated the significant impact of DPN (\* $P < 0.05$ , \*\* $P < 0.01$ , \*\*\* $P < 0.001$ ) on the expression of *HEY1* (E) and *IFN $\beta$ 1* (F), respectively **(G)** Network formation assay using HECCs showing that incubation with Mithramycin A (50 nM) rescued the DPN-mediated decrease in network formation. MA, Mithramycin A.  $n = 6$ . **(H)** Representative images for the different treatments reported in (G). Scale bar is 100  $\mu$ m.

natural and synthetic estrogens on EC function needs to be conducted in models appropriate to the target tissue. Finally, this is the first study to suggest a role for Sp1 in ER $\beta$ -dependent changes in uterine EC function. Binding of liganded ER $\beta$  to Sp1 sites has been shown in cells expressing endogenous levels of ER $\beta$  (Vivar *et al.*, 2010), and Sp1 has previously been implicated in uterine cell-specific expression of the HOXA10 gene in response to estrogen (Martin *et al.*, 2007). However, this is the first study highlighting an important role for Sp1 in ER $\beta$ -directed transcription in ECs and drawing attention to the importance of ERE-independent, ‘tethered’ mechanisms in estrogen regulation of gene expression (Nilsson *et al.*, 2001). Further studies are now merited to explore whether targeting Sp1-ER $\beta$ -dependent gene expression offers an alternative treatment option for targeting specific cell types in reproductive pathologies.

### ER $\beta$ induces contrasting effects on uterine vascular function

There have been reports that myometrial ECs are heterogeneous in nature, that a subpopulation express ER $\alpha$  and ER $\beta$  and that ER $\alpha$  agonists promote angiogenesis in these cells (Zaitseva *et al.*, 2004). We have not found this to be the case in present or past studies using full-thickness biopsies of normal human uteri; the myometrial EC model (UtMVECs) used in this study did not express ER $\alpha$ . Our robust characterization of ECs both *in situ* and in our chosen models failed to detect either ER $\alpha$  mRNA or protein in the EC lines. Of particular interest, was our finding that the ER $\beta$ -selective agonist, DPN, decreases network formation in endometrial ECs (HEECs). During the normal menstrual cycle, there is a significant increase in angiogenesis during the proliferative phase that replenishes the vascular bed. Although it may be presumed that E2 levels are responsible, the direct or indirect mechanism of the regulation of angiogenesis remains uncertain (Girling and Rogers, 2005). The endometrium is a complex multi-cellular tissue and we speculate that *in vivo*, an E2-dependent increase in angiogenesis may be mediated via ER $\alpha$ -positive cells such as perivascular cells, stromal fibroblasts or epithelial cells. For example, vascular endothelial growth factor (VEGF) mRNA has been shown to increase in stromal and epithelial cells of the endometrium in baboons supplemented with estrogen (Niklaus *et al.*, 2003). In support of this idea, it has been reported that there is an increase in network formation when uterine microvascular cells are co-cultured with epithelial cells treated with E2 (Albrecht *et al.*, 2003).

Targeted gene profiling of angiogenesis factors in each uterine cell line was consistent with observations made in functional assays. In HEECs, pro-angiogenic growth factors were down-regulated, a finding which correlated with the decrease in network formation. In UtMVECs, there was a general up-regulation in pro-angiogenic factors and down-regulation in inhibitors, corresponding with the identified increase in network formation.

Surprisingly, we found that DPN caused a decrease in angiogenesis in HEECs while E2 had no effect. DPN consistently had a strikingly more potent effect on HEEC and UtMVEC network formation than the naturally occurring ligand E2. Additionally, gene expression analysis revealed that treatment of cells with DPN often had a different impact to E2. The planar ligand DPN is both ER $\beta$  affinity and potency selective (Meyers *et al.*, 2001). The specific chemical structure of DPN means that it docks in the LBD of ERs differently from E2 (Sun *et al.*, 2003). Because of these structural differences, these

two agonists induce ligand-specific changes in receptor conformation (Leitman *et al.*, 2010), precipitating recruitment of different co-regulatory molecules. The nature of the estrogenic ligand is, therefore, the driving force of the composition of co-regulatory complexes, and ultimate ligand-specific gene expression and biological response ensues (Nilsson *et al.*, 2011). Our results appear to mirror those in a previous study that compared changes in response to activation of ER $\beta$  by the natural product liquiritigenin and those induced by E2 and found only a few common candidates, prompting the authors to state that different ER $\beta$  agonists may produce distinct biological effects (Paruthiyil *et al.*, 2009). Their study in combination with ours, reporting specific functional effects of DPN on uterine angiogenesis may inform the future use of selective estrogen receptor modulators. If an ER $\beta$ -selective agonist can be used to treat endometrial disorders, this would be preferential to the current therapies using GnRH analogues as it would avoid some of the side-effects of an induced hypoestrogenic state.

### EC models possess unique ER $\beta$ profiles

Targeted gene profiling revealed striking differences in the response of the three EC lines analyzed with very few shared candidates observed. Regulation of three common genes was detected: *HEY1*, *ICAM1*, and *CASP1*. While the two uterine EC lines exhibited very different expression profiles, the HUVEC profile was comparatively unique from either of the other ECs. This reiterates that although HUVECs are used as a common model of vascular function, they do not represent an appropriate substitute in the context of the uterus. Additional genes regulated in the two uterine cell lines were *IFNB1* and *ENPP2*. *ENPP2* has previously been identified as a primary ER $\beta$  target gene using chromatin immunoprecipitation in HEK293 (embryonic kidney) cells engineered to over-express ER $\beta$  (Zhao *et al.*, 2009). In studies profiling ER $\beta$ -dependent genes in malignant cell lines, *ENPP2* was one of the few common genes identified (Monroe *et al.*, 2003). In addition to *ICAM1*, *ITGB2* (integrin beta 2) was also regulated in HEECs and UtMVECs, consistent with a role for estrogens in the regulation of vascular permeability (Cho *et al.*, 1998). A number of protein families had members that were regulated in two or all of the EC lines. We found that the expression of genes associated with prostaglandin metabolism was altered in all three ECs. In HEECs, thromboxane A synthase I (*TBXAS1*) and prostaglandin I2 receptor (*PTGIR*) were reduced, in UtMVECs thromboxane A2 receptor (*TBXA2R*) was increased and, in HUVECs, the cyclooxygenase enzymes (*PTGS1* and *PTGS2*) and *TBXAS1* were all reduced. Estrogen regulates prostanoid synthesis in the placental vasculature (Su *et al.*, 2011) and up-regulates the expression of *PTGS1* via ER $\beta$  in a mixed population of uterine microvascular cells (Tamura *et al.*, 2004). Our results indicate that prostanoid biosynthesis is ER $\beta$  regulated in all three ECs, albeit at different steps of the pathway, and possibly with differing outcomes.

### ER $\beta$ mediates changes in transcription in endometrial ECs via non-classical ER signaling involving the Sp1 transcription factor

In an extension of our observations on gene expression, we also used reporter assays to demonstrate that ER $\beta$  was unable to induce transcription via binding to classical EREs in uterine ECs. This finding was consistent with the results obtained by another group performing

studies in HUVECs: they concluded that these cells lacked estrogen responsiveness (Jensen et al., 1998), while our studies have shown this is not the case. Bioinformatic analysis revealed that many of our identified ER $\beta$ -dependent gene candidates in HEECs had known associations with the transcription factor Sp1. Using immunoprecipitation, we found that ER $\beta$  and Sp1 co-exist in a complex in HEECs. We found that the association was not dependent on ligand (DPN) binding to ER $\beta$  indicating that the protein complex is pre-formed within the nucleus. Consistent with this hypothesis, our unpublished studies and another report (Muyan et al., 2012) have shown that in the absence of ligand, the ER $\beta$  protein appears less mobile within the nucleus than ER $\alpha$  suggesting that ER $\beta$  is already bound to chromatin regardless of the presence of ligand. As an extension of these findings, we determined whether Sp1 was essential or dispensable for ER $\beta$ -dependent changes in gene expression and EC function by using both Mithramycin A, an inhibitor of Sp binding to GC-rich promoter sequences and Sp1-specific siRNA knockdown. Sp1 and ER $\beta$  were both found to be essential for DPN-dependent changes in angiogenesis (network formation) and we therefore suggest that DPN induces a conformation in ER $\beta$  that favours changes in gene expression via a 'tethered' Sp1-dependent mechanism (Nilsson et al., 2001) in endometrial ECs.

## Summary

Taken together, gene expression analysis of HEECs, UtMVECs and HUVECs in response to DPN demonstrated: (i) very few common genes but a defined set of unique regulated genes in each cell line; (ii) common genes in HEECs and UtMVECs being regulated in opposing directions; (iii) a general down-regulation of pro-angiogenic factors in HEECs, but a general down-regulation of angiogenesis inhibitors in UtMVECs and (iv) that the latter correlates with the results of functional angiogenesis assays. Moreover, ER $\beta$ -mediated changes in gene expression in HUVECs were not similar to that in HEECs or UtMVECs, indicating that this EC type is not suitable for modeling the impacts of ligand-binding ER $\beta$  in uterine vascular function. Finally, we showed (v) that the transcription factor Sp1 is required in HEECs for ER $\beta$ -dependent changes in gene expression associated with angiogenesis to take place.

## Uterine EC models represent paradigms in anatomically diverse microvascular function

We propose that uterine ECs represent good models in which to investigate the potential impacts of ligands capable of high-affinity binding to ER $\beta$  in health and disease. Notably, these cells do not express ER $\alpha$  *in vivo* or *in vitro* and so estrogen action must be mediated via ER $\beta$  alone. Endometrial ECs were obtained from a tissue subject to cyclical regeneration and the formation of new blood vessels, a quality rare in most adult tissues, the exception being those subject to malignant transformation. We have demonstrated that the ER $\beta$  activation in HEECs induces a decrease in network formation by these cells consistent with a reduction in the rate of angiogenesis. In contrast, although also exposed to fluctuating concentrations of estrogens, the vasculature of the normal myometrium is relatively inert although it may be disturbed by the presence of uterine fibroids. We observed an increase in angiogenesis in myometrial ECs in response to ER $\beta$  activation, which might complement previous findings that ER $\beta$  signaling may have positive effects on angiogenesis within quiescent tissues. Our results suggest that ER $\beta$  agonists, both natural, e.g. genestein, and synthetic, e.g. 8b-VE2 and ERb-041, may have unique

cell-specific impacts in cells expressing ER $\beta$  alone. Although further functional studies are required to validate the therapeutic potential of the above findings, the results presented here may have implications for the *in vivo* application of ER $\beta$  subtype-selective ligands.

## Supplementary data

Supplementary data are available at <http://humrep.oxfordjournals.org/>.

## Acknowledgements

We thank Katharina Späth and Arantza Esnal-Zufiurre for technical assistance and advice. We are very grateful to Dr Douglas Gibson and Dr Patrick Hadoke for critical feedback and to Ronnie Grant for preparation of figures.

## Authors' roles

E.G. designed and carried out experimental work and wrote the manuscript; F.C. carried out experimental work; H.O.D.C. designed the work; P.T.K.S. designed the work and wrote the manuscript.

## Funding

The study was funded by a Medical Research Council Programme Grant. E.G. is the recipient of an MRC Career Development Fellowship. Funding to pay the Open Access publication charges for this article was provided by an MRC Programme Grant G1100356/1 to PTKS.

## Conflict of interest

The authors have nothing to disclose.

## References

- Abraham GE. Ovarian and adrenal contribution to peripheral androgens during the menstrual cycle. *J Clin Endocrinol Metab* 1974;**39**:340–346.
- Albrecht ED, Babischkin JS, Lidor Y, Anderson LD, Udoff LC, Pepe GJ. Effect of estrogen on angiogenesis in co-cultures of human endometrial cells and microvascular endothelial cells. *Hum Reprod* 2003;**18**:2039–2047.
- Bao P, Kodra A, Tomic-Canic M, Golinko MS, Ehrlich HP, Brem H. The role of vascular endothelial growth factor in wound healing. *J Surg Res* 2009;**153**:347–358.
- Cho MM, Ziats NP, Abdul-Karim FW, Pal D, Goldfarb J, Utian WH, Gorodeski GI. Effects of estrogen on tight junctional resistance in cultured human umbilical vein endothelial cells. *J Soc Gynecol Investig* 1998;**5**:260–270.
- Critchley HO, Brenner RM, Henderson TA, Williams K, Nayak NR, Slayden OD, Millar MR, Saunders PT. Estrogen receptor beta, but not estrogen receptor alpha, is present in the vascular endothelium of the human and nonhuman primate endometrium. *J Clin Endocrinol Metab* 2001;**86**:1370–1378.
- Critchley HO, Henderson TA, Kelly RW, Scobie GS, Evans LR, Groome NP, Saunders PT. Wild-type estrogen receptor (ERbeta1) and the splice variant (ERbetacx/beta2) are both expressed within the human endometrium throughout the normal menstrual cycle. *J Clin Endocrinol Metab* 2002;**87**:5265–5273.
- Farhat MY, Lavigne MC, Ramwell PW. The vascular protective effects of estrogen. *FASEB J* 1996;**10**:615–624.

- Gibson DA, Saunders PT. Estrogen dependent signaling in reproductive tissues - a role for estrogen receptors and estrogen related receptors. *Mol Cell Endocrinol* 2012;**348**:361–372.
- Girling JE, Rogers PA. Recent advances in endometrial angiogenesis research. *Angiogenesis* 2005;**8**:89–99.
- Gustafsson JA. What pharmacologists can learn from recent advances in estrogen signalling. *Trends Pharmacol Sci* 2003;**24**:479–485.
- Heldring N, Pike A, Andersson S, Matthews J, Cheng G, Hartman J, Tujague M, Strom A, Treuter E, Warner M *et al*. Estrogen receptors: how do they signal and what are their targets. *Physiol Rev* 2007;**87**:905–931.
- Hermenegildo C, Cano A. Pure anti-oestrogens. *Hum Reprod Update* 2000;**6**:237–243.
- Hewitt SC, Harrell JC, Korach KS. Lessons in estrogen biology from knockout and transgenic animals. *Annu Rev Physiol* 2005;**67**:285–308.
- Jabbour HN, Kelly RW, Fraser HM, Critchley HO. Endocrine regulation of menstruation. *Endocr Rev* 2006;**27**:17–46.
- Jabbour HN, Sales KJ, Catalano RD, Norman JE. Inflammatory pathways in female reproductive health and disease. *Reproduction* 2009;**138**:903–919.
- Jensen I, Rinaldo CH, Nordbo Berge L, Seternes OM, Moens U. Human umbilical vein endothelial cells lack expression of the estrogen receptor. *Endothelium* 1998;**6**:9–21.
- Kayisli UA, Luk J, Guzeloglu-Kayisli O, Seval Y, Demir R, Arici A. Regulation of angiogenic activity of human endometrial endothelial cells in culture by ovarian steroids. *J Clin Endocrinol Metab* 2004;**89**:5794–5802.
- Krikun G, Mor G, Huang J, Schatz F, Lockwood CJ. Metalloproteinase expression by control and telomerase immortalized human endometrial endothelial cells. *Histol Histopathol* 2005a;**20**:719–724.
- Krikun G, Schatz F, Taylor R, Critchley HO, Rogers PA, Huang J, Lockwood CJ. Endometrial endothelial cell steroid receptor expression and steroid effects on gene expression. *J Clin Endocrinol Metab* 2005b;**90**:1812–1818.
- Leitman DC, Paruthiyil S, Vivar OI, Saunier EF, Herber CB, Cohen I, Tagliaferri M, Speed TP. Regulation of specific target genes and biological responses by estrogen receptor subtype agonists. *Curr Opin Pharmacol* 2010;**10**:629–636.
- Martin R, Taylor MB, Krikun G, Lockwood C, Akbas GE, Taylor HS. Differential cell-specific modulation of HOXA10 by estrogen and specificity protein 1 response elements. *J Clin Endocrinol Metab* 2007;**92**:1920–1926.
- Matthews J, Gustafsson JA. Estrogen signaling: a subtle balance between ER alpha and ER beta. *Mol Interv* 2003;**3**:281–292.
- McCrohon JA, Woo KS, Celermajer DS. A comparison of endothelial function in Caucasian and Chinese women before and after the menopause. *Maturitas* 2000;**35**:31–37.
- Meyers MJ, Sun J, Carlson KE, Marriner GA, Katzenellenbogen BS, Katzenellenbogen JA. Estrogen receptor-beta potency-selective ligands: structure-activity relationship studies of diarylpropionitriles and their acetylene and polar analogues. *J Med Chem* 2001;**44**:4230–4251.
- Monroe DG, Getz BJ, Johnsen SA, Riggs BL, Khosla S, Spelsberg TC. Estrogen receptor isoform-specific regulation of endogenous gene expression in human osteoblastic cell lines expressing either ERalpha or ERbeta. *J Cell Biochem* 2003;**90**:315–326.
- Muyan M, Callahan LM, Huang Y, Lee AJ. The ligand-mediated nuclear mobility and interaction with estrogen-responsive elements of estrogen receptors are subtype specific. *J Mol Endocrinol* 2012;**49**:249–266.
- Nayak NR, Brenner RM. Vascular proliferation and vascular endothelial growth factor expression in the rhesus macaque endometrium. *J Clin Endocrinol Metab* 2002;**87**:1845–1855.
- Niklaus AL, Aberdeen GW, Babischkin JS, Pepe GJ, Albrecht ED. Effect of estrogen on vascular endothelial growth/permeability factor expression by glandular epithelial and stromal cells in the baboon endometrium. *Biol Reprod* 2003;**68**:1997–2004.
- Nilsson S, Gustafsson JA. Estrogen receptors: therapies targeted to receptor subtypes. *Clin Pharmacol Ther* 2010;**89**:44–55.
- Nilsson S, Makela S, Treuter E, Tujague M, Thomsen J, Andersson G, Enmark E, Pettersson K, Warner M, Gustafsson JA. Mechanisms of estrogen action. *Physiol Rev* 2001;**81**:1535–1565.
- Nilsson S, Koehler KF, Gustafsson JA. Development of subtype-selective oestrogen receptor-based therapeutics. *Nat Rev Drug Discov* 2011;**10**:778–792.
- O'Lone R, Frith MC, Karlsson EK, Hansen U. Genomic targets of nuclear estrogen receptors. *Mol Endocrinol* 2004;**18**:1859–1875.
- Paruthiyil S, Cvorova A, Zhao X, Wu Z, Sui Y, Staub RE, Baggett S, Herber CB, Griffin C, Tagliaferri M *et al*. Drug and cell type-specific regulation of genes with different classes of estrogen receptor beta-selective agonists. *PLoS One* 2009;**4**:e6271.
- Rocha SF, Adams RH. Molecular differentiation and specialization of vascular beds. *Angiogenesis* 2009;**12**:139–147.
- Schatz F, Soderland C, Hendricks-Munoz KD, Gerrets RP, Lockwood CJ. Human endometrial endothelial cells: isolation, characterization, and inflammatory-mediated expression of tissue factor and type I plasminogen activator inhibitor. *Biol Reprod* 2000;**62**:691–697.
- Smith SK. Angiogenesis and reproduction. *BJOG* 2001;**108**:777–783.
- Su EJ, Ernst L, Abdallah N, Chatterton R, Xin H, Monsivais D, Coon J, Bulun SE. Estrogen receptor- $\beta$  and fetoplacental endothelial prostanoid biosynthesis: a link to clinically demonstrated fetal growth restriction. *J Clin Endocrinol Metab* 2011;**96**:E1558–E1567.
- Sun J, Baudry J, Katzenellenbogen JA, Katzenellenbogen BS. Molecular basis for the subtype discrimination of the estrogen receptor-beta-selective ligand, diarylpropionitrile. *Mol Endocrinol* 2003;**17**:247–258.
- Sunkara SK, Khairy M, El-Toukhy T, Khalaf Y, Coomarasamy A. The effect of intramural fibroids without uterine cavity involvement on the outcome of IVF treatment: a systematic review and meta-analysis. *Hum Reprod* 2010;**25**:418–429.
- Tamura M, Deb S, Sebastian S, Okamura K, Bulun SE. Estrogen up-regulates cyclooxygenase-2 via estrogen receptor in human uterine microvascular endothelial cells. *Fertil Steril* 2004;**81**:1351–1356.
- Vitale C, Fini M, Speziale G, Chierchia S. Gender differences in the cardiovascular effects of sex hormones. *Fundam Clin Pharmacol* 2010;**24**:675–685.
- Vivar OI, Zhao X, Saunier EF, Griffin C, Mayba OS, Tagliaferri M, Cohen I, Speed TP, Leitman DC. Estrogen receptor beta binds to and regulates three distinct classes of target genes. *J Biol Chem* 2010;**285**:22059–22066.
- Weis SM, Cheresch DA. Tumor angiogenesis: molecular pathways and therapeutic targets. *Nat Med* 2011;**17**:1359–1370.
- Yang XP, Reckelhoff JF. Estrogen, hormonal replacement therapy and cardiovascular disease. *Curr Opin Nephrol Hypertens* 2011;**20**:133–138.
- Zaitseva M, Yue DS, Katzenellenbogen JA, Rogers PA, Gargett CE. Estrogen receptor-alpha agonists promote angiogenesis in human myometrial microvascular endothelial cells. *J Soc Gynecol Investig* 2004;**11**:529–535.
- Zhao C, Putnik M, Gustafsson JA, Dahlman-Wright K. Microarray analysis of altered gene expression in ERbeta-overexpressing HEK293 cells. *Endocrine* 2009;**36**:224–232.