

Internalisation of membrane progesterone receptor- α after treatment with progesterone: Potential involvement of a clathrin-dependent pathway

HELEN FOSTER¹, ALAN REYNOLDS², GUDRUN STENBECK¹, JING DONG³,
PETER THOMAS³ and EMMANOUIL KARTERIS¹

¹Centre for Cell Chromosome Biology, Biosciences, School of Health Sciences and Social Care,
and ²Experimental Techniques Centre, Brunel University, Uxbridge UB8 3PH, UK;

³Marine Science Institute, University of Texas at Austin, Port Aransas, TX 78373, USA

Received July 13, 2009; Accepted October 15, 2009

DOI: 10.3892/mmr_00000214

Abstract. Internalisation and recycling of seven transmembrane domain receptors is a critical regulatory event for their signalling. The mechanism(s) by which membrane progesterone receptor- α (mPR α) number is regulated on the cell surface is unclear. In this study, we investigated the cellular distribution of mPR α and mechanisms of mPR α trafficking using a cell line derived from a primary culture of human myometrial cells (M11) as an experimental model. RT-PCR and immunofluorescent analysis demonstrated expression of mPR α in M11 cells with mPR α primarily distributed on the cell surface under basal conditions. For the first time, plasma membrane localisation of mPR α was confirmed using immunogold transmission electron microscopy. Stimulation of M11 cells with progesterone (P4, 100 nM) resulted in internalisation of mPR α from the plasma membrane to the cytoplasm (10 min) and subsequent limited translocation back to the cell surface (20 min). We investigated potential endocytotic pathways involved in trafficking of mPR α after its internalisation. Partial co-localisation of clathrin with mPR α was obvious after 10 min of P4 treatment. Of note, chlorpromazine (inhibitor of clathrin-mediated pathway) inhibited the endocytosis of mPR α , whereas treatment with nystatin (inhibitor of caveolae-mediated pathway) did not affect internalisation. Collectively, these data suggest that mPR α is expressed on the cell surface of M11 cells and undergoes endocytosis after P4 stimulation primarily via a clathrin-mediated pathway.

Introduction

The large group of seven transmembrane domain receptors (7TMRs) include the well-known superfamily of G protein

coupled receptors (GPCRs) as well as the phylogenetically distinct family of membrane progesterone receptors (mPRs) (1,2). Trafficking of 7TMRs between the various cell compartments is crucial for their ligand-binding and signalling functions. Internalisation of 7TMRs by endocytosis controls important receptor functions in the cell, fine tuning the binding characteristics of the receptor and regulating the activation of different signal transduction pathways. Some cell-surface receptors can also activate signal transduction pathways from intracellular compartments, suggesting that signalling can be regulated by compartmentalization (3).

Internalisation of many GPCRs involves rapid clathrin-mediated endocytosis (3-5). The agonist-occupied receptor is recruited into clathrin-coated pits (CCP), which then form vesicles for entry into the endocytic pathway. At this stage, vesicles and their cargo can be directed for either degradation or recycling back to the cell surface (6,7). For example, it has been shown that different internalisation routes seem to predetermine whether transforming growth factor β (TGF- β) receptors will trigger a signalling response or be degraded (3). The precise mechanisms influencing the fate of the CCP-receptor complex are not fully elucidated, but emerging data suggest that they are receptor specific and may vary between cell types (8). Another route by which GPCRs can be internalised involves caveolae and is independent of clathrin-coated pits (4,7). To date, nothing is known about the internalisation of another family of 7TMRs, the mPRs.

The mPRs were initially discovered in a teleost fish. More than 20 closely related genes have been cloned from other vertebrate species, including 3 mPR subtypes in humans, named α , β and γ , which show high levels of expression in human reproductive, brain and kidney tissues, respectively (1,2). Recently, ligand binding of another two members of the mPR family, named mPR δ and mPR ϵ , has been characterised (9). Structural analyses of the translated cDNAs suggest that they encode membrane proteins with seven transmembrane domains. Thomas *et al* have shown that mPR α is a membrane-bound progestin receptor that activates G proteins, despite having a different ancestral origin to GPCRs (10). Karteris and co-workers have also shown that mPR α is expressed

Correspondence to: Dr Emmanouil Karteris, Centre for Cell Chromosome Biology, Biosciences, School of Health Sciences and Social Care, Brunel University, Uxbridge UB8 3PH, UK
E-mail: emmanouil.karteris@brunel.ac.uk

Key words: progesterone, receptors, internalisation, clathrin

on myometrial cells and couples to inhibitory G proteins, resulting in an increased phosphorylation of myosin light chain (11). However, regulation of mPR α at the cell surface remains unclear, since there is a debate regarding the cellular distribution of these receptors. Therefore, in the present study we investigated the localisation of mPR α in M11 cells and potential endocytotic pathways involved in mPR α trafficking.

Materials and methods

Tissue culture. M11 cells were obtained from John A. Copland (Mayo Clinic College of Medicine, Jacksonville, FL, USA). These cells were derived from dispersed human myometrial cells by repeated passage without the use of any immortalising or transforming agents. M11 cells were maintained in Dulbecco's modified Eagle's medium (DMEM) high glucose (with D-Valine) supplemented with 10% fetal bovine serum (FBS), 50 U penicillin and 50 μ g streptomycin (Invitrogen, UK) and cultured at 37°C in 5% CO₂.

RNA isolation, cDNA synthesis and RT-PCR. Total RNA was extracted using an RNA extraction kit (Sigma-Aldrich, UK) and treated with DNase I according to the manufacturer's instructions. RNA concentration was determined by spectrophotometric analysis (NanoDrop; Thermo Scientific, UK) and agarose gel electrophoresis. RNA (100 ng) was reverse-transcribed into cDNA using 5 IU/ μ l RNase H reverse transcriptase (Invitrogen). PCR amplification was carried out using Taq polymerase (Invitrogen) and oligonucleotide primers (Invitrogen) for human mPR α (Acc. AF313620). The primers for mPR α were forward 5'-GCTGTTCACATCCC-3' and reverse 5'-TGGTGCAACCCCAAGA-3', resulting in a 289-bp PCR product. The primers for clathrin (138 bp) were forward 5'-TTAGCCGGTGCTGAAGAACT-3' and reverse 5'-CTGGAACCGACGGA TAGTGT-3'. The primers for β -actin (216 bp) were forward 5'-AAGAGAGGCATCCTCACCT-3' and reverse 5'-TACATGGCTGGGGTGTGAA-3'. Thirty-three cycles for mPR α and 28 cycles for clathrin and β -actin were performed, consisting of an initial denaturing step at 94°C for 30 sec followed by extension at 60°C for 1 min and elongation at 72°C for 1 min.

Treatment of M11 cells with progesterone (P4). Prior to P4 treatments, M11 cells were cultured in phenol red-free DMEM containing 2.5% charcoal-stripped FBS, penicillin and streptomycin, and incubated at 37°C in 5% CO₂ for 24 h. Cells were exposed to 100 nM P4 for 0 (NS, unstimulated), 10 and 20 min.

Indirect immunofluorescence analyses using mPR α antibody. M11 cells were fixed in 4% paraformaldehyde for 10 min prior to washes in PBS and permeabilization with 0.2% Tween-20 for 20 min. After subsequent washes in PBS, samples were blocked for 1 h at room temperature using 10% bovine serum in PBS. Fixed M11 cells were then incubated with a 1:100 dilution of mPR α (hmPR α , 836-4) antibody in 1.5% bovine serum PBS overnight at 4°C. The following day, preparations were washed with PBS prior to incubation with a 1:100 dilution of anti-rabbit IgG-fluorescein isothiocyanate (FITC)-conjugated antibody (Santa Cruz Biotechnology,

USA) for 1 h. Sample preparations were washed with PBS and mounted in Vectashield® Mounting Medium (Vector labs) containing the DNA-specific dye 4,6-diamido-2-phenylindole (DAPI) to counterstain nuclei. Preparations were incubated with only secondary antibody as a negative control. Images were captured using a Plan Apo Neofluor x63 NA 1.25 oil objective (Zeiss; Carl Zeiss International) on a Zeiss Axiovert 200M microscope, and viewed using AxioVision software (Zeiss; Carl Zeiss International). Images were collected at set exposure times of 3000 msec, with the exception of the nuclei counterstained with DAPI, which were collected under an automatic exposure time.

Dual-indirect immunofluorescence using mPR α and clathrin antibodies. The general indirect immunofluorescence protocol described previously was adhered to, with several modifications. Samples were blocked for 1 h at room temperature in 10% bovine serum and 10% donkey serum in PBS. Preparations were incubated at 4°C overnight in a 1:100 dilution of mPR α (hmPR α , 836-4) antibody and a 1:200 dilution of anti-clathrin heavy chain antibody (Abcam, UK) respectively diluted with 1.5% bovine serum and 1.5% donkey serum in PBS. The secondary antibody incubation consisted of a 1:100 dilution of anti-rabbit IgG-FITC antibody and a 1:100 dilution of anti-goat IgG rhodamine antibody (both from Santa Cruz Biotechnology, USA) respectively composed with 3% bovine serum and 3% donkey serum in PBS for 1 h.

Treatment of M11 cells with endocytosis inhibitors. The dual-indirect immunofluorescence protocol described previously using antibodies directed against mPR α and clathrin was used on M11 cells treated with the following inhibitors for various endocytotic pathways: chlorpromazine, dansylcadaverine, nystatin and sucrose. M11 cells were cultured in phenol red-free DMEM containing 2.5% charcoal-stripped serum, penicillin and streptomycin, and incubated at 37°C in 5% CO₂ 24 h prior to inhibitor and P4 treatment. A negative control was prepared in each instance. M11 cells were incubated for 15 min at 37°C with 50 μ M chlorpromazine hydrochloride (Sigma-Aldrich) using a protocol described previously by Wang *et al* (12), then assessed under basal conditions (NS) and exposed to 100 nM P4 for 10 min. M11 cells were treated with 25 μ g/ml nystatin (Sigma-Aldrich) at 37°C for 30 min as previously described (13,14). Cells were subsequently exposed to 100 nM P4 for 10 min, but also treated under basal conditions (NS). M11 cells were incubated with 0.45 M sucrose (Sigma-Aldrich) at 37°C for 15 min, described by Heuser and Anderson at basal conditions and prior to P4 exposure of 10 min (15).

Protein extraction from cultured M11 cells. M11 cells were cultured in 6-well dishes until reaching 80% confluency and maintained overnight in phenol red-free DMEM containing 2.5% charcoal-stripped FBS, penicillin and streptomycin, before the addition of agonists/inhibitors. Cells were lysed using 200 μ l 2X Laemmli Buffer (Sigma-Aldrich) and denatured for 5 min at 100°C.

Immunogold electron microscopy. M11 cells were grown to confluency on 35-mm polystyrene dishes at 37°C in the presence of 5% CO₂ in high glucose DMEM with 10% heat-

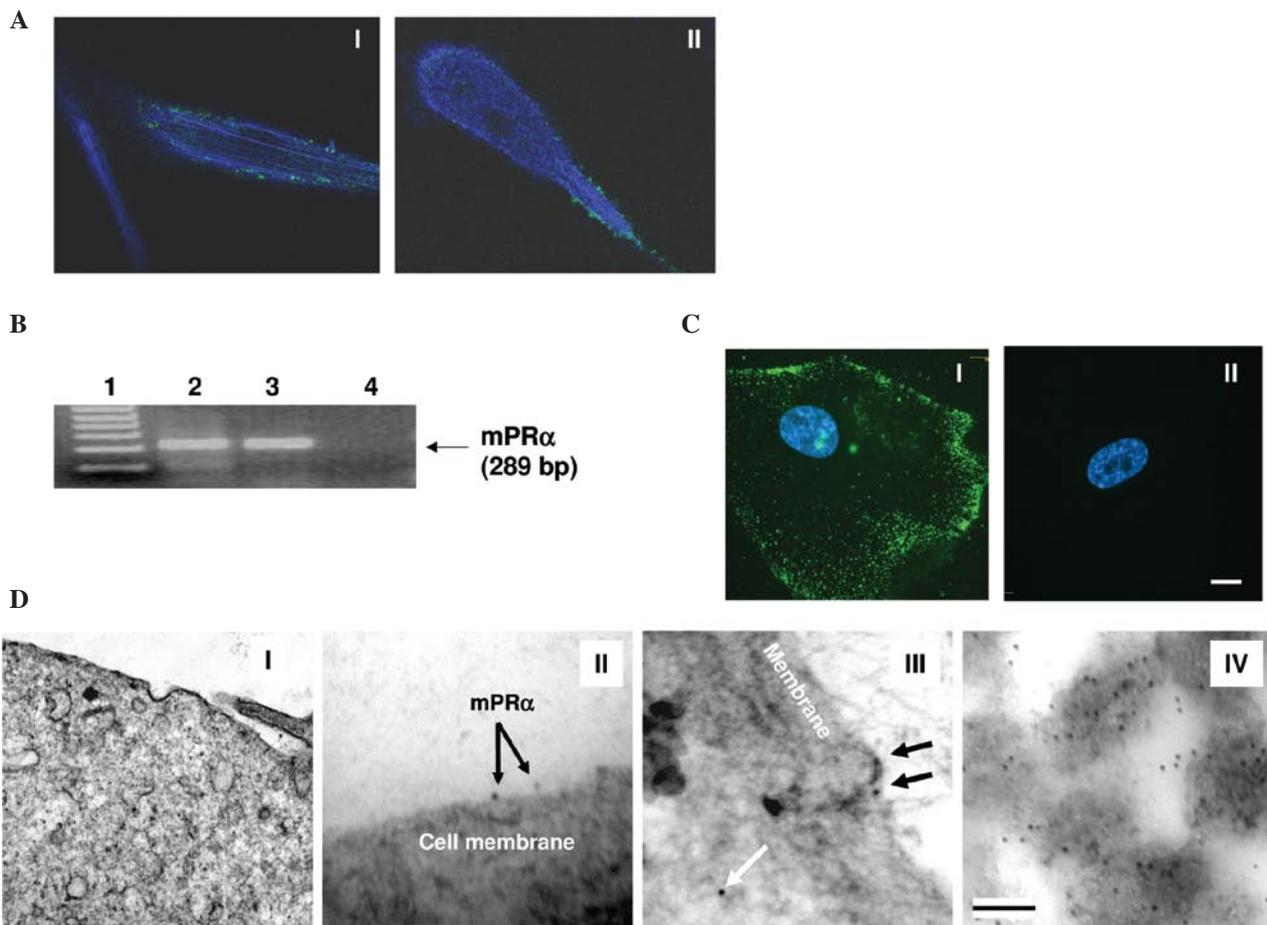


Figure 1. P4 binding, expression and cellular distribution of mPR α in M11 cells. (A) Confocal images of M11 cells incubated with P4 3-(O-carboxymethyl) oxime-BSA-FITC at room temperature for 20 min (I) and 45 min (II). Green represents progesterone and blue, phalloidin. (B) RT-PCR analysis for mPR α : Lane 1, DNA ladder; lane 2, cDNA from M11 cells; lane 3, cDNA from myometrial tissue; lane 4, negative control (no cDNA input). (C) Immunofluorescent analysis for mPR α in an M11 cell showing the distribution of mPR α (green) across the cell membrane. The nucleus was counterstained with DAPI (blue) (I); II is the negative control. Scale bar, 10 μ m. (D) mPR α localisation and the cellular morphology of M11 cells using TEM. M11 cells had intact cytoplasmic machinery and a distinct cell membrane (I). Immunogold electron microscopy revealed mPR α localisation and distribution detected via a secondary antibody conjugated to 10-nm gold beads. This revealed specific staining on the cell membrane (indicated by black arrows, II and III) and within the cytoplasm (indicated by white arrow, III). IV is a control preparation depicting the size of the 10-nm gold beads conjugated to the anti-rabbit secondary antibody used in these preparations. Scale bar, 100 nm, with the exception of I, 250 nm.

inactivated FBS, penicillin and streptomycin. Cells were washed with 0.1 M Sorensen's phosphate buffer (pH 7.0) and fixed in 0.1% glutaraldehyde for 30 min at room temperature. Cells were washed and then blocked with 10% donkey serum for 30 min at room temperature. Anti-clathrin antibody (Sigma-Aldrich) diluted 1:40 with Sorensen's phosphate buffer containing 1% donkey serum and 0.1% sodium azide was applied to the cells and incubated overnight at 4°C. Washed cells were incubated in 18-nm gold labelled donkey anti-goat IgG secondary antibody, 1% donkey serum and 0.1% sodium azide for 1 h at room temperature. Post-fixation was performed in 2% glutaraldehyde for 10 min followed by fixation with 1% osmium tetroxide for 1 h at room temperature. The cells were dehydrated through a graded ethanol series and embedded in epoxy resin. Ultrathin sections were collected on copper grids and stained with uranyl acetate and lead citrate prior to observation by transmission electron microscopy (EM) using a JEOL 2000 FX Transmission Electron Microscope.

M11 cells were also probed with mPR α (hmPR α , 836-4) antibody and goat anti-rabbit IgG 10-nm gold labelled secondary antibody. These cells were treated using the aforementioned

protocol with the following exceptions: firstly, cells were blocked in 1% bovine serum albumin (BSA), 10% goat serum; secondly, antibodies were diluted in 1% goat serum, 1% BSA and 0.1% sodium azide made up in 0.1 M Sorensen's phosphate buffer pH 7.0.

P4 binding. M11 cells incubated in Opti-MEM (Invitrogen) supplemented with 30 mM HEPES and 0.2% BSA were grown on glass bottomed Petri dishes. These were incubated with 100 nM progesterone 3-(O-carboxymethyl)oxime: BSA-fluorescein isothiocyanate conjugate (Sigma-Aldrich) for 10 and 45 min at room temperature prior to fixation with 4% paraformaldehyde for 10 min. After subsequent washes with PBS, the cells were permeabilised with 0.1% saponin, 0.5% BSA in PBS for 20 min. Fixed cells were then washed with PBS and incubated with a 1:300 dilution of phalloidin-Alexa fluor 568 (Molecular probes, UK) in 0.5% BSA PBS for 15 min prior to further PBS washes. The M11 cells were mounted with antifade solution (Citifluor-PBS, Citifluor Ltd., UK) and visualised using a Nikon Eclipse TE2000S confocal microscope.

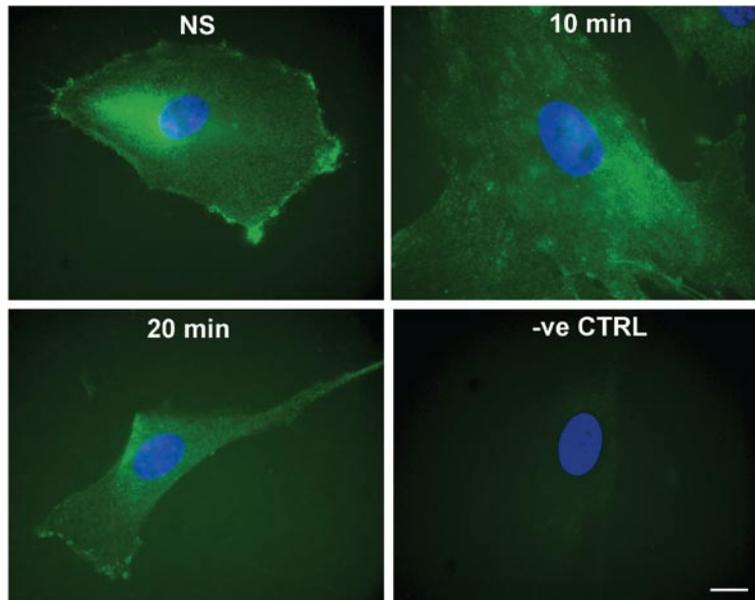
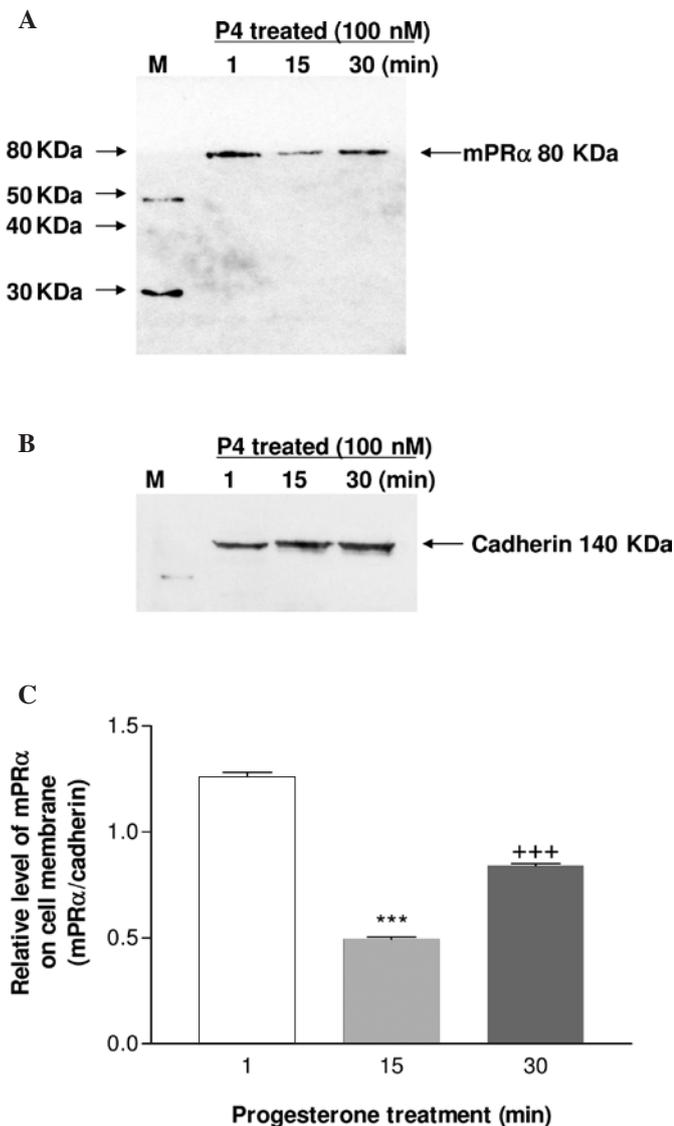


Figure 2. Distribution of mPR α in M11 cells upon stimulation with P4. Under basal conditions (NS), mPR α was predominantly confined to the cell surface. After 10 min of treatment with 100 nM P4, translocation of mPR α from the cell surface towards the cytoplasm was evident. However, after exposure to P4 for 20 min, a substantial amount of mPR α protein was localised back at the plasma membrane. Scale bar, 10 μ m. -ve CTRL, negative control immunostaining with secondary antibody only.



Statistical analysis. Expression mPR α protein was determined using Western blot analysis as described previously (11) and with semi-quantitative densitometry performed using NIH ImageJ (v1.26).

Results

Membrane binding of progesterone, expression and cellular distribution of mPR α in M11 cells. Membrane progesterone sites were detected in M11 cells upon incubation with P4 3-(O-carboxymethyl)oxime-BSA-FITC at room temperature for 20 min (Fig. 1A, panel I) and 45 min (Fig. 1A, panel II).

Expression of mPR α at the gene level was confirmed in M11 cells via RT-PCR (Fig. 1B). Furthermore, mPR α expression was verified at the protein level through indirect immunofluorescence (Fig. 1C) and immunogold electron microscopy (Fig. 1D), both of which depict characteristic plasma membrane localisation in M11 cells under basal conditions.

Electron microscopy is the gold standard and the most robust technique for determining the cellular distribution of mPR α within M11 cells. Using this technique, we verified that M11 cells have an intracellular environment rich in the mandatory organelles essential for transcription and translation processes (Fig. 1D, panel I). Immunogold EM provided

Figure 3. Western blot analysis of mPR α protein M11 plasma membranes after exposure to P4 for a 1-, 15- and 30-min duration. (A) M11 plasma membrane preparations (P4 100 nM for 1, 15 and 30 min) probed with an mPR α antibody resulting in 80 kDa bands. (B) Immunoblotting with a cadherin antibody shows equal membrane protein loading on the gel for each time point. (C) Semi-quantification of mPR α protein on M11 plasma membrane samples by the normalisation of mPR α protein with cadherin protein and semi-quantitative densitometry performed using NIH ImageJ (v1.26). Statistical differences were determined for each of the different P4 exposure times (***P<0.001 compared with 1 min; +++P<0.001 compared with 1 and 15 min; one way ANOVA).

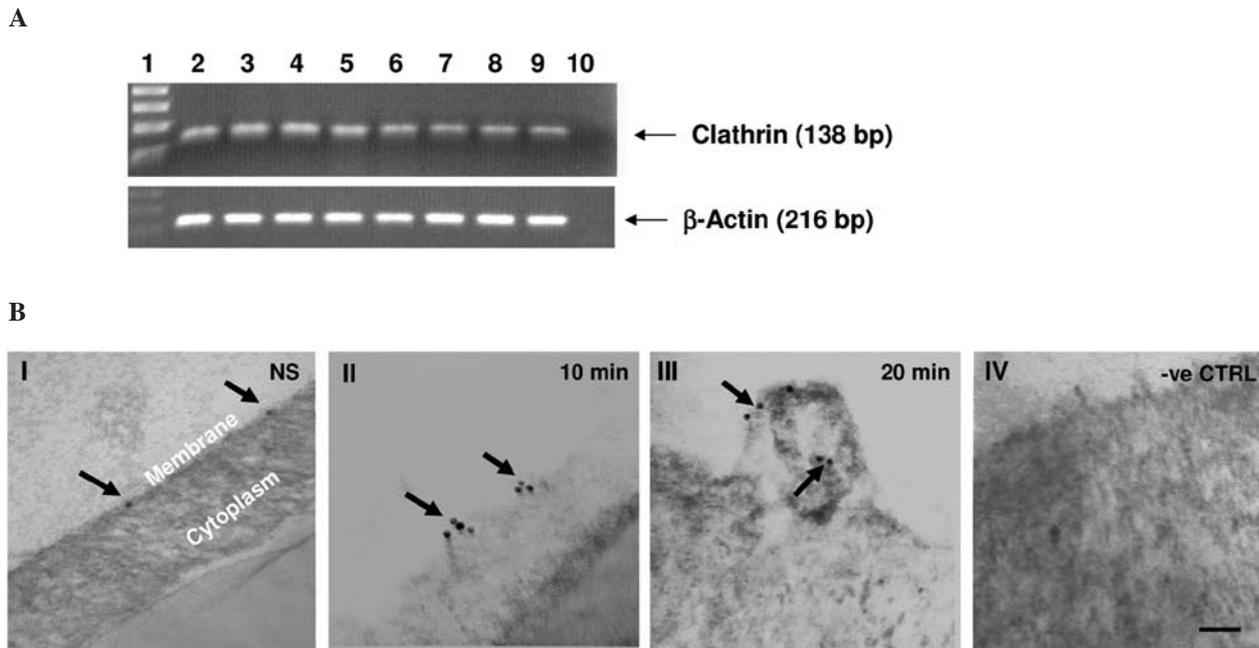


Figure 4. Expression of clathrin in M11 cells and its cellular distribution. (A) RT-PCR analysis for clathrin and β -actin in P4-treated M11 samples. Lane 1, DNA ladder; lane 2, NS; lanes 3-9, cDNA from M11 cells treated with P4 for 1, 3, 5, 10, 15, 20 and 30 min respectively; lane 10, negative control. (B) Immunogold electron microscopy illustrating the localisation and distribution of clathrin in M11 cells detected via a secondary antibody conjugated to 18 nm gold beads. This revealed clathrin (arrows) to be dispersed in non-P4-treated M11 cells (I). After exposure to P4 for 10 min, clathrin appeared to form clusters (II). At 20 min of P4 treatment, clathrin was present both on the cell membrane and internalised within the cytoplasm (III). IV, negative control. Scale bar, 100 nm.

irrefutable evidence for the first time that mPR α occupies a location at the cell membrane in M11 cells under basal conditions (Fig. 1D, panel II). Nevertheless, mPR α also occasionally occupied an intracellular locality within the cell cytoplasm (Fig. 1D, panel III).

Sequestration and trafficking of mPR α from the plasma membrane after P4 stimulation. To study the potential trafficking of mPR α and to further determine its distribution pattern, immunofluorescent analyses were conducted in M11 cells treated with P4 (100 nM) for 5, 10 and 20 min. In untreated cells, mPR α was localised both at the cell surface and cytoplasm (Fig. 2; NS). Following 5 min of P4 treatment, there was an altered distribution of the receptor with mPR α present both on the cell membrane and in the cytoplasm (data not shown). At 10 min of treatment, there was a clear decline in mPR α localised to the cell membrane (Fig. 2; 10 min), whereas at 20 min the receptor was again detected on the plasma membrane (Fig. 2; 20 min).

To confirm trafficking of mPR α following progesterone treatment, solubilised M11 plasma membrane preparations treated with 100 nM P4 for 1, 15 and 30 min (Fig. 3A) were subjected to Western blot analysis with mPR α specific antibodies. Plasma membrane levels of mPR α protein varied with the duration of P4 exposure. The highest level of mPR α protein was present at the membrane after a 1-min exposure to P4, with a subsequent reduction in levels at 15 min of treatment and an increase at 30 min. Western blot analysis using an antibody directed against cadherin (Fig. 3B), a transmembrane protein involved in cell adhesion, was used as a control to normalise mPR α protein levels in the plasma membrane (Fig. 3B). Normalised mPR α /cadherin levels showed a significant dif-

ference ($P < 0.001$) when comparing protein from the 15-min P4 exposure to the 1-min exposure, with a reduction in mPR α present at the plasma membrane at 15 min. A significant difference ($P < 0.001$) in mPR α protein levels also occurred when comparing the 30-min P4 exposure to the 1- and 15-min P4 exposures, with 30-min P4 levels being statistically lower than the 1-min levels, but higher than the 15-min levels (Fig. 3C). These data support the hypothesis that mPR α is expressed on the cell membrane, rapidly internalised after stimulation with P4, and then recycled/shuttled back to the plasma membrane.

Expression and distribution of clathrin in M11 cells. As mentioned previously, a major mechanism for the internalisation of GPCRs is via clathrin-mediated endocytosis. Therefore, in order to investigate the potential involvement of clathrin in the endocytosis of mPR α , we characterised its expression and trafficking in M11 cells. Semi-quantitative RT-PCR analysis revealed that, firstly, clathrin mRNA is expressed in M11 cells, and, secondly, that its expression remains unaltered with up to 30 min of P4 treatment (Fig. 4A). Immunogold EM was also used to reveal that there are distinct changes in the distribution of clathrin in P4-stimulated M11 cells. After 10 min of P4 treatment, there was a change in clathrin distribution, with a noticeable increase in cluster sequestration (Fig. 4B, panel II; 10 min compared to panel I; NS). At 20 min of P4 treatment, there was a distinct internalisation of clathrin in the cytoplasm, with some remaining on the plasma membrane (Fig. 4B, panel III; 20 min).

Co-distribution of mPR α with clathrin. Under basal conditions, clathrin was distributed throughout the cell (Fig. 5A; NS), whereas mPR α was predominantly limited to the plasma membrane. Little colocalisation between clathrin and mPR α

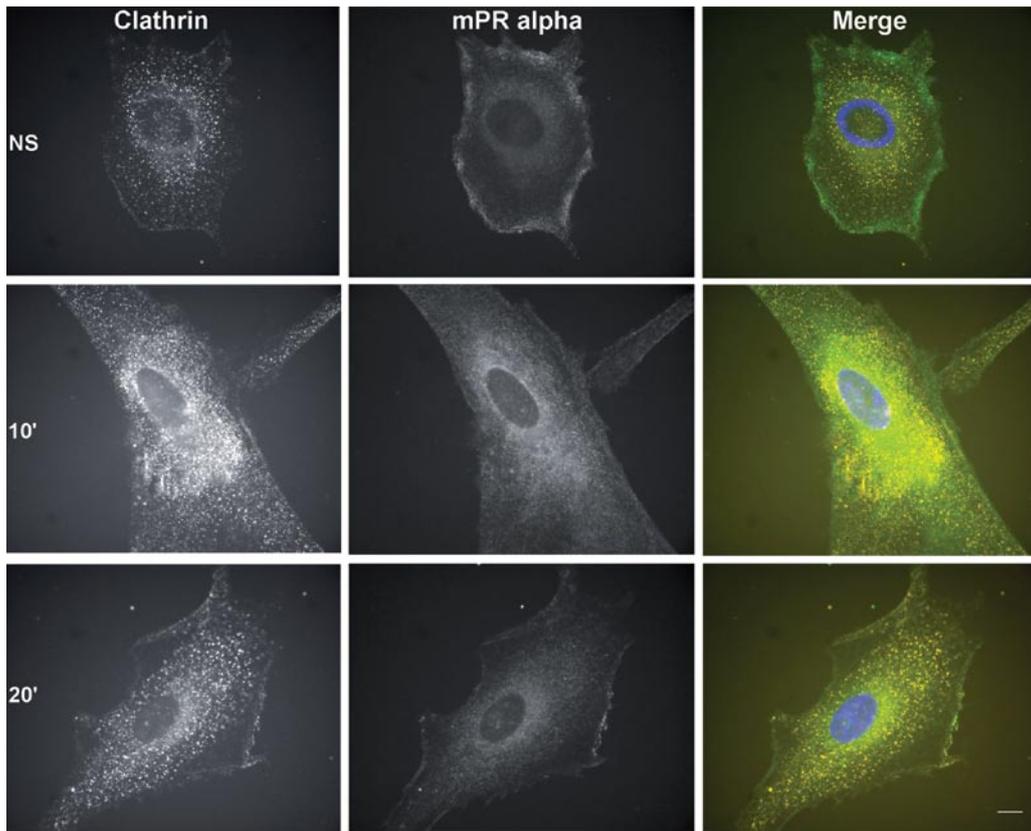


Figure 5. Colocalisation of mPR α and clathrin in P4-treated M11 cells. The immunofluorescent images depict the distribution and partial colocalisation of mPR α (green) and clathrin (orange) in M11 cells. Nuclei were counterstained with DAPI (blue). Clathrin and mPR α colocalisation was determined in M11 cells after treatment with P4 for 10 and 20 min. Scale bar, 10 μ M.

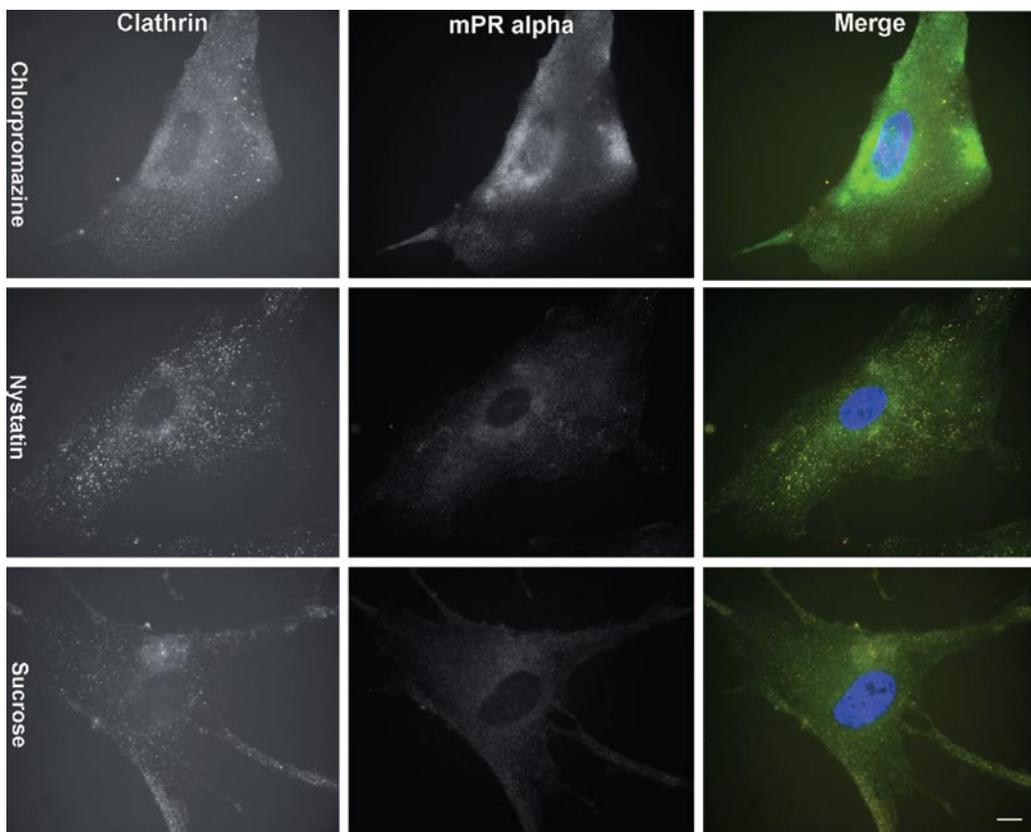


Figure 6. Effect of inhibitors on clathrin and mPR α endocytosis in M11 cells. M11 cells were exposed to P4 for 10 min prior to treatment with specific inhibitors to determine how this influences clathrin and mPR α endocytosis. The immunofluorescent images depict clathrin (orange) and mPR α (green) treated with chlorpromazine, nystatin or sucrose. Scale bar, 10 μ M.

was evident (Fig. 5A; NS). At 10 min of P4 exposure, both clathrin and mPR α were increasingly localised within the cell (Fig. 5A; 10 min). Partial colocalisation between mPR α and clathrin was determined, visible in the merged image as orange-coloured speckles (Fig. 5A; 10 min). The distribution of both mPR α and clathrin at 20 min of P4 treatment seemingly reverted to that observed under basal conditions (Fig. 5A; 20 min).

Use of endocytotic inhibitors to investigate potential internalisation pathways of mPR α . At 10 min of P4 exposure, internalisation and partial colocalisation of mPR α and clathrin was evident in the M11 cells (Fig. 5A; 10 min). Inhibitors of endocytosis were used on M11 cells, which were then exposed to 10 min of P4 treatment to examine the resultant distribution and colocalisation properties of clathrin and mPR α . Treatment of M11 cells with chlorpromazine resulted in an atypical clathrin distribution, with a reduction in observed clathrin speckles (Fig. 6; chlorpromazine). mPR α appeared to be sequestered in much larger, but fewer, clusters localised at either the cell membrane or the cellular interior (Fig. 6; chlorpromazine). No clear colocalisation between clathrin and mPR α was apparent (Fig. 6; chlorpromazine). Nystatin inhibitor did not alter the clathrin or mPR α distribution, nor their partial colocalisation, which is readily observed under standard conditions (Fig. 6; nystatin). Sucrose treatment of M11 cells altered mPR α distribution (Fig. 6; sucrose). The internal clustering of mPR α typically seen in M11 cells was also less apparent, with no observable internal sequestration of mPR α (Fig. 6; sucrose). Clathrin and mPR α did not appear to colocalise when treated with sucrose.

Discussion

In this study, we investigated the cellular distribution and trafficking of mPR α in a human myometrial cell line (M11). We chose this experimental model since it has been shown to have morphological characteristics typical of myometrial cells (16), and also expresses mPR α (11,17).

Immunofluorescent analysis revealed that mPR α has a similar subcellular distribution to that previously observed in human myometrial cells under basal conditions (11), and is localised on the plasma membrane, with some cytoplasmic expression. In agreement with these results, membrane localisation of mPRs has been demonstrated by several research groups in a variety of cell types (1,10,18-22). Other researchers have reported mPRs to be localised intracellularly in the endoplasmic reticulum (23-25). EM is the gold standard in high resolution imaging, and was used to conclusively determine the sub-cellular distribution of mPR α . mPR α occupies a cell membrane location under basal conditions, but intracellular mPR α is also apparent. These novel data incorporated EM for the first time to address mPR α distribution in any given cell type.

An important characteristic of 7TMRs is that they are rapidly internalised upon activation in a ligand-dependent manner, an event critical for their proper functioning (26). Currently, there is no information on the trafficking of mPR α . Therefore, we utilised an immunofluorescent approach to investigate the trafficking of mPR α . mPR α protein was re-distributed from the cell membrane in unstimulated cells,

becoming internalised at 10 min of P4 exposure. mPR α was presented back on the cell membrane at 20 min, but not to the levels previously seen under basal conditions. This was ligand specific, since treatment with the unrelated steroid cortisol (100 nM) and the nuclear PR activator R5020 (30 nM) did not induce any significant internalisation of the receptor in M11 cells (data not shown). The mPR α internalisation was confirmed by specific single-point P4 binding studies. At 20 min, there was a significant decrease in [³H]-P4 binding on the plasma membrane of M11 cells as compared with 1-min P4 treatment (data not shown). The decrease in membrane-bound mPR α may act as a desensitisation process to modulate rapid P4 signalling responses.

These data are consistent with the data in the literature, which indicate that the intracellular segregation of receptors due to endocytotic events is a common fate for 7TMRs. This provides another explanation for why several 7TMRs appear to be expressed in the cytoplasm (27), and may also explain why some investigators have observed mPRs intracellularly. In kidney tissue, mPR α was found to be restricted to the endoplasmic reticulum (ER) due to a C-terminal ER retention motif (25). This is not unusual for 7TMRs, since many require accessory proteins to ensure transport to the plasma membrane (28,29). An example is the melanocortin 2 receptor, which is localised within the ER and cannot be transported to the plasma membrane unless it is co-expressed with the melanocortin 2 receptor accessory protein (28). It is possible, therefore, that mPR α requires an accessory protein that is expressed in tissue- or cell-specific manner, thus affecting its transport to the membrane. These studies highlight the difficulty in drawing any firm conclusions on 7TMR trafficking (30), and present an argument for a higher order of complexity regarding mPR α distribution.

The next step of this study was to further dissect the endocytotic pathway(s) involved in mPR α trafficking. Endocytosis of activated receptors can be mediated via caveolae/lipid raft mechanisms (32) and clathrin-dependent endocytosis. Lipid rafts are sterol- and sphingolipid-rich membrane domains comprising caveolae subdomains involved in the endocytosis of various ligands (32,33). However, for most 7TMRs, endocytosis is implemented via clathrin-mediated mechanisms involving the formation of coated pits at the cell surface that concentrate surface protein/cargo for internalisation (34).

The role of clathrin in the endocytosis of mPR α in M11 cells was investigated. Following progesterone treatment, there was partial co-localisation of clathrin with mPR α , evident in Fig. 5 as orange speckles. In addition, co-immunoprecipitation studies show that clathrin is immunoprecipitated with mPR α , indicating a close association between these two proteins and suggesting that they may be coupled under certain conditions (data not shown). M11 cells were treated with various inhibitors of endocytosis prior to progesterone treatment. Inhibitors were chosen according to their ability to discriminate and inhibit different types of endocytotic pathways. Treatments included chlorpromazine and sucrose inhibitors specific for clathrin-mediated internalisation and nystatin, which inhibits caveolae/lipid-raft mediated endocytosis (35,36). These inhibitors do not demonstrate absolute selectivity between endocytotic pathways; nevertheless, they are commonly used to differentiate trafficking routes (37). Chlorpromazine inhibitor acts by preventing the adapter protein AP2 from binding to clathrin-

coated pits (12,38), whereas sucrose inhibitor acts by interfering with clathrin recruitment, coated pit formation and endocytosis (39). These inhibitors prevented the clathrin-mediated endocytosis of mPR α . Nystatin is a polyene antibiotic that inhibits caveolae/lipid raft-mediated endocytosis by the sequestration of cholesterol within the membrane, but does not affect clathrin-mediated endocytosis. Nystatin pre-treatment did not alter the internalisation of mPR α after 10 min of P4 exposure. Collectively, these data do not support a role for caveolae in the mediation of mPR α endocytosis. In line with these observations, 7TMRs have been found to predominantly use the clathrin-dependent endocytotic pathway, whereas caveolin and clathrin/caveolin-independent pathways appear to be used to a lesser extent (8,40,41). Interestingly, other uncharacterised endocytotic pathways may be involved in receptor trafficking. For instance, corticotropin-releasing hormone receptors appear to undergo endocytosis independent of clathrin or caveolin upon activation by urocortin (42). It is therefore possible that mPR α is also capable of internalising via another route, independent of clathrin or caveolin.

Potential changes in the phosphorylation status of the receptor may also affect its trafficking dynamics. There are two different types of kinases that can phosphorylate GPCRs: i) second-messenger-dependent kinases (e.g., PKC), and ii) GPCR kinases (GRKs). β -arrestins have an essential role following receptor phosphorylation, functioning as adaptor molecules that link receptors to clathrin-coated pits (43-45). Potential phosphorylation sites of mPR α were predicted using the NetPhosK Server. mPR α can be phosphorylated at two serine sites (positions 219, 229), three threonine sites (positions 32, 57 and 232) and three tyrosine sites (positions 143, 194 and 304). Future studies, using mutational analysis of these sites, will provide better insight regarding the potential role of mPR α phosphorylation in endocytotic events.

In summary, these data provide the first definitive evidence that mPR α can be localised on the plasma membrane and within the cytoplasm. This is particularly important given that receptor number on the cell surface is a fine balance between the rate of internalisation, recycling and new synthesis, and the fact that many receptors may also signal from endosomal compartments (3). Potential mechanisms involved in P4-mediated endocytosis have also been investigated, providing novel insight on mPR-mediated responses. Future studies should focus on determining mPR α degradation, recycling to the cell surface and activation of distinct intracellular pathways while internalised.

Acknowledgements

The authors thank John A. Copland for the kind gift of M11 cells. This research was funded by a National Institutes of Health Grant ESO ESO12961 to P.T. and E.K. We would also like to thank Dr David Ribé for the assistance in confocal microscopy.

References

- Zhu Y, Bond J and Thomas P: Identification, classification and partial characterization of genes in humans and other vertebrates homologous to a fish membrane progesterin receptor. *Proc Natl Acad Sci USA* 100: 2237-2242, 2003.
- Zhu Y, Rice CD, Pang Y, Pace M and Thomas P: Cloning, expression and characterization of a membrane progesterin receptor and evidence it is an intermediary in meiotic maturation of fish oocytes. *Proc Natl Acad Sci USA* 100: 2231-2236, 2003.
- Felberbaum-Corti M, van der Goot FG and Gruenberg J: Sliding doors: clathrin-coated pits or caveolae? *Nat Cell Biol* 5: 382-384, 2003.
- Mueller A, Kelly E and Strange PG: Pathways for internalization and recycling of the chemokine receptor CCR5. *Blood* 99: 785-791, 2002.
- Koenig JA and Edwardson JM: Endocytosis and recycling of G protein-coupled receptors. *Trends Pharmacol Sci* 18: 276-287, 1997.
- Von Zastrow M: Mechanisms regulating membrane trafficking of G protein-coupled receptors in the endocytic pathway. *Life Sci* 74: 217-274, 2003.
- Le Roy C and Wrana JL: Clathrin- and non-clathrin-mediated endocytic regulation of cell signalling. *Nat Rev Mol Cell Biol* 6: 112-126, 2005.
- Grampp T, Sauter K, Markovic B and Benke D: Gamma-aminobutyric acid type B receptors are constitutively internalized via the clathrin-dependent pathway and targeted to lysosomes for degradation. *J Biol Chem* 282: 24157-24165, 2007.
- Smith JL, Kupchak BR, Garitaonandia I, Hoang LK, Maina AS, Regalla LM and Lyons TJ: Heterologous expression of human mPR α , mPR β and mPR γ in yeast confirms their ability to function as membrane progesterone receptors. *Steroids* 73: 1160-1173, 2008.
- Thomas P, Pang Y, Dong J, Groenen P, Kelder J, De Vlieg J, Zhu Y and Tubbs C: Steroid and G protein binding characteristics of the seatrout and human progesterin membrane receptor-alpha subtypes and their evolutionary origins. *Endocrinology* 148: 705-718, 2007.
- Karteris E, Zervou S, Pang Y, Dong J, Hillhouse EW, Randeva HS and Thomas P: Progesterone signalling in human myometrium through two novel membrane G protein-coupled receptors: potential role in functional progesterone withdrawal at term. *Mol Endocrinol* 20: 1519-1534, 2006.
- Wang LH, Rothberg KG and Anderson RG: Mis-assembly of clathrin lattices on endosomes reveals a regulatory switch for coated pit formation. *J Cell Biol* 123: 1107-1117, 1993.
- Hartung A, Bitton-Worms K, Rechtman MM, Wenzel V, Boergermann JH, Hassel S, Henis YI and Knaus P: Different routes of bone morphogenic protein (BMP) receptor endocytosis influence BMP signalling. *Mol Cell Biol* 26: 7791-7805, 2006.
- Idkowiak-Baldys J, Becker KP, Kitatani K and Hannun YA: Dynamic sequestration of the recycling compartment by classical protein kinase C. *J Biol Chem* 281: 22321-22333, 2006.
- Heuser JE and Anderson RG: Hypertonic media inhibit receptor-mediated endocytosis by blocking clathrin-coated pit formation. *J Cell Biol* 108: 389-400, 1989.
- Devost D and Zingg HH: Novel in vitro system for functional assessment of oxytocin action. *Am J Physiol Endocrinol Metab* 292: 1-6, 2007.
- Fernandes MS, Pierron V, Michalovich D, Astle S, Thornton S, Peltoketo H, Låam EW, Gellersen B, Huhtaniemi I, Allen J and Brosens JJ: Regulated expression of putative membrane progesterin receptor homologues in human endometrium and gestational tissues. *J Endocrinol* 187: 89-101, 2005.
- Dosiou C, Hamilton AE, Pang Y, Overgaard MT, Tulac S, Dong J, Thomas P and Guidice LC: Expression of membrane progesterone receptors (mPRs) on human T lymphocytes and Jurkat cells and activation of G proteins by progesterone. *J Endocrinol* 196: 67-77, 2008.
- Hanna R, Pang Y, Thomas P and Zhu Y: Cell surface expression, progesterin binding and rapid nongenomic signaling of zebrafish membrane progesterin receptors α and β in transfected cells. *J Endocrinol* 190: 247-260, 2006.
- Ben-Yehoshua LF, Lewellyn AL, Thomas P and Maller JL: The role of Xenopus membrane progesterone receptor β in mediating the effect of progesterone on oocyte maturation. *Mol Endocrinol* 21: 664-673, 2007.
- Nutu M, Weijdegård B, Thomas P, Bergh C, Thurin-Kjellberg A, Pang Y, Billig H and Larsson DG: Membrane progesterone receptor-gamma: tissue distribution and expression in ciliated cells in the fallopian tube. *Mol Reprod Dev* 74: 843-850, 2007.
- Tubbs C and Thomas P: Progesterin signaling through an olfactory G protein and membrane progesterin receptor-alpha in Atlantic croaker sperm: potential role in induction of sperm hypermotility. *Endocrinology* 150: 473-484, 2009.

23. Krietsch T, Fernandes MS, Kero J, Lösel R, Heyens M, Lam EW, Huhtaniemi I, Brosens JJ and Gellersen B: Human homologs of the putative G protein-coupled membrane progesterin receptors (mPR α , β and γ) localize to the endoplasmic reticulum and are not activated by progesterone. *Mol Endocrinol* 20: 3146-3164, 2006.
24. Ashley RL, Clay CM, Farmerie TA, Niswender GD and Nett TM: Cloning and characterization of an ovine intracellular seven transmembrane receptor for progesterone that mediates calcium mobilization. *Endocrinology* 147: 4151-4159, 2006.
25. Lemale J, Bloch-Faure M, Grimont A, El Abida B, Imbert-Teboul M and Crambert G: Membrane progesterin receptors alpha and gamma in renal epithelium. *Biochim Biophys Acta* 1783: 2234-2240, 2008.
26. Moore CA, Milano SK and Benovic JL: Regulation of receptor trafficking by GRKs and arrestins. *Annu Rev Physiol* 69: 451-482, 2007.
27. Thompson MD, Burnham WM and Cole DE: The G protein-coupled receptors: pharmacogenetics and disease. *Crit Rev Clin Lab Sci* 42: 311-392, 2005.
28. Cooray SN, Almiro do Vale I, Leung KY, Webb TR, Chapple JP, Egertová M, Cheetham ME, Elphick MR and Clark AJ: The melanocortin 2 receptor accessory protein exists as a homodimer and is essential for the function of the melanocortin 2 receptor in the mouse y1 cell line. *Endocrinology* 149: 1935-1941, 2008.
29. Cooray SN, Chan L, Metherell L, Storr H and Clark AJ: Adrenocorticotropin resistance syndromes. *Endocr Dev* 13: 99-116, 2008.
30. Gellersen B, Fernandes MS and Brosens JJ: Non-genomic progesterone actions in female reproduction. *Hum Reprod Update* 15: 119-138, 2009.
31. Thomas P: Characteristics of membrane progesterin receptor alpha (mPR α) and progesterone membrane receptor component one (PGMRC1) and their roles in mediating rapid progesterin actions. *Front Neuroendocrinol* 29: 292-312, 2008.
32. Nabi IR and Le PU: Caveolae/raft-dependent endocytosis. *J Cell Biol* 161: 673-677, 2003.
33. Lajoie P and Nabi IR: Regulation of raft-dependent endocytosis. *J Cell Mol Med* 11: 644-653, 2007.
34. Mousavi SA, Malerød L, Berg T and Kjekken R: Clathrin-dependent endocytosis. *Biochem J* 377: 1-16, 2004.
35. Grewal JS, Luttrell LM and Raymond JR: G protein-coupled receptors desensitize and down-regulate epidermal growth factor receptors in renal mesangial cells. *J Biol Chem* 276: 27335-27344, 2001.
36. Rakhit S, Pyne S and Pyne NJ: Nerve growth factor stimulation of p42/p44 mitogen-activated protein kinase in PC12 cells: role of G(i/o), G protein-coupled receptor kinase 2, beta-arrestin I and endocytic processing. *Mol Pharmacol* 60: 63-70, 2001.
37. Tulapurkar ME, Schäfer R, Hanck T, Flores RV, Weisman GA, González FA and Reiser G: Endocytosis mechanism of P2Y2 nucleotide receptor tagged with green fluorescent protein: clathrin and actin cytoskeleton dependence. *Cell Mol Life Sci* 62: 1388-1399, 2005.
38. Kanerva A, Raki M, Ranki T, Särkioja M, Koponen J, Desmond RA, Helin A, Stenman UH, Isoniemi H, Höckerstedt K, Ristimäki A and Hemminki A: Chlorpromazine and apigenin reduce adenovirus replication and decrease replication associated toxicity. *Gene Med* 9: 3-9, 2007.
39. Smith J, Yu R and Hinkle PM: Activation of MAPK by TRH requires clathrin-dependent endocytosis and PKC but not receptor interaction with beta-arrestin or receptor endocytosis. *Mol Endocrinol* 15: 1539-1548, 2001.
40. Ferguson SS: Evolving concepts in G protein-coupled receptor endocytosis: the role in receptor desensitization and signaling. *Pharmacol Rev* 53: 1-24, 2001.
41. Marchese A, Chen C, Kim YM and Benovic JL: The ins and outs of G protein-coupled receptor trafficking. *Trends Biochem Sci* 28: 369-376, 2003.
42. Tu H, Kastin AJ and Pan W: Corticotropin-releasing hormone receptor (CRHR)1 and CRHR2 are both trafficking and signaling receptors for urocortin. *Mol Endocrinol* 21: 700-711, 2007.
43. Ferguson SS, Downey WE III, Colapietro AM, Barak LS, Ménard L and Caron MG: Role of beta-arrestin in mediating agonist-promoted G protein-coupled receptor internalization. *Science* 27: 363-366, 1996.
44. Lefkowitz RJ and Shenoy SK: Transduction of receptor signals by beta-arrestins. *Science* 308: 512-517, 2005.
45. Pierce KL and Lefkowitz RJ: Classical and new roles of beta-arrestins in the regulation of G-protein-coupled receptors. *Nat Rev Neurosci* 2: 727-733, 2001.
46. Felberbaum-Corti M and Gruenberg J: Signaling from the far side. *Mol Cell* 10: 1259-1260, 2002.