Inducible upregulation of oestrogen receptor-β1 affects oestrogen and tamoxifen responsiveness in MCF7 human breast cancer cells

L C Murphy1,2, B Peng1,2, A Lewis1,2, J R Davie1,2, E Leygue1,2, A Kemp2, K Ung2, M Vendetti3 and R Shiu2,3

1Department of Biochemistry and Medical Genetics, University of Manitoba, Winnipeg, Manitoba, Canada
2Manitoba Institute of Cell Biology, University of Manitoba, Winnipeg, Manntoba, Canada
3Department of Physiology, University of Manitoba, Winnipeg, Manitoba, Canada

Abstract

To investigate the effect of altered oestrogen receptor (ER)α and ERβ expression on oestrogen and anti-oestrogen action in breast cancer, we have stably expressed an inducible ERβ1 in MCF7 breast cancer cells. Stably expressing clones were isolated and over-expression of ERβ1 correlated with increased levels of specific radiolabelled oestradiol (E2) binding. Increased ERβ1 did not affect endogenous levels of ERα but increased progesterone receptor (PR) levels. Over-expression of ERβ1 reduced growth responses to E2 in contrast to little if any effect of over-expression of ERα. In oestrogen-replete conditions, over-expression of ERβ1 but not ERα reduced proliferation. Over-expression of ERβ1 did not result in anti-oestrogen resistance but was associated with increased sensitivity to 4-hydroxytamoxifen. Our results suggested that over-expression of ERβ1 in the presence of an endogenously expressed ERα was associated with tamoxifen sensitivity but may negatively modulate ERα-mediated growth. However, not all ERα activities were inhibited since endogenous PR expression was increased by both ERα and ERβ1 over-expression. These data parallel those seen in some in vivo studies showing a relationship between PR and ERβ expression as well as ERβ expression and tamoxifen sensitivity of ER-positive breast cancer patients. These models are relevant and will be useful for dissecting the role of ERβ1 expression in ER-positive breast cancer.

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Introduction

Oestrogens are considered to be major driving forces in breast tumourigenesis and breast cancer progression (Colditz 1998, Clemons & Goss 2001). Current evidence suggests that oestrogen action is primarily mediated through two receptors, oestrogen receptor (ER)α and ERβ (Kuiper et al. 1996). These structurally related receptors are generally considered to be ligand-regulated transcription factors which classically modulate target gene transcription by binding to oestrogen responsive sequences (ERE) in target gene promoters (McDonnell & Norris 2002). There is evidence that ERα and ERβ can be expressed together in some cell types and independently expressed in others (Dotzlaw et al. 1997, Enmark et al. 1997). Based on studies in which ERβ expression was determined at the protein level by immunohistochemistry (IHC) (Jarvinen et al. 2000, Jensen et al. 2001, Mann et al. 2001, Omoto et al. 2002, Saunders et al. 2002) and ERα was determined by IHC or by enzyme-linked immunoassay, an estimated frequency of ERα and ERβ status in breast tumors was obtained (Murphy et al. 2003). The most frequently occurring status is ERα positive/ERβ positive (59%) with similar frequencies of between 11 and 17% for the other three ER phenotypes. It is important to note that there are two groups of ERβ-expressing breast tumors, those with coexpression of ERα, and those that express ERβ alone. The former occurs most frequently and, under experimental conditions when ERα and ERβ are coexpressed, they form heterodimers preferentially over homodimerization (Cowley et al. 1997). It is likely that homodimers of ERα, homodimers of ERβ and ERα/ERβ heterodimers will differentially affect gene expression. Further, transient coexpression of ERα and ERβ in cell lines results in ERβ-induced reduction of ERα activity at low ligand concentrations, as measured using ERE-regulated reporters (Hall & McDonnell 1999), suggesting that ERβ can directly modulate ERα activity in an inhibitory fashion. This may be a mechanism for differential oestrogen sensitivity and some reports have documented the differential expression of these two receptors under conditions of altered oestrogen sensitivity (Leygue et al. 1998a,
Interestingly, ERβ expression is downregulated and ERα expression upregulated during human breast tumourigenesis, suggesting that the ability of ERβ to modulate ERα may be altered during breast tumourigenesis (Leygue et al. 1998a, Roger et al. 2001). This correlates with altered oestrogen sensitivity and activity occurring during breast tumourigenesis (Murphy & Watson 2002). In addition, altered oestrogen action can occur during breast cancer progression and this is thought to underlie the development of tamoxifen resistance (Clarke et al. 2001). Increased expression and/or activity of ERβ has been suggested as a mechanism of tamoxifen resistance, but the data are controversial (Paech et al. 1997, Speirs et al. 1999, Mann et al. 2001, Murphy et al. 2002).

To investigate further the effect of altered relative expression of ERα and ERβ on oestrogen and anti-oestrogen action in human breast cancer cells, we have stably expressed a tetracycline-inducible (Tet-on) human ERβ in MCF7 human breast cancer cells, which endogenously express high ERα but low ERβ levels (Dotzlaw et al. 1997, Fuqua et al. 1999). The effect of altering the relative expression of these two ERs on oestrogen- and anti-oestrogen-regulated proliferation, as well as on endogenous markers of ER activity such as progesterone receptor (PR) (Osborne 1998), has been determined in this model system.

Materials and methods

Plasmids

Epitope-tagged tetracycline-inducible human ERβ1 (full-length) expression plasmids were generated. Human ERβ1 long form of 530 amino acids (Leygue et al. 1998a, Ogawa et al. 1998b) was tagged at its N-terminus with a polyhistidine and an Xpress epitope tag using the pcDNA4/HisMax(A) plasmid (Invitrogen Canada Inc., Burlington, Ontario, Canada) and characterized as previously described (Peng et al. 2003). This cDNA was then subcloned downstream of the tetracycline-inducible promoter in the pTRE2hyg plasmid (Gossen et al. 1995) (Clontech Laboratories Inc., Palo Alto, CA, USA). This construct contains the selectable hygromycin resistance gene on the same plasmid as the inducible gene.

Hormones and reagents

Oestradiol-17β (E2) and the tetracycline analogue doxycycline were obtained from Sigma Chemical Co. (Oakville, Ontario, Canada). Hygromycin B was obtained from Clontech and G418 was from Invitrogen Canada Inc.

Cell culture and transfection

The cells were routinely cultured in Dulbecco’s modified Eagles’ medium (DMEM) containing 5% (v/v) foetal calf serum (FBS), 0·4% (w/v) glucose, glutamine and penicillin–streptomycin and 10 nM E2 (5% CM) as previously described (Peng et al. 2003). To obtain oestrogen-depleted cells, the culture medium of stock cells (approximately 50% confluent) was changed to phenol red-free DMEM supplemented with 5% (v/v) FBS that has been treated twice with charcoal/dextran, glucose, glutamine and penicillin-streptomycin (5% CS) and replaced every 2 days. The cells were grown for a least a week and not more than 2 weeks in this oestrogen-depleted medium, and were passaged once during this time. When oestrogen-depleted cells were around 50% confluent, they were harvested and used for experiments. For transfection, MCF7-clone 89 cells (Venditti et al. 2002) were grown in 10% CM in 100 mm dishes until 90% confluent. The cells were then split into three 100 mm dishes and the next day transfected (2–4 µg linearized plasmid per dish) using the Effectene transfection reagent according to the manufacturer’s instruction (QIAGEN, Mississauga, Ontario, Canada). Two days after transfection the medium was changed to 10% CM plus 500 µg/ml G418 and 400 µg/ml hygromycin, and the medium was changed every day for 4 days and then every 3 days. Approximately 2 weeks later, hygromycin resistance colonies began to appear and 120 large, healthy colonies were transferred to 96-well plates and screened after suitable numbers of cells were achieved as described below.

Generation of MCF7 human breast cancer cells with doxycycline-inducible epitope tagged human ERβ1

The generation and characterization of MCF7 cells stably expressing reverse tetracycline transactivator (rTA), clone 89 rTA) have been previously described (Venditti et al. 2002). These cells (clone 89) were transfected and selected as described above. Resistant clones were screened by Western blotting for doxycycline-inducible His-Xpress-ERβ1 expression (tagged-ERβ1), using anti-Xpress antibody (no. R910–25; Invitrogen Canada Inc.; 1/5000 in 20 mM Tris base, 0·137 M NaCl, pH 7·5 and 0·1% (v/v) Tween-20 (TBST)) as previously described (Peng et al. 2003). Multiple positive clones were isolated and two independent clones were selected for further characterization.

RNA extraction and RT-PCR conditions

Total RNA was extracted from frozen cell pellets using Trizol reagent (Life Technologies, New York, NY, USA) according to the manufacturer’s instructions. One
microgram of total RNA was reverse transcribed, as previously described (Miksicek et al. 2002).

The primers used consisted of PR-U primer (5'-CACAAAACCTGACACCTCCACTTC-3'; sense; located in PR 2290–2313) and PR-L primer (5'-GCAAAATACAGGATCTTGCAC-3'; antisense; located in PR 2490–2513). Nucleotide positions given correspond to sequences of the human PR cDNA (accession number M15716). PCR amplifications were performed and PCR products analyzed as previously described (Miksicek et al. 2002). Each PCR consisted of 28 cycles (30 s at 94 °C, 30 s at 55 °C and 30 s at 72 °C). PCR products were then resolved by electrophoresis on 1·5% agarose gels. Following electrophoresis, the gels were stained with ethidium bromide, as previously described (Miksicek et al. 2002). Amplification of the ubiquitously expressed glyceraldehyde-3-phosphate dehydrogenase (GAPDH) cDNA was performed in parallel and PCR products were visualized on agarose gels stained with ethidium bromide as previously described (Miksicek et al. 2002). Three independent PCRs for PR and GAPDH were performed for each experiment. Signals visualized by u.v. irradiation on a GelDoc 2000/ChemiDoc System (Bio-Rad, Mississauga, Ontario, Canada) were quantified by densitometry using the Quantity One software (version 4·2; Bio-Rad). PR was normalized to GAPDH in each experiment as previously described (Miksicek et al. 2002).

Whole cell ligand-binding assays

ER ligand-binding assays were done using the whole cell binding method as previously described (Coutts et al. 1996) following oestrogen depletion of the cells by two passages in 5% CS as previously described (Coutts et al. 1996).

Western blotting

Western blotting was carried out essentially as previously described (Adeyinka et al. 2002, Peng et al. 2003) with minor modifications. ERα was detected using 1/1000 dilution of an ERα mouse monoclonal antibody (NCL-ER-6F11; Novacastra Labs Ltd, Newcastle on Tyne, Tyne and Wear, UK) in TBST buffer. PR was detected using 1/1000 dilution of a PR mouse monoclonal antibody (NCL-PGR-AB; Novocastra Labs Ltd) in TBST and α-tubulin was detected using 1/12 000 dilution of tubulin-α antibody 2 (mouse monoclonal, clone DM1A; Neomarkers, Fremont, CA, USA). All membranes were incubated for 1 h at room temperature in 0·2% I-block (Tropix, Bedford, MA, USA) in Tris-buffered Saline (TBS). The blot was washed for 10 min at room temperature in TBST and then incubated with the appropriate dilution of primary antibody overnight at 4 °C. This incubation was followed by five 5-min washes in TBST, and then incubation with secondary antibody for 1 h at room temperature (goat anti-mouse IgG-HRP; Jackson Immuno Research Labs Inc., West Grove, PA, USA; 1/5000 in TBST). The blot was washed five times for 5 min with TBST and the signal was visualized using Supersignal West Dura Extended Duration Substrate kit (Pierce, Rockford, IL, USA) according to the manufacturer’s instructions. Signal detection and documentation used the ChemiDoc Gel Documentation System 2000 (Biorad Labs Canada, Mississauga, Ontario, Canada).

Immunofluorescence

Eleven days prior to slide preparation, stock cells were placed in medium containing 5% tetracycline-free FBS (BD Bioscience Clontech, Palo Alto, CA, USA), and the medium was changed every 3 days. These cells were then harvested and 1 × 10⁴ cells in 1 ml medium was added to each well of 4-chambered Falcon culture slides (Becton Dickinson, Franklin Lakes, NJ, USA). For every cell line used, one well was treated with vehicle alone and the duplicate well was treated with 1 µg/ml doxycycline for 48 h. Each chamber slide consisted of two wells of control MCF7-clone 89 cells and two wells of a tagged-ERβ1 subclone of cells. Following incubation, the medium was removed by aspiration and the slides were washed with 1 × phosphate-buffered saline (PBS) for 2 min. The PBS was removed and the cells were fixed and permeabilized with paraformaldehyde solution (3·7% formaldehyde and 0·18% Triton-X-100 in PBS) for 30 min at 37 °C. The slides were then washed in 1 × PBS for 5 min at room temperature, with agitation. Slides were then removed from the washing solution and, while still damp, they were coated with a hydrophobic barrier around the outside edge using an ImmEdge pen (Vector Laboratories Inc., Burlingame, CA, USA). Inside the barrier the cells were covered in 1 ml blocking solution (1% (w/v) BSA and 1% (v/v) normal goat serum in PBS) and incubated for 30 min at 37 °C in a humidified chamber to prevent evaporation. The blocking solution was removed and the cells were incubated with mouse anti-Xpress antibody (1/750 in blocking solution; Invitrogen Canada Inc.) for 1 h at room temperature. The slides were then washed three times with PBS for 5 min with agitation. Slides were then moved to a dark room and then incubated with CY3-labelled goat anti-mouse secondary antibody (1/10 000 in blocking solution) for 1 h at room temperature. This was followed by three 5-min washes at room temperature with PBS with agitation. The cells were stained with Hoechst dye (no. 33258; Sigma Chemical Co., catalogue number B2883; 1/10 000 in blocking solution) for 20 min at room temperature, followed by two washes in PBS for 6 min at room temperature.
temperature. Slides were allowed to stand in PBS for a further 20 min at room temperature, then drained and one drop of Fluorsave reagent (Calbiochem, Hornby, Ontario, Canada) per well was applied. A coverslip was then added and sealed with clear nail polish. The slides were stored in the dark overnight at 4°C and fluorescent images obtained using a Nikon Eclipse E1000 microscope (Nikon, Mississauga, Ontario, Canada) using ACT-1 software (Nikon). All exposure times were for 1 s.

Half-life determination of tagged-ERβ1

To determine the effect of various ligands on the half-life of tagged-ERβ1, cells were set-up in 5% CS and left overnight. The media were changed and then the cells were treated for 48 h with 2 µg/ml doxycycline. The next day the cells were washed three times with 5% CS without doxycycline, and then treated with ethanol alone, E2 (10 nM), 4-hydroxy-tamoxifen (4-OH-tamoxifen; 500 nM) or ICI 182780 (500 nM; a gift kindly provided by AstraZeneca, Macclesfield, Cheshire, UK). Cells were harvested at 0, 2, 3, 4, 6, 8, 10, 12, 15 and 24 h after treatment. Cell extracts were analyzed by Western blot for tagged-ERβ1 and tubulin expression. Tagged-ERβ1 normalized to the tubulin signals from the same blot was quantified by densitometry using the Quantity One software (version 4·2; Bio-Rad). The half-life of tagged-ERβ1 when bound to various selective ER modulators (SERMs) was estimated using the line of best fit on a semi-log plot from two independent experiments.

Cell proliferation assay

Cells depleted of oestrogen for at least a week by passage in 5% CS were set-up at 5×10⁴ cells per well in 6-well plates in 5% CS. The cells were left overnight and then treated with 2 µg/ml doxycycline or vehicle alone for 48 h. Cells maintained in the presence or absence of doxycycline then were either treated with E2 (10 nM) or vehicle alone. Triplicate wells were counted electronically (Beckman Coulter Canada Inc., Mississauga, Ontario, Canada) at the times indicated after the start of E2 treatment. Medium was changed every 2 days.

Cells grown in 5% CM were set-up at 10⁴ cells per well in 6-well plates in 5% CM, left overnight and then treated with 2 µg/ml doxycycline or vehicle alone for 48 h. Cells were maintained in the presence or absence of doxycycline and treated with varying concentrations of 4-OH-tamoxifen or vehicle alone. Triplicate wells were counted electronically (Beckman Coulter Canada Inc.) at the indicated times after the start of treatment. Medium was changed every 2 days. Doubling times were calculated from the initial (nᵢ) and final (nₜ) cell numbers from the equation: doubling time (DT) = t log₂/
log(n\textsubscript{i})/(n\textsubscript{t}), where \( t \) is time in days between \( n\textsubscript{i} \) and \( n\textsubscript{t} \).

Proliferation rate =\( \frac{\text{DT (control)}}{\text{DT (treated)}} \times 100\% \).

**Statistical analysis**

ANOVA followed by \( t \)-test analyses was used as appropriate.

**Results**

**Identification of doxycycline-inducible tagged-ER\textbeta\textsubscript{1}-expressing MCF7 cell lines**

Two clones, a low-expressor (\( \beta \)-low) and a high expressor (\( \beta \)-high) shown to express doxycycline-inducible tagged-ER\( \beta \text{1} \) by Western blot analysis were chosen for further characterization. Controls were the original previously described MCF7 cell line stably expressing rTA (Venditti et al. 2002) and these MCF7 cells transfected with the empty pTRE2 hgy plasmid alone (V). As an additional control we included an MCF7 cell line stably transfected with a doxycycline-inducible GFP-tagged ER\( \alpha \) expression vector (\( \alpha \)-high) (Htun et al. 1999, Zhao et al. 2002). Preliminary experiments showed that induction of the tagged-ER\( \beta \text{1} \) was dependent on the dose of doxycycline used, and maximum induction in any one clone was achieved by treating the cells for 48 h with 1–2 \( \mu \)g/ml doxycycline. A Western blot of the cell lines grown in 5% CS+doxycycline treatment for 48 h is shown in Fig. 1A. A single band of approximately 62 kDa was detected only in the doxycycline-treated tagged-ER\( \beta \text{1} \)-transfected lines but not in control cell lines, MCF7, V and \( \alpha \)-high. The level of tagged-ER\( \beta \text{1} \) expression in each of the clones was different with \( \beta \)-high>\( \beta \)-low. When these cell lines were grown on glass slides, fixed and the tagged-ER\( \beta \text{1} \) visualized using anti-Xpress antibody, significant fluorescence was only found over the nucleus (determined by Hoechst staining) of doxycycline-treated tagged-ER\( \beta \text{1} \) clones, with little, if any, signal detected in doxycycline-treated MCF7 cells. An example of the data obtained is shown in Fig. 2. These data were consistent with a general localization of the tagged-ER\( \beta \text{1} \) product in or associated with the nucleus, although we cannot exclude localization of minor levels.
of tagged-ERβ to other subcellular compartments such as the mitochondria (Yang et al. 2004).

**Effect of tagged-ERβ1 expression on ERα expression and E2 ligand-binding assays**

Under conditions where the medium was depleted of oestrogen (5% CS as described in Materials and methods), little if any effect of tagged-ERβ1 expression on endogenous ERα expression was seen (Fig. 1B), and similar amounts of endogenous ERα were expressed in control and tagged-ERβ1 over-expressing cells. Protein loading was assessed by alpha-tubulin levels on the same blot (Fig. 1C). In order to determine the functional level of tagged-ERβ1 over-expression achieved relative to the endogenous level of ER (primarily due to ERα since only very low levels of ERβ have been identified in these cells (Dotzlau et al. 1997, Fuqua et al. 2003)) under these conditions, whole cell ligand-binding assays were carried out on cells grown in 5% CS with and without treatment for 48 h with 2 µg/ml doxycycline. The results of several independent experiments are presented in Table 1. A significant increase in specific [3H]E2 binding compared with the non-expressing controls (MCF7 and V) as well as the no doxycycline treatment controls was measured in all doxycycline-treated tagged-ERβ1 (β-high, β-low) and the α-high over-expressing cell lines. In addition, the levels of binding induced by doxycycline correlated with the level of tagged-ERβ1 induced by doxycycline as determined by Western blot analysis, β-high>β-low (Fig. 1A). Doxycycline induction of tagged-ERα in the α-high cell line under these same conditions led to an increase in ligand binding similar to that obtained in β-high tagged-ERβ1 cells. These data were consistent with the increased E2 binding being due to the induced expression of tagged-ERβ1 or tagged-ERα after 48 h doxycycline treatment in 5% CS.

Treatment of cells containing doxycycline-induced ERβ1 with E2 (10 nM) for 24 h resulted in down-regulation of the tagged-ERβ1 (Fig. 3A) in parallel to the expected down-regulation of the endogenous ERα (Fig. 3B), as did treatment with ICI 182780 (500 nM). In contrast, the tagged-ERβ1 was stabilized by 24 h of 4-OH-tamoxifen (500 nM) treatment (Fig. 3A). These data are similar to previously published data demonstrating differential effects of various SERMs on steady-state levels of ERα (Fig. 3B) (Wijayaratne & McDonnell 2001). The functional consequences of the various ligands were assessed by PR expression and are consistent with previous reports (Read et al. 1988, Aronica & Katzenellenbogen 1991). Signals obtained from Western blot analyses of time-course experiments of tagged-ERβ normalized to the tubulin signals from the same blot were quantified by densitometry using the Quantity One software (version 4.2; Bio-Rad). The half life of tagged-ERβ using the line of best fit on a semi-log plot was estimated when bound to various SERMs. The estimated half-life of tagged-ERβ1 in the absence of E2 was 7.75 h, while in the presence of E2 it was 2.25 h. Treatment with 4-OH-tamoxifen stabilized the receptor, increasing its half-life to approximately 28.5 h, while treatment with ICI 182780 resulted in a decreased tagged-ERβ1 half-life compared with vehicle-treated controls. The estimated half-life of tagged-ERβ1 in the presence of ICI 182780 was 4.5 h.

**Effect of tagged-ERβ1 expression on endogenous PR expression in MCF7 human breast cancer cells**

To determine if tagged-ERβ1 expression affected known oestrogen-responsive endogenous targets, we investigated the level of expression of a known oestrogen-responsive gene product, PR. Under oestrogen-depleted conditions in MCF7 cells, the level of PR expression is markedly reduced and usually not detectable using our Western blot conditions. However, after doxycycline treatment, PR levels were significantly increased in all tagged-ERβ1 over-expressing clones (Figs 3B and 4). Furthermore, the increase in level of PR expression was correlated to the level of transgene expression in the different clones, β-high>β-low (Fig. 4). When the cells were treated with E2 for 24 h following 48 h of doxycycline, there was a further induction of PR expression in all tagged-ERβ1-expressing clones (Fig. 3B).
for β-low, data not shown for β-high) as well as the expected E2-induced PR expression in the non-tagged-ERβ1-expressing MCF7 control cells (data not shown).

Since PR is regarded as a gold standard downstream marker of ERα activity we determined what effects upregulation of tagged-ERα (α-high) would have on PR expression. As shown in Fig. 4, increased tagged-ERα (α-high) also resulted in an induction of PR expression found under these conditions. A further increase in PR expression was seen in α-high cells with E2 treatment as well (data not shown).

To determine if this apparently ligand-independent increase in PR following doxycycline-induced tagged-ERβ1 or tagged-ERα was due to effects at the
transcriptional level, PR mRNA was measured under the conditions described above. PR mRNA levels (determined by RT-PCR) were increased by 126 ± 9% in β-low, 148 ± 7% in β-high compared with 93 ± 5% in MCF7 control cells (means ± s.e.m. or range, n=2–7) in a ligand-independent manner due to doxycycline induction of the tagged-ERβ1 expression. The increased PR mRNA level in the tagged-ERβ1-expressing cells was significant (ANOVA, P=0.0014), suggesting that the effect of ERβ over-expression on PR protein level was, at least in part, due to altered steady-state levels of RNA, suggesting a transcriptional effect.

These data suggest that over-expression of ERβ1 does not universally inhibit the activity of the endogenous ERα, at least at the level of a known marker gene transcription in breast cancer cell lines.

**Effect of tagged-ERβ1 expression on proliferation in MCF7 human breast cancer cells**

When the different cell lines were grown in complete medium containing 5% FBS, induction of tagged-ERβ1 but not tagged-ERα inhibited the growth of the cells, compared with MCF7, the control parent cell line. Both β-high (DT+doxycycline, 1·84 ± 0·24 days, means ± s.e.m., n=6; DT − doxycycline, 1·23 ± 0·09 days, n=6) and β-low (DT+doxycycline, 1·84 ± 0·30 days, n=6; DT − doxycycline, 1·34 ± 0·10 days, n=6) tagged-ERβ1 over-expressors showed a significant increase in DT (change in DT shown as the ratio of DT+doxycycline/ DT − doxycycline, Fig. 5) in the presence of doxycycline than without (ANOVA, P=0·002, n=6) compared with no significant alterations in the parent (MCF7: (DT+ doxycycline, 1·11 ± 0·13 days, n=6; DT − doxycycline, 1·11 ± 0·13 days) and α-high cells (DT+doxycycline, 1·32 ± 0·10 days, n=6; DT − doxycycline, 1·29 ± 0·10 days). Therefore over-expression of ERβ1 but not ERα can decrease the growth of MCF7 breast cancer cells in culture.

To determine the effect of over-expression of tagged-ERβ1 on the proliferation of MCF7 cells in the
Effect of tagged-ERβ1 expression on the proliferative response of MCF7 human breast cancer cells to 4-OH-tamoxifen

An important hypothesis developed from basic studies on the function of ERβ1 using transient transfection and various reporter constructs is that upregulated expression of ERβ1 may result in tamoxifen resistance. Therefore in the inducible tagged-ERβ1 over-expressing cells the responsiveness to 4-OH-tamoxifen-induced growth inhibition was determined. We determined the effect of various concentrations of 4-OH-tamoxifen on the proliferation rate of β-high, β-low, α-high and MCF7 parent cell lines. Interestingly, with induction of tagged-ERs (+doxycycline) a biphasic dose–response was observed in the β-high and β-low cells, but not in α-high or MCF7 control cells (Fig. 7A). At low 4-OH-tamoxifen concentrations (<50 nM), a significant stimulation of proliferation rate was observed (ANOVA, P<0.0001, n=5). This increase in proliferation rate was higher in β-high compared with β-low cells (ANOVA, P<0.0001, n=5). At higher concentrations (>50 nM), growth was inhibited in all cell lines (Fig. 7A). Comparing the growth inhibition phase, both β-high and β-low were significantly more sensitive to 4-OH-tamoxifen than either α-high (ANOVA, P<0.0001) or MCF7 parental cells (ANOVA, P<0.0001). Both β-high and β-low dose–response curves were significantly to the left of both α-high and MCF7 curves. However, β-low was more sensitive than the β-high so a dose-dependent effect of tagged-ERβ1 expression was not observed for growth inhibition. The biphasic growth response to 4-OH-tamoxifen was also not found in MCF7 cells inducibly over-expressing the tagged-C-terminally truncated ERβ variant, ERβ2/cx (Ogawa et al. 1998a). In contrast to the tagged-ERβ1, the tagged-ERβ2/cx over-expressing MCF7 cells only showed a growth inhibition in response to 4-OH-tamoxifen (data not shown). Together, these data support the specificity of the biphasic growth response to tagged-ERβ1 over-expression in multiple independent clones.

In the absence of tagged-ERs (−doxycycline, Fig. 7B), there was a complete loss of the 4-OH-tamoxifen-induced growth stimulation in β-low and β-high. In addition, lack of tagged-ER expression (no doxycycline) eliminated any significant differences in sensitivity to 4-OH-tamoxifen growth inhibition between the β-high, β-low and α-high, but not the parental MCF7 cell line (Fig. 7B).

Discussion

During human breast tumourigenesis and breast cancer progression a marked alteration of oestrogen action occurs. First, the responsiveness of ER+ breast tumour cells to the proliferative effect of oestrogen is direct

presence and absence of 10 nM E2, the cells were depleted of oestrogen as described in the Materials and methods section, treated with doxycycline for 2 days, followed by treatment with or without 10 nM E2 in the continued presence of doxycycline. All cell lines, including those expressing either tagged-ERβ1 or tagged-ERα, showed a statistically significant increase in their growth, i.e. a decrease in DT (ANOVA, P<0.0001, n=12–13, followed by t-tests) in response to 10 nM E2 (Fig. 6). However, those cell lines that over-express tagged-ERβ1 (either at a low or a high level) had a reduced response to E2 as determined by a reduced % decrease in DT in the presence of E2 (ANOVA, P=0.012, n=12–13, followed by t-tests). Both the low and high tagged-ERβ1 over-expressors were statistically significantly different from both the parent MCF7 and the high ERα over-expressor (α-high) controls (Fig. 6).
Over-expression of ERβ1 in MCF7 cells.

Figure 7 (A) Effect of tagged-ER over-expression (+doxycycline) on 4-OH-tamoxifen sensitivity in MCF7 breast cancer cells. Cells were grown in 5% CM and set-up on day zero at 10^4 cells per well in 5% CM-containing medium, treated for 48 h with doxycycline and then various concentrations of 4-OH-tamoxifen or vehicle alone. Cells were harvested and counted electronically at various times after anti-oestrogen treatment. DT and proliferation rates were calculated as described under Materials and methods, and the means±S.E.M. of n=5 (for 4-OH-tamoxifen concentrations 1–75 nM) and n=3 (for 4-OH-tamoxifen concentrations 100–1000 nM) independent experiments with results expressed as proliferation rate % of control (ethanol alone-treated cells). Medium was changed every 2 days. Solid squares are parental control cells, MCF7 clone 89 (rTA, Tet-on transcription factor expressor only). Open squares are β-low over-expressing MCF7 cells. Solid circles are β-high over-expressing MCF7 cells. Solid triangles are α-high over-expressing MCF7 cells. (B) 4-OH-tamoxifen sensitivity in MCF7 breast cancer cell lines in the absence of tagged ER over-expression (−doxycycline). Cells were grown as described above except that they were not treated with doxycycline. Cells were harvested and counted electronically at various times after anti-oestrogen treatment. DT and proliferation rates were calculated as described under Materials and methods, and the means±S.E.M. of n=3 independent experiments with results expressed as proliferation rate % of control (ethanol alone-treated cells). Medium was changed every 2 days. Solid squares are parental control cells, MCF7 (rTA, Tet-on transcription factor expressor only). Open squares are α-high over-expressing MCF7 cells. Solid circles are β-low over-expressing MCF7 cells. Solid triangles are β-high over-expressing MCF7 cells.

Lippman & Bolan 1975, Clarke et al. 1997), in contrast to normal breast epithelial cells where the growth effects of oestrogen appear to be indirect (Anderson et al. 1998). Secondly, the expression of ERs is markedly altered between normal breast tissue and breast tumours (Leygue et al. 1998a, Roger et al. 2001, Murphy & Watson 2002). ERα is up-regulated in ER+ tumours relative to normal breast epithelium whereas current data suggest that ERβ is downregulated in breast tumours compared with normal breast epithelium (Leygue et al. 1998a, Roger et al. 2001). Since there are both in vitro and in vivo studies (Hall & McDonnell 1999, Weihua et al. 2000, Forster et al. 2002, Peng et al. 2003) suggesting that ERβ may be a negative modulator of ERα action, it has been speculated that the downregulation of ERβ during breast tumourigenesis removes a modulatory factor of ERα that is important for maintaining normal sensitivity of breast epithelial cells to oestrogen action. However, despite the general decreased expression of ERβ in ER+ breast tumours compared with normal tissue, many breast tumours continue to express ERβ and the levels of expression can vary widely amongst tumours (Dotzlaw et al. 1997, Jarvinen et al. 2000). And although still controversial, often when ERβ protein is determined, its expression can be correlated with good prognostic markers such as ERα and PR expression (Jarvinen et al. 2000, Murphy et al. 2002, Saunders et al. 2002, Skliris et al. 2003). This is also consistent with data suggesting that higher ERβ expression is associated with sensitivity to tamoxifen therapy rather than resistance to tamoxifen therapy. However, other data have suggested ERβ association with anti-oestrogen resistance and poor prognostic markers (Speirs et al. 1999, Speirs 2002). The development of an inducible tagged-ERβ1-expressing MCF7 breast cancer cell line has allowed us to address the functional outcome of altering the relative expression of ERβ1 to ERα in the ‘gold standard’ model of oestrogen/anti-oestrogen-responsive human breast cancer. The development of such breast cancer cell line models is highly relevant to human breast cancer in vivo, since the majority of human breast tumours (~59%) have been shown to co-express both ERα and ERβ1 (Murphy et al. 2003).

Consistent with studies in which stable over-expression of ERβ1 alone in cell lines was investigated, a
Over-expression of ER-β1 in MCF7 cells · L C MURPHY and others

predominantly nuclear location of the transfected derivative ERβ1 (in our case epitope tagged) was observed (Lazennec et al. 2001). We have isolated various clones of the tetracycline-inducible tagged-ERβ1 that under maximal induction conditions express low and high levels of the tagged-ERβ1 protein. Using the ligand-binding assay, we have determined that in low ERβ clones the tetracycline analogue doxycycline increased specific binding of radiolabelled E2 around 200% that of the non-induced (no doxycycline treatment) and/or non-expressing control cells, while doxycycline treatment of the high ERβ1-expressing clones resulted in around a 300% increase in specific E2 binding over controls. Since parental MCF7 cells contain predominantly ERα, the control and uninduced levels of ligand binding reflect predominantly endogenous ERα levels. After doxycycline treatment, ERβ was induced to less than or equimolar levels (estimating from ligand-binding assays) to the endogenous ERα in the β-low clones, suggesting that the majority of the ERβ would be in the form of heterodimers with ERα (Cowley et al. 1997) in these clones. However, this depends on the kinetics of dimer formation in vivo and hence some homodimers of ERα may also exist. In β-high, the tagged-ERβ1 was induced to higher levels than β-low clones, suggesting that all the ERα molecules may be heterodimerized with ERβ1, with the possibility that a small population of ERβ1 homodimers may also exist. Although in vitro ERα–ERβ1 heterodimer is apparently favoured (Cowley et al. 1997) it is unclear if this is the case in vivo. However, recently it was demonstrated using Fluorescence resonance energy transfer (FRET) analysis in living cells that ER homodimers of each receptor and ERα–ERβ1 heterodimers can occur in vivo independently of the presence of ligand (Bai & Giguere 2003), supporting the presence in our cell line models of ERα predominantly in the form of ERα–ERβ1 heterodimers. Little, if anything, however is known about the differential function of the various homo- and heterodimers of the ER isoforms, although the models described in this study may be useful in addressing such questions.

ERβ1 over-expression alone in the absence of ERα-negative MDAMB231 human breast cancer cells has resulted in variable results with both growth inhibition (Lazennec et al. 2001) and growth stimulation being reported (Tonetti et al. 2003). However, when over-expression of ERβ1 in an ERα-positive background has been achieved, more consistent results have been obtained, and in particular over-expressed ERβ1 results in growth inhibition (Paruthiyil et al. 2004, Strom et al. 2004). Our results are consistent with these latter data in that ERβ1 but not ERα over-expression results in reduced growth and increased DT when cells are grown in complete medium containing FBS and oestrogen. In addition, over-expression of ERβ1 but not ERα reduced the magnitude of oestrogen-induced growth when cells are grown in oestrogen-depleted medium. These effects of ERβ1 on the proliferation of ERα-expressing breast cancer cells are dose-dependent since smaller effects were seen in the low ERβ1-expressing cells compared with the high ERβ1-expressing cells. These data are consistent with the hypothesis that ERβ1 can negatively modulate the activity of ERα when the two ERs are co-expressed. They also suggest that the downregulation of ERβ1 in breast tumours compared with normal breast tissue which altered the relative expression of the two ERs is functionally involved in breast tumourgenesis at least for ER+ breast cancer.

However, negative modulation of ERα activity is not a universal effect of over-expression of ERβ1 since, in contrast to the effect on E2-induced proliferation, ERβ1 over-expression significantly increased endogenous PR expression, previously considered a specific downstream marker of ERα activity in breast cancer cells. Again, in contrast to the growth effects, the increase in PR expression is not ERβ1 specific since over-expression of ERα as seen in α-high cells similarly increased PR expression. These results support a mechanistic connection associated with the observation in vivo where increased ERβ expression determined at the protein level in human breast tumours is often correlated with PR status and expression (Jarvinen et al. 2000, Mann et al. 2001, Murphy et al. 2002). Therefore ERβ1 regulation of PR expression has in vivo physiological and/or pathophysiological relevance. Interestingly, the effect of ER over-expression on PR expression occurs apparently without added ligand (E2) suggesting ligand independence, although further increases in PR expression were seen when the over-expressed ER was bound to E2 (ligand dependent). Indeed, since the majority of human breast tumors arise in older, and therefore likely postmenopausal women, one could speculate that PR expression in many breast tumors may reflect the ligand-independent activity of the combination of ERα and ERβ1 expressed in the tumour. Alternatively, oestrogen generated due to aromatase expression by tumor cells as well as the surrounding stroma would also contribute to the steady-state PR expression in breast tumours. However, we cannot exclude the possibility that trace amounts of oestrogens are still present in the medium and contribute to the increased PR expression. The molecular mechanism by which ERβ1 may regulate PR remains to be determined, although it is due, at least in part, to increased transcription since steady-state PR RNA levels were also increased. However, since ERE half-sites adjacent to both AP-1 and Sp1 sites have been previously implicated in the mechanism by which ERα regulates PR expression, it is speculated that these may also be involved in the mechanism by which ERβ1 can regulated PR expression. However, if the AP-1 site is important in this regard, this would be an example of E2 activation of ERβ1 being involved in increased rather
than decreased transcription of an AP-1-regulated oestrogen responsive promoter. We cannot however exclude effects on PR mRNA stability at this stage.

The involvement of ERβ1 in tamoxifen sensitivity is controversial, and in a previous study when inducible over-expression of ERβ1 was investigated after stable expression in T-47D breast cancer cells, which also express endogenous ERα, only growth inhibition due to tamoxifen was observed (Strom et al. 2004). No stimulation of growth was reported. However, full dose–response analyses covering low and high concentrations of 4-OH-tamoxifen were not undertaken (Strom et al. 2004). To the best of our knowledge, our data are the first to show any effect of altered ERβ1 expression on tamoxifen-regulated proliferation in breast cancer cells. In the presence of oestrogen-replete (phenol-red and FBS-containing) medium, a biphasic growth response to 4-OH-tamoxifen was observed only in tagged-ERβ1 over-expressing cells. Neither the parental control nor the tagged-ERα over-expressing cells showed a biphasic response. The biphasic growth response was lost when tagged-ERβ1 over-expression was not induced (no doxycycline), and was not present when the tagged-ERβ variant, ERβ2-cx, was over-expressed under the same conditions. The growth stimulatory response seen at low doses of 4-OH-tamoxifen was only seen when tagged-ERβ1 was over-expressed, its magnitude was correlated with the level of ERβ1 and was completely eliminated in the absence of ERβ1 induction (i.e. no doxycycline). These data suggest that tagged-ERβ1 expression was functionally involved in the 4-OH-tamoxifen stimulation of proliferation seen at low doses of the anti-oestrogen. When considering the growth inhibition phase, doxycycline treatment of all cell lines except α-high significantly moved the dose–response curves to the left, compared with the no doxycycline treatment, i.e. no induction of expression of the tagged-ER. This suggested that a higher ERβ1 but not ERα increased sensitivity to the growth-inhibitory effects of 4-OH-tamoxifen. However, removal of doxycycline also reduced the sensitivity of the MCF7 control cells to 4-OH-tamoxifen, suggesting that clonal variation may also in part contribute to, but not entirely explain, the differences seen in sensitivity to the growth-inhibitory, but not the growth-stimulatory effects of tamoxifen in these cell lines. In particular, there was no evidence that ERβ1 over-expression resulted in a shift of the dose–response curve to the right of any of the control cells, supporting the conclusion that acute over-expression of ERβ1 is not associated with resistance or decreased sensitivity to tamoxifen. Overall, these data support the hypothesis that increased expression of ERβ1 but not over-expression of ERα in the presence of endogenous expression of ERα increases the sensitivity of human breast cancer cells to the growth-modulatory effects of tamoxifen.

Our results showing that ERβ1 over-expressing cells display an increased sensitivity to tamoxifen are consistent with increased expression being associated with tamoxifen sensitivity and not resistance in vivo in breast cancer patients (Mann et al. 2001, Murphy et al. 2002, Esslimani-Sahla et al. 2004, Myers et al. 2004). The stimulation of proliferation due to 4-OH-tamoxifen seen at low doses is interesting and we would argue that rather than be interpreted as representing a potential form of tamoxifen resistance (Clarke et al. 2003), since it only occurs at very low concentrations (tamoxifen resistance occurs in vivo at varying periods of time following or during high doses of tamoxifen), it is likely to resemble and/or be a model of ‘tamoxifen flare’ that has been observed clinically (Plotkin et al. 1978, Mortimer et al. 2001, Biersack et al. 2004). In this condition, an apparent worsening of the disease is seen in some patients in the first few weeks of starting tamoxifen treatment; likely before sufficiently high steady-state concentrations of tamoxifen and its active metabolites have accumulated. This is often a favourable sign for responsiveness to tamoxifen therapy since, in the cases where tamoxifen therapy was continued, subsequent tumour regression often occurred (Plotkin et al. 1978, Vogel et al. 1995). Interestingly, only one other breast cancer cell culture model of ‘tamoxifen flare’ has been documented previously. In this case the cell line was T-47D and several laboratories have often described a relatively higher natural level of ERβ expression in T47-D cells compared with other ER+ breast cancer cell lines. The mechanism by which ERβ1 may increase the sensitivity of breast cancer cells to tamoxifen is unknown, but the higher relative binding affinity of ERβ1 compared with ERα for 4-OH-tamoxifen may contribute in part (Kuijer et al. 1997).

In conclusion, our data using inducible, ERβ1 over-expressing MCF7 cells do not support the hypothesis that up-regulation of ERβ1 in the presence of ERα is a mechanism of anti-oestrogen resistance per se. However, we cannot exclude a role of over-expression of ERβ in resistance in combination with other changes, such as altered cofactor expression and/or activity. In addition, our data support the hypothesis that ERβ1 can be a negative modulator of ERα-mediated growth response since over-expression of ERβ in a dose-dependent fashion inhibits the magnitude of the E2-induced growth response in ER+ human breast cancer cells. However, over-expression of ERβ1 does not inhibit or reduce all ERα-regulated activities since endogenous PR expression is not decreased in these cells. Indeed, ERβ1 upregulates the endogenous expression of PR in possibly both a ligand-independent and -dependent fashion. It is acknowledged that due to space limitations our interpretation of the data shown here is likely too narrow since it underestimates the complexity of the variables (only one of which is relative to the response of an AP-1-regulated oestrogen responsive promoter). We cannot however exclude effects on PR mRNA stability at this stage.
expression of ER isoforms) involved in the response to E2 as previously demonstrated (Hewitt et al. 2003, Stossi et al. 2004). The parallels seen with our over-expressing ERβ1 MCF7 cell lines and some in vivo studies showing a relationship between PR and ERβ expression as well as ERβ expression and tamoxifen sensitivity of breast cancer patients suggest that these models are relevant and useful for dissecting the role of ERβ1 expression in ER+ breast cancer.

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