

The Biarylpyrazole Compound AM251 Alters Mitochondrial Physiology via Proteolytic Degradation of ERR α

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ABSTRACT

The orphan nuclear receptor estrogen-related receptor alpha (ERR α) directs the transcription of nuclear genes involved in energy homeostasis control and the regulation of mitochondrial mass and function. A crucial role for controlling ERR α -mediated target gene expression has been ascribed to the biarylpyrazole compound 1-(2,4-dichlorophenyl)-5-(4-iodophenyl)-4-methyl-N-1-piperidinyl-1H-pyrazole-3-carboxamide (AM251) through direct binding to and destabilization of ERR α protein. Here, we provide evidence that structurally related AM251 analogs also have negative impacts on ERR α protein levels in a cell-type-dependent manner while having no deleterious actions on ERR γ . We show that these off-target cellular effects of AM251 are mediated by proteasomal degradation of nuclear ERR α . Cell treatment with the nuclear export inhibitor leptomycin B did not prevent AM251-induced destabilization of ERR α protein,

whereas proteasome inhibition with MG132 stabilized and maintained its DNA-binding function, indicative of ERR α being a target of nuclear proteasomal complexes. NativePAGE analysis revealed that ERR α formed a ~220-kDa multiprotein nuclear complex that was devoid of ERR γ and the coregulator peroxisome proliferator-activated receptor γ coactivator-1. AM251 induced SUMO-2,3 incorporation in ERR α in conjunction with increased protein kinase C activity, whose activation by phorbol ester also promoted ERR α protein loss. Down-regulation of ERR α by AM251 or small interfering RNA led to increased mitochondria biogenesis while negatively impacting mitochondrial membrane potential. These results reveal a novel molecular mechanism by which AM251 and related compounds alter mitochondrial physiology through destabilization of ERR α .

Introduction

The biarylpyrazole class of cannabinoid 1 receptor (CB $_1$ R) inverse agonists, which includes AM251 and rimonabant (SR141716A), has therapeutic potential; animal and clinical data suggest that they mediate suppression of appetite and improve glucose homeostasis (Padwal and Majumdar, 2007). However, administration of rimonabant still stimulates neurogenesis and induces cannabinoid-like effects in mice deficient in cannabinoid 1 receptors (Jin et al., 2004; Wiley et al., 2012), indicating the involvement of additional targets. Indeed, the neuroprotective effect of rimonabant requires the vanilloid receptor VR1, independent of the CB $_1$ R interaction

(Jin et al., 2004; Pegorini et al., 2006). These biarylpyrazole compounds also appear to have targets other than CB $_1$ R, CB $_2$ R, and VR1 (Raffa and Ward, 2012); for example, AM251 and rimonabant are agonists of GPR55, a recently deorphanized G protein-coupled receptor that is expressed in peripheral tissues and is positively associated with obesity in human (Moreno-Navarrete et al., 2012). However, the effect of these compounds on the cellular functions of GPR55 requires low micromolar concentrations. For instance, AM251 induces sustained and oscillatory Ca $^{2+}$ responses reminiscent of responses triggered by the endogenous GPR55 ligand lysophosphatidylinositol, using a maximally effective concentration of AM251 (3 μ M), with an EC $_{50}$ of 612 \pm 86 nM (Henstridge et al., 2009). Moreover, the redistribution of β -arrestin 2 in U2OS cells containing GPR55 is visualized after treatment with 30 μ M rimonabant and 30 μ M AM251 (Kapur et al., 2009). Finally, 1–10 μ M rimonabant and AM251 are used to demonstrate the

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ABBREVIATIONS: AM251, 1-(2,4-dichlorophenyl)-5-(4-iodophenyl)-4-methyl-N-1-piperidinyl-1H-pyrazole-3-carboxamide; BSA, bovine serum albumin; CB $_1$ R, cannabinoid 1 receptor; CHX, cycloheximide; DMEM, Dulbecco's modified Eagle's medium; ERE, estrogen-response element; ERR, estrogen-related receptor; ERRE, ERR-response element; FBS, fetal bovine serum; GPR55, G protein-coupled receptor 55; MARCKS, myristoylated alanine-rich C-kinase substrate; PBS, phosphate-buffered saline; PGC-1, peroxisome proliferator-activated receptor γ coactivator-1; PKC, protein kinase C; PMA, phorbol 12-myristate 13-acetate; rimonabant (SR141716A), 5-(4-chlorophenyl)-1-(2,4-dichlorophenyl)-4-methyl-N-(piperidin-1-yl)-1H-pyrazole-3-carboxamide; RIPA, radioimmune precipitation assay; RT-PCR, real-time polymerase chain reaction; siRNA, small interfering RNA; SLV319 (lbinabant), 3-(4-chlorophenyl)-N-[(4-chlorophenyl)sulfonyl]-4,5-dihydro-N'-methyl-4-phenyl-1H-pyrazole-1-carboxamide; TMRM, tetramethylrhodamine methyl ester; VR1, vanilloid receptor 1; XCT790, thiazoleacrylamide; $\Delta\psi_m$, mitochondrial membrane potential.

involvement of GPR55 in cannabinoid-triggered calcium signaling in endothelial cells (Waldeck-Weiermair et al., 2008).

Our recent study has revealed that the cellular responses to AM251 (5 μ M) relied on the binding to and destabilization of estrogen-related receptor alpha (ERR α) protein (Fiori et al., 2011). Importantly, mice lacking ERR α exhibit reduced fat mass and were resistant to diet-induced obesity (Luo et al., 2003), a phenotype similar to that of mice lacking CB₁R (Ravinet Trillou et al., 2004). Members of the ERR subfamily, which encompasses ERR α , ERR β , and ERR γ , are constitutively active and do not require specific ligands for transcriptional activity (Ariazi and Jordan, 2006). The orphan hormone nuclear receptor ERR α binds to promoter sites of target genes as dimers (Horard et al., 2004). The binding of ERR α to estrogen-response element (ERE) or ERR-response element (ERRE) on specific DNA target sites leads to either transcriptional activation or repression, partly depending on the presence of coregulators (Ariazi and Jordan, 2006). A number of nuclear receptor coactivators, including the peroxisome proliferator-activated receptor γ coactivator-1 (PGC-1) α and β , interact with ERR α and potentiate its transcriptional activity (Xie et al., 1999; Zhang and Teng, 2000). The recent report of the crystal structure of the ERR α ligand-binding domain in complex with PGC-1 α has provided new evidence for ligand-independent transcriptional activation of ERR α (Kallen et al., 2004). PGC-1 α and ERR α work in concert to promote regulation of genes that control key aspects of metabolism including mitochondrial biogenesis (Schreiber et al., 2004; Eichner and Giguère, 2011).

It is therefore possible that alterations in ERR α levels may be responsible for some of the off-target effects of AM251 that led to up-regulation of epidermal growth factor receptor expression and signaling (Fiori et al., 2011). We have investigated the molecular mechanisms involved in the regulation of ERR α protein stability by AM251. Moreover, because of the important role of ERR α in the control of cellular metabolism, we also sought to determine whether AM251 treatment resulted in altered mitochondrial biogenesis and function through destabilization of this orphan nuclear receptor. Our findings provide novel mechanistic insight into inducible posttranslational modifications of ERR α that subsequently augment mitochondrial mass but reduce mitochondrial bioenergetic functions.

Materials and Methods

Chemicals. AM251 was purchased from Cayman Chemical (Ann Arbor, MI). Ammonium chloride, cycloheximide, leptomycin B, MG132, XCT790, and phorbol 12-myristate 13-acetate (PMA) were purchased from Sigma-Aldrich (St. Louis, MO). Leupeptin was purchased from Fischer Scientific (Pittsburgh, PA), and rimonabant and SLV-319 were obtained from J. F. McElroy (Jenrin Discovery, Inc., West Chester, PA).

Cell Culture and Treatments. Human PANC-1 cells (ATCC, Manassas, VA) were cultured in phenol red-free Dulbecco's modified Eagle's medium (DMEM) supplemented with 4.5 g/L D-glucose, 4 mM glutamine, 1 mM pyruvate, 1.5 g/L sodium bicarbonate, 10% heat-inactivated fetal bovine serum (FBS; HyClone, Logan, UT), and penicillin/streptomycin. Human ES-2 cells were cultured in McCoy's 5A medium supplemented with 1 mM pyruvate, 1.5 mM glutamine, 0.1 mM nonessential amino acids, 1.5 g/L sodium bicarbonate, 10% heat-inactivated fetal bovine serum (FBS), and penicillin/streptomycin. Human HepG2 cells were cultured in minimum essential medium

supplemented with 4 mM glutamine, 1 mM pyruvate, 1.5 g/L sodium bicarbonate, 10% heat-inactivated FBS, and penicillin/streptomycin. All cell lines were maintained at 37°C with 5% CO₂, and the medium was replaced every 2 to 3 days. Unless otherwise indicated, cells were rinsed twice with phosphate-buffered saline (PBS), and serum starvation was performed for 3 hours before treatment began.

RNA Extraction, cDNA Synthesis, and Quantitative PCR. After treatments, cells were washed twice with ice-cold PBS and snap frozen in liquid nitrogen. RNA was extracted using an RNeasy Mini kit (Qiagen, Valencia, CA), and 1 μ g RNA was reverse transcribed using qScript cDNA SuperMix (Quanta Biosciences, Gaithersburg, MD) according to the manufacturer's instructions. Gene expression was quantified and analyzed using quantitative polymerase chain reaction (PCR), as described previously elsewhere (Fiori et al., 2011).

Small Interfering RNA for ERR α . Small interfering RNA (siRNA) targeting ERR α was purchased from Qiagen and contained the following sequences: ERR α siRNA: [forward 5'-GAGAGAUGUG-GUC-ACCAUTT-3'; reverse 5'-AUGGUGACCACAAUCUCGG-3'] and negative control siRNA: [forward 5'-UUCUCCGACUGUCAC-GUdTdT-3'; reverse 5'-ACGUGACACGUU-CGGAGAAdTdT-3']. These siRNAs have been validated to perform efficient knockdown with minimal off-target effects (Fiori et al., 2011). PANC-1 cells were reverse transcribed using Lipofectamine RNAiMAX reagent (Invitrogen, Carlsbad, CA) according to the manufacturer's instructions. Briefly, for each well of a four-well chamber slide (Laboratory-Tek; Nunc, Rochester, NY), the RNAi duplex-Lipofectamine RNAiMAX complex was prepared using 0.1 nmol siRNA duplex and 1 μ l of lipofectamine RNAiMAX in 100 μ L of Opti-MEM I, and incubated for 15 minutes at room temperature. PANC-1 cells (40,000 cells/well) in complete growth medium without antibiotics were then plated into chambers and incubated for 48 hours before use. Knockdown efficiency was determined by Western blot analyses. Three independent transfection experiments were performed.

Subcellular Fractionation. Fractionation of cytoplasmic and nuclear protein extracts was carried out using NE-PER nuclear and cytoplasmic extraction reagents (Thermo Scientific, Rockford, IL) supplemented with 1 mM sodium orthovanadate, protease inhibitor cocktail set I, and phosphatase inhibitor cocktail set II (Calbiochem-EMB, San Diego, CA). Mitochondrial and cytosolic fractions were isolated using the mitochondria isolation kit for cultured cells (MitoSciences Inc., Eugene, OR) following the manufacturer's protocol. The cytosolic fractions were concentrated using Microcon YM-3 concentrators (Millipore-Amicon, Billerica, MA).

Immunoprecipitation. After treatments, cells were washed twice with ice-cold PBS and snap frozen in liquid nitrogen. Cells were lysed, and nuclear extracts were prepared as described previously. Equal amounts of nuclear extracts were diluted in radioimmune precipitation assay (RIPA) buffer (25 mM HEPES, 134 mM NaCl, 1% NP-40, 0.1% SDS, 1 mM sodium orthovanadate, 0.5% sodium deoxycholate, 100 mM NaF) supplemented with phosphatase and protease inhibitor cocktails, and precleared with protein G agarose beads (50% v/v, cat. no. 16-266, Millipore). Immunoprecipitation was performed using a 1:40 dilution of either ERR α (cat. no. ab76228) or SUMO-2,3 (cat. no. ab3742) (Abcam, Cambridge, MA) overnight at 4°C, followed by incubation with protein G-agarose for 3 hours at 4°C. As a negative control, nuclear extracts were incubated with protein G beads alone. The resin was then centrifuged at 6000g for 30 seconds and washed 3 times in RIPA and twice in 50 mM HEPES, pH 7.4, containing 0.1% Triton X-100. Bound proteins were eluted in 2 \times Laemmli sample buffer and resolved by SDS-PAGE followed by Western blotting with the anti-SUMO-2,3 or anti-ERR α antibodies.

DNA-Binding Activity of ERR α . The protein content in PANC-1 nuclear extracts was quantified using the bicinchoninic acid assay kit (Thermo Scientific). Protein-DNA binding activity was assessed using a streptavidin-agarose pulldown assay as previously described elsewhere (Wu, 2006). Briefly, 150 μ g of nuclear extracts were incubated with 1.5 μ g of biotinylated oligonucleotide duplex and 10 μ L of streptavidin agarose beads (Vector Laboratories, Burlingame, CA)

in 200 μ L of PBS supplemented with 1 mM sodium orthovanadate and protease and phosphatase inhibitor cocktails. The biotinylated double-stranded oligonucleotides contained either the wild-type ERRE binding motif (5'-biotin-AGGTCACAGTGACCTAGGTCACAGTGACCTAGGT-3' and 5'-biotin-ACCTAGGTCAGTGTGACCTAGGTCAGTGTGACCT-3') or an ERRE mutant oligonucleotide (5'-biotin-AGTACACATAGACCTAGTACACATAGACCTAGTA-3' and 5'-biotin-TACTAGGTCTATGTGTACTAGGTCTATGTGTACT-3') (Integrated DNA Technologies, Inc., Coralville, IA). After 2 hours incubation at room temperature, the complexes were sedimented by centrifugation at 550g for 1 minute at 4°C, washed three times with PBS, and eluted in Laemmli sample buffer. Proteins were resolved by SDS-PAGE and analyzed by Western blot.

Gel Electrophoresis and Western Blot Analysis. Unless otherwise noted, total cell extracts were prepared by lysing cells in ice-cold RIPA buffer supplemented with 1 mM sodium orthovanadate, phosphatase, and protease inhibitor cocktails for 20 minutes on ice with occasional vortexing. After centrifugation at 12,000g for 15 minutes at 4°C to remove insoluble material, the lysates were collected and protein quantified using the bicinchoninic acid assay kit. To perform traditional denatured SDS-PAGE analyses, protein extracts were prepared with Laemmli sample buffer and resolved on Novex 4%–12% Tris-glycine gels (Invitrogen) under reducing conditions. For blue native gel electrophoresis, samples were prepared using the NativePAGE Sample Buffer and G-250 Sample Additive (Invitrogen), and they were resolved on Novex NativePAGE 4%–16% Bis-Tris gels (Invitrogen), according to the manufacturer's instructions. Proteins were then transferred to polyvinylidene difluoride membranes using the iBLOT apparatus (Life Technologies).

Rabbit polyclonal antibodies generated against ERR α (ab76228), ERR γ (ab49129), SUMO-2,3 (ab3742), and VDAC1/Porin (ab15895) were purchased from Abcam. Rabbit polyclonal antibodies against PGC-1 (sc-13067) and cytochrome C (H-104), and monoclonal antibodies against Hsp70 (sc-32239) and GAPDH (sc-32233) were obtained from Santa Cruz Biotechnology (Santa Cruz, CA). Monoclonal antibodies against complex II subunit 70 kDa (MS204/C582) and complex III subunit core 2 (MS304) were obtained from MitoSciences (Eugene, OR), while monoclonal anti-Hsp90 (cat. no. 610419) was from BD Transduction Laboratories (Sparks, MD). Rabbit polyclonal antiphosphorylated myristoylated alanine-rich C-kinase substrate (MARCKS; cat. no. 2741) was purchased from Cell Signaling Technology (Danvers, MA). Unless otherwise indicated, a dilution of 1:1000 was used for all primary antibodies. The membrane-bound primary antibodies were visualized after incubation with horseradish peroxidase-conjugated secondary antibodies (GE Healthcare, Piscataway, NJ) and enhanced chemiluminescence with ECL or ECL Plus reagents (GE Healthcare). The quantitation of the immunoreactive bands was performed by volume densitometry using ImageJ software (NIH, Bethesda, MD).

Immunofluorescence Microscopy. Cells were seeded at 5×10^4 cells/well in complete medium into chamber slides (Nunc). Forty-eight hours later, cells were maintained in serum-free medium for 3 to 4 hours and then were treated as indicated. After completion of the treatments, the medium was replaced with serum-free medium containing 100 nM MitoTracker Red CMXRos (Invitrogen/Molecular Probes, Eugene, OR) for 10 minutes at 37°C, after which the cells were rinsed in PBS, fixed with 4% paraformaldehyde for 20 minutes, and then permeabilized for 5 minutes in 0.3% Triton-X100/0.1% bovine serum albumin (BSA) in PBS. After a blocking step (5% BSA in PBS), cells were incubated with rabbit anti-ERR α antibody overnight at 4°C, followed by incubation with AlexaFluor 488-conjugated goat anti-rabbit IgG (Invitrogen). Cells were mounted in Prolong Gold antifade reagent containing 4',6-diamidino-2-phenylindole (Invitrogen) and analyzed by confocal microscopy using a Zeiss LSM 710 microscope (Thornwood, NY). Images were processed using the Zeiss Zen software.

Measurement of Mitochondrial Mass and Mitochondrial Membrane Potential. Mitochondrial mass was measured by MitoTracker Green FM staining (20 nM, cat. no. M-7514; Invitrogen). Mitochondrial membrane potential ($\Delta\psi_m$) was measured with the

fluorescent lipophilic cationic dye tetramethylrhodamine methyl ester (TMRM; 20 nM, cat. no. T-668; Invitrogen), which accumulates within mitochondria according to the $\Delta\psi_m$. After treatment with AM251 (5 μ M) or XCT790 (2.5 μ M) for 16 hours, cells were stained either with Mitotracker Green FM or TMRM for 15 minutes at 37°C, and fluorescence was measured by flow cytometry using the BD Accuri C6 flow cytometer (Accuri Cytometers, Ann Arbor, MI). In each analysis, 10,000 events were recorded and FL-1 (Mitotracker green) and FL-2 (TMRM) fluorescence was obtained after gating for live cells.

Statistical Analysis. Results are represented as mean \pm S.E.M. unless otherwise specified. Data were analyzed using KaleidaGraph software (version 4.1; Synergy Software, Reading, PA). Statistical analyses were performed using either a Student's *t* test for unpaired data or analysis of variance (ANOVA) with Fisher's least significant difference post hoc test analysis. *P* < 0.05 was considered statistically significant.

Results

The Biarylpyrazole Class of Compounds Destabilizes ERR α Protein. Our previous study has shown that AM251 down-regulates the expression of ERR α protein in PANC-1 cells (Fiori et al., 2011), and an independent study has reported that the selective ERR α inverse agonist XCT790 induces the degradation of ERR α (Lanvin et al., 2007). We compared the effects of other compounds that are structurally related to AM251, specifically rimonabant and SLV319, in terms of potency toward regulation of ERR α protein levels. A 16-hour treatment of PANC-1 cells with the maximal concentration (5 μ M) of AM251, rimonabant, and SLV319 significantly decreased the levels of ERR α protein by ~60%–70% (*P* < 0.001), but the effect was maximal (~95% reduction) with XCT790 (Fig. 1A). Incubation of PANC-1 cells with increasing concentrations of AM251 and related compounds produced a dose-dependent reduction in ERR α levels, with an IC₅₀ ranging from 0.7 to 1.0 μ M (Fig. 1B).

Two other cell lines were also tested for their sensitivity to the biarylpyrazole compounds. Although ES-2 and HepG2 cells were very responsive to XCT790, HepG2 cells showed refractoriness to the suppressive action of AM251, rimonabant, and SLV319 (Supplemental Fig. 1A, B). In contrast, the sensitivity of ES-2 cells to these compounds was reminiscent of PANC-1 cells. Under these experimental conditions, the levels of ERR γ were unaffected by the biarylpyrazole compounds or XCT790 (Fig. 1A; Supplemental Fig. 1). These data suggest that the effect of AM251 and related analogs on the accumulation of ERR α protein is cell-type dependent.

AM251-Mediated Proteasomal Degradation of ERR α .

The half-life of ERR α protein was determined by treating PANC-1 cells with either the protein-synthesis inhibitor cycloheximide (CHX, 10 μ g/ml) or AM251 in a time-course experiment. Immunoblot analysis of total cell lysates showed a rapid degradation rate of ERR α by CHX, with a half-life ($t_{1/2}$) of 5 hours (Fig. 2A). However, the half-life of ERR α protein was ~10 hours after being treated with AM251, suggesting minimal contributions from transcription and/or translation. Neither PGC-1 nor GAPDH protein expression was altered by these treatments. To assess whether the destabilization of ERR α in response to AM251 stemmed from proteasomal degradation, PANC-1 cells were pretreated with the proteasome inhibitor MG132 for 1 hour followed by the addition of AM251 for 6 hours (Fig. 2B). The results show complete suppression in ERR α protein degradation in MG132-treated

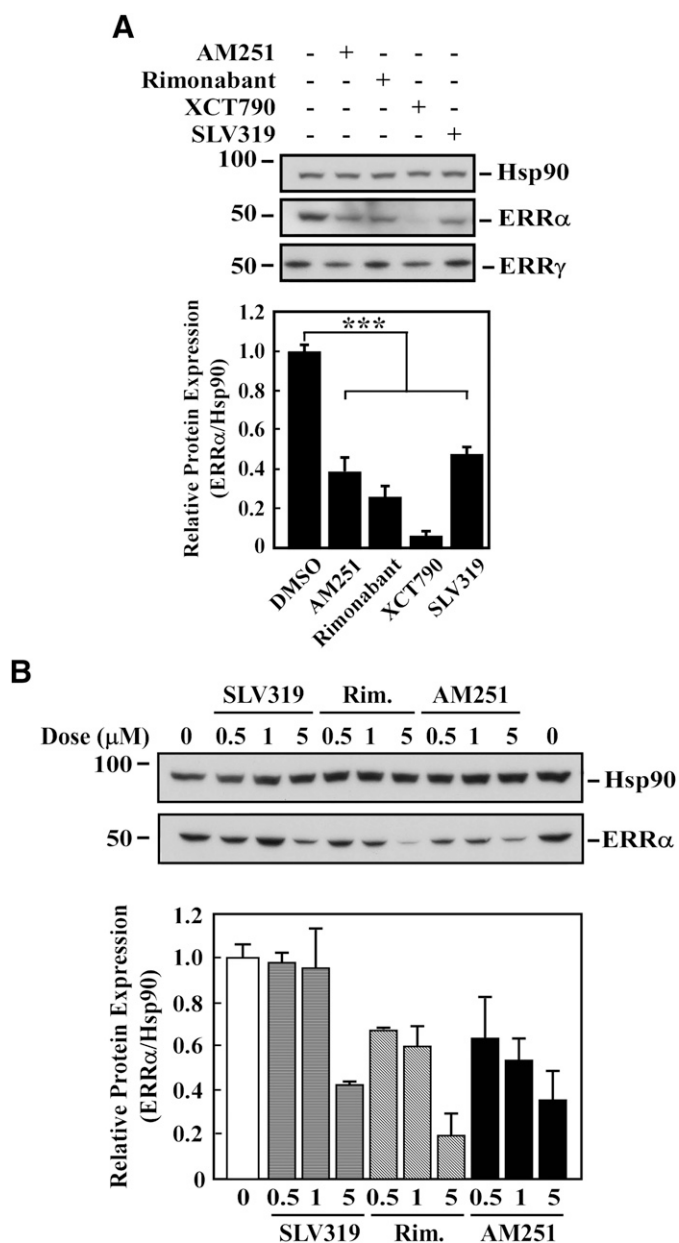


Fig. 1. Biarylpyrazole compounds destabilize ERR α protein in PANC-1 cells. (A) Serum-depleted PANC-1 cells were incubated either with vehicle (DMSO) or 5 μ M biarylpyrazole compounds AM251, rimonabant, or SLV319 for 16 hours. The ERR α inverse agonist XCT790 (2.5 μ M) was included as a positive control. (B) PANC-1 cells were incubated with the indicated concentrations of the biarylpyrazole compounds for 16 hours. Total cellular extracts were prepared and analyzed by immunoblotting with antibodies against ERR α , ERR γ , and Hsp90, with the latter serving as a loading control. The relative expression of ERR α was determined by densitometry and normalized to Hsp90. Bars represent mean \pm S.E.M. from 4 to 6 independent experiments (A) or mean \pm range of two sets of dishes (B). The migration of molecular-mass markers (values in kilodaltons) is shown on the left of immunoblots. *** P < 0.001 versus DMSO-treated cells.

cells, indicating that proteasome activity likely plays a key role in the AM251-mediated destabilization of this orphan nuclear receptor.

To assess the effect of AM251 on the localization of ERR α , nuclear and cytosolic fractions were isolated and subjected to Western blot analysis. As shown in Fig. 2C, ERR α was found predominantly in the nuclear fraction, although a significant

amount was detected in the extranuclear compartment as well. Treatment with AM251 caused a decrease in ERR α levels in both subcellular fractions; however, inhibition of the proteasome complex with MG132 completely prevented the loss or redistribution of ERR α upon AM251 treatment (Fig. 2C, upper panel). Analysis of BRG-1 and I κ B α as markers of nuclear and cytosolic proteins, respectively, confirmed the absence of cross-contamination during the subcellular fractionation process (Fig. 2C, lower panel).

DNA-Binding Properties of the ERR α -Containing Multiprotein Complexes. We determined whether AM251 altered the DNA-binding property of ERR α . It was previously reported elsewhere that ERR α can bind to estrogen-response elements (ERE) containing the recognition motif AGGT-CAnnnTGACCT and that ERR α also recognizes the single consensus half-site sequence TNAAGGTCA, referred to as an ERR-response element (ERRE) (Sladek et al., 1997). Here, a DNA affinity immunoprecipitation assay was used to assess the binding of ERR α to the agarose-conjugated ERRE consensus or mutated recognition sequences. The assay combines an affinity step with Western blot analysis to detect the DNA-bound ERR α (Wu, 2006). In the absence of MG132, the level of binding of ERR α to its target DNA was markedly reduced by treatment of PANC-1 cells with AM251 or XCT790, as compared with control cells (Fig. 3A, lanes 4 and 6 versus 2). In contrast, treatment with MG132 alone clearly increased the amount of DNA-bound ERR α and conferred protection against alteration in the DNA-binding capacity of ERR α elicited by AM251 and XCT790 (Fig. 3A, lanes 5 and 7 versus 3). The oligonucleotide dimer with a mutated ERRE recognition sequence bound poorly with ERR α (Fig. 3A, lane 1 versus 2). These results suggest that inhibition of the proteasome complex blocked the adverse effects of AM251 and XCT790 on the DNA-binding capacity of ERR α .

The orphan nuclear receptor ERR α interacts with a number of binding partners for full transcriptional activity. We analyzed ERR α -containing multiprotein complexes using NativePAGE gels, a technique that offers a higher resolution than gel filtration or sucrose density ultracentrifugation (Swamy et al., 2006). Western blotting of the nuclear extract from untreated PANC-1 cells showed a stable ERR α -containing multiprotein complex of ~220 kDa, whose relative abundance increased in MG132-treated cells (Fig. 3B, lane 2 versus 1). Consistent with the DNA pull-down experiment, the abundance of the complex was markedly lower in PANC-1 cells treated with AM251 and XCT790 in the absence of MG132; however, inhibition of the proteasome caused a marked accumulation of the 220-kDa species (Fig. 3B, lanes 3 and 5 versus 4 and 6). No free monomeric or dimeric forms of ERR α were observed by these treatments. Immunoblot analysis of duplicate membranes demonstrated that the 220-kDa complex was devoid of known ERR α -interacting proteins, including ERR γ and the coregulators PGC-1 and RIP140 (Fig. 3C).

Nuclear ERR α as a Putative Target for Phosphorylation-Mediated SUMOylation in Response to AM251. Because ERR α could be interacting with components of the proteasome in both the nuclear and cytosolic compartments, PANC-1 cells were pretreated with the nuclear export inhibitor leptomycin B, alone or together with MG132, followed by subsequent incubation with AM251 or XCT790. As shown in Fig. 4A, leptomycin alone did not confer protection whereas the combination leptomycin plus MG132 prevented ERR α

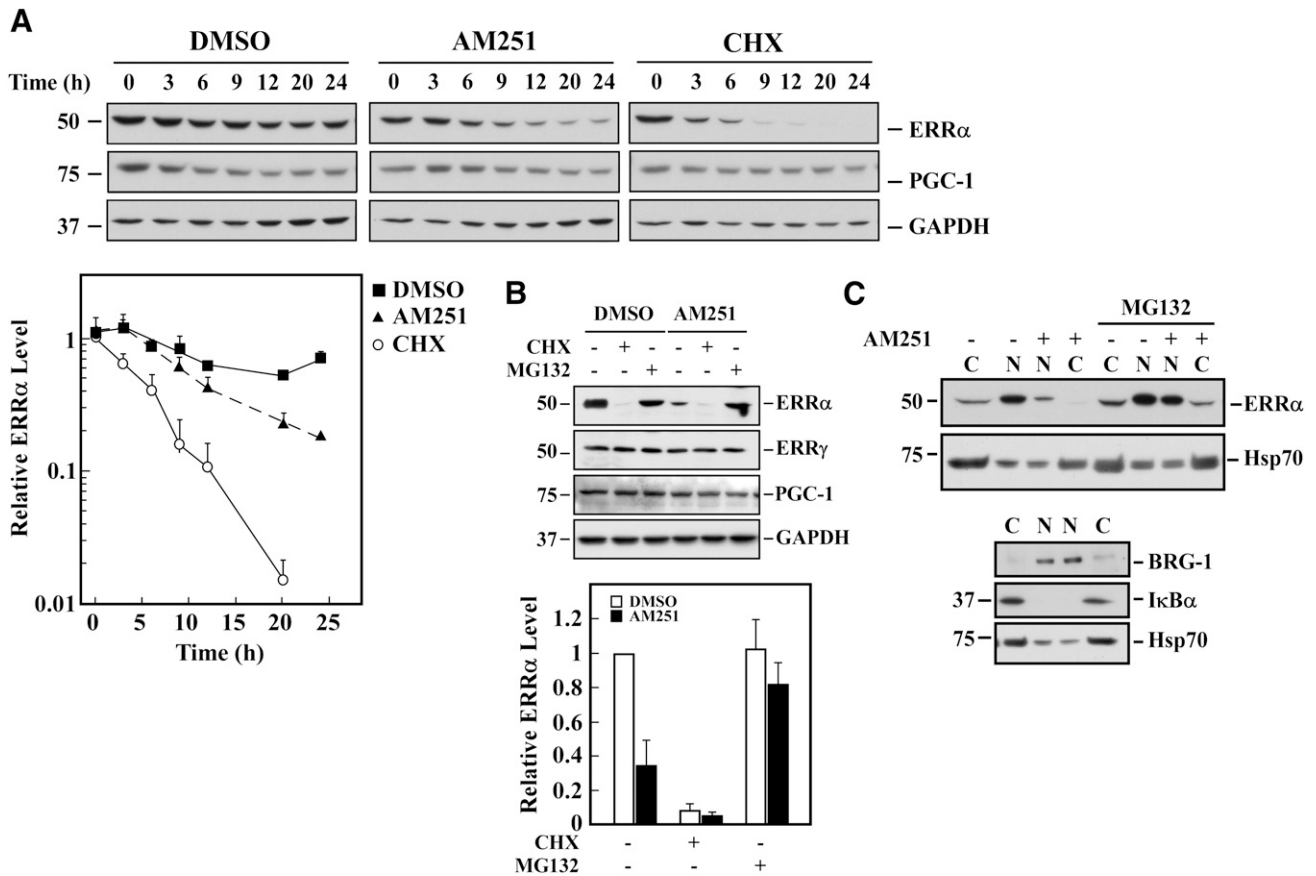


Fig. 2. AM251-mediated proteasomal degradation of nuclear ERR α . (A) Serum-depleted PANC-1 cells were treated in the absence or presence of 10 μ g/ml cycloheximide (CHX) or AM251 (5 μ M) for the indicated periods of time. Total cellular extracts were prepared and analyzed by immunoblotting with antibodies against ERR α and PGC-1. GAPDH was used as a loading control. The relative expression of ERR α was determined by densitometry and normalized to GAPDH. Data represent means \pm range of two sets of dishes. (B) Serum-depleted PANC-1 cells were treated with MG132 (10 μ M) for 1 hour followed by the addition either of CHX (10 μ g/ml) or AM251 (5 μ M) for 15 hours. Western blot analysis was performed as in A. Left panel, representative blots; right panel, bars representing the mean \pm range of two sets of dishes. (C) Serum-depleted PANC-1 cells were treated with MG132 (10 μ M) for 1 hour followed by the addition of vehicle (DMSO, 0.1%) or AM251 (5 μ M) for 15 hours. Nuclear (N) and cytosolic (C) fractions were prepared and analyzed by immunoblotting with antibodies against ERR α and Hsp70, which was used as a loading control (upper panels). The membranes were then reprobbed with antibodies specific for the nuclear marker BRG-1 and cytoplasmic marker I κ B α (lower panels). Similar results were obtained in a second independent experiment.

degradation induced by AM251 and XCT790. These results indicate that nuclear proteolytic activity may be responsible for the destabilization of ERR α .

Because proteasome inhibition results in impaired degradation of ERR α , we tested directly whether ERR α was a SUMOylation target in response to AM251. SUMOylation is a known posttranslational modification of ERR α (Tremblay et al., 2008) and functions as a signal for proteasomal degradation (Miteva et al., 2010). The anti-ERR α immunoprecipitates from nuclear fractions were analyzed by immunoblotting with anti-SUMO-2,3 antibody, and showed inducible SUMOylation of ERR α when cells were stimulated with AM251 (Fig. 4B, upper panel). Similar results were obtained in a reciprocal experiment, whereby anti-SUMO-2,3 immunoprecipitates were immunoblotted with ERR α antibody (Fig. 4B, second panel). No signal was observed in the immunoprecipitation control with protein G beads alone.

Phosphorylation has been shown to be a requirement for ERR α SUMOylation (Vu et al., 2007; Tremblay et al., 2008), with protein kinase C δ being one of the potential kinases involved (Barry and Giguère, 2005). Similar to AM251, activation of protein kinase C (PKC) with the phorbol ester PMA resulted in a significant reduction in ERR α protein levels (Fig.

4C) in the absence of detectable alteration in ERR α mRNA expression (Fig. 4D). Moreover, both AM251 and PMA elicited rapid and significant phosphorylation of MARCKS, a major PKC substrate (Fig. 4E). These data indicate that PKC-dependent phosphorylation may be a prerequisite for AM251-mediated SUMOylation and proteolytic degradation of ERR α .

ERR α Degradation Alters the Number of Mitochondria and Mitochondrial Membrane Potential. Through transcriptional regulation of respiratory gene expression, ERR α controls the energy-generating functions of mitochondria (Eichner and Giguère, 2011). Interestingly, AM251-treated PANC-1 cells exhibited a sharp reduction in MitoTracker Red CMXRos staining, which is dependent on mitochondrial membrane potential ($\Delta\psi_m$) (Fig. 5A). In support of this finding, down-regulation of ERR α expression by siRNA led to a marked reduction in MitoTracker Red CMXRos staining, as compared with cells transfected with control siRNA (Fig. 5B). Consistent with the refractoriness of HepG2 cells to AM251-dependent reduction in ERR α protein levels, the mitochondrial membrane potential remained unaffected by AM251 treatment in these cells (Supplemental Fig. 2).

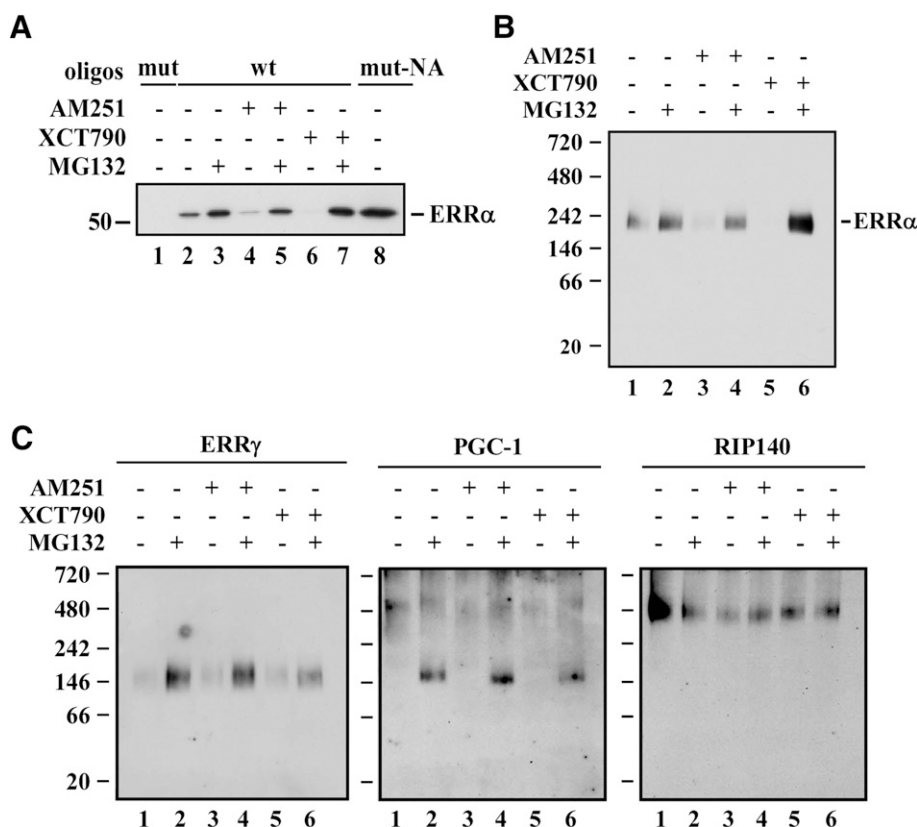


Fig. 3. DNA-binding properties of a nuclear multimeric protein complex encompassing ERR α . (A) Control and MG132-treated PANC-1 cells were incubated with AM251 (5 μ M) or XCT790 (2.5 μ M) for 16 hours. Nuclear extracts were prepared, and the DNA-binding activity of ERR α was determined (as described in *Materials and Methods*). Nuclear extracts were incubated with agarose-bound oligonucleotide probe containing the wild-type (wt) ERRE consensus sequence (lanes 2–7) or the same probe mutated (mut) at the ERRE site (lanes 1, 8). Bound ERR α (lanes 1–7) and unbound ERR α from the mut oligonucleotide incubation (mut-NA, lane 8) were immunoblotted with antibodies against ERR α . Identical results were obtained in a second independent experiment. (B and C) Nuclear extracts from (A) were also resolved by NativePAGE, enabling the separation of native ERR α -containing multiprotein complexes (B), and complexes expressing ERR γ , PGC-1, and RIP140 (C). Similar results were obtained in a second independent experiment. The migration of molecular-mass markers (values in kiloDaltons) is shown on the left of the immunoblots.

Mitotracker Green is a probe used to evaluate the mitochondrial mass and differentiate intact mitochondria from cellular debris while the measure of mitochondrial membrane potential, monitored by the fluorescence of mitochondrially loaded cationic potentiometric dye TMRM, serves to measure the electrical gradient across the mitochondria inner membrane established by electron transport chain activity (Seppet et al., 2009). Flow cytometric analyzes of Mitotracker Green and TMRM fluorescence profiles were performed in PANC-1 cells treated with AM251 (5 μ M) and XCT790 (2.5 μ M) for 16 hours (Fig. 5C). Preincubation with either drug led to an increase in mitochondrial mass (Fig. 5C, left panel) and marked $\Delta\psi_m$ depolarization (Fig. 5C, middle panel). Normalization of $\Delta\psi_m$ values with those of Mitotracker Green demonstrated that both AM251 and XCT790 treatments caused a significant $\Delta\psi_m$ depolarization, which was associated with ERR α protein destabilization (Fig. 5C, bars).

Mitochondrial mass is controlled through biogenesis, degradation, or both processes (Michel et al., 2012). To further examine mitochondrial dysfunction in response to AM251, we compared the expression levels of mitochondrial proteins in the absence or presence of leupeptin and NH₄Cl, two known lysosomal inhibitors. Western blot analysis demonstrated that the expression of COXII and COXIII subunits, cytochrome C and VDAC/porin were unaffected in serum-depleted cells treated or not with leupeptin and NH₄Cl for 5 hours (Fig. 5D). However, there was higher expression of VDAC/porin in AM251-treated cells when compared with vehicle controls while the level of COXII and COXIII subunits expression remained constant (data not shown). Taken together, these data indicate that AM251 induces alterations to both mitochondrial mass and bioenergetics via depletion of ERR α .

We further investigated the possibility that AM251 and XCT790 negatively affected mitochondrial integrity. Treatment of PANC-1 cells with AM251 resulted in the retention of cytochrome C in the mitochondrial compartment whereas a small but detectable amount of cytochrome C was present in the cytosolic fraction of XCT790-treated cells (Fig. 5E). Neither AM251 nor XCT790 treatment of PANC-1 cells resulted in poly-(ADP-ribose) polymerase-1 cleavage, a process known to occur during apoptosis (Soldani and Scovassi, 2002) (Supplemental Fig. 3). From these data, we conclude that the loss in ERR α protein by AM251 and related biarylpyrazole compounds was not accompanied by loss in cell integrity.

Discussion

The nuclear receptor ERR α has important modulatory roles in numerous aspects of energy metabolism, including fatty acid oxidation, glucose metabolism, and mitochondrial biogenesis (Ariazi and Jordan, 2006; Giguère 2008; Villena and Kralli, 2008). Therefore, synthetic inverse agonists targeting ERR α may be useful in the treatment of metabolic diseases as well as cancer. Recently, we have shown that AM251 promotes cellular degradation of ERR α protein (Fiori et al., 2011). In the current study, a variety of approaches were used to detect DNA-binding properties, native oligomeric protein complexes, and posttranslational modifications that are known mechanisms for the destabilization and proteolytic degradation of ERR α . We provide novel evidence that AM251 and related biarylpyrazole compounds induce proteasomal degradation of ERR α via posttranslational modifications and that such degradation subsequently alters mitochondrial function.

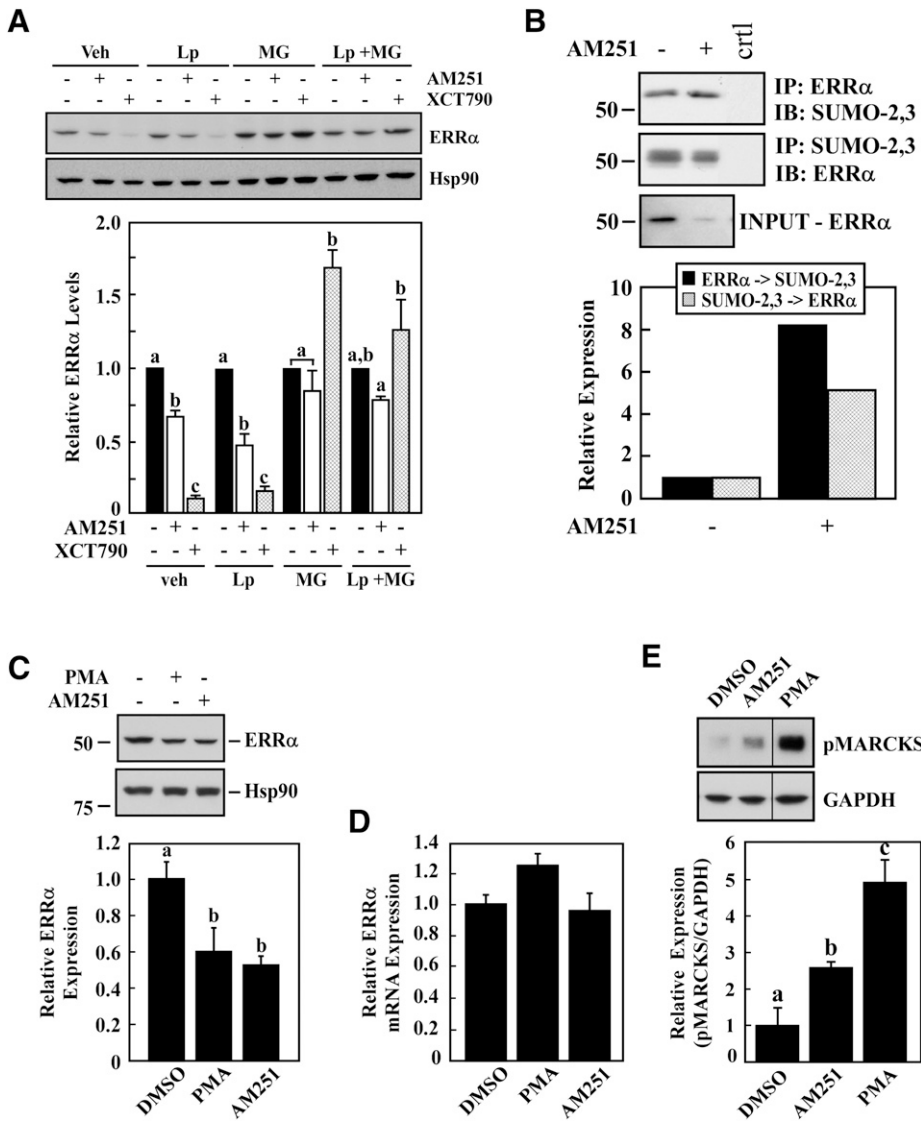


Fig. 4. AM251 induces posttranslational modifications of ERR α and its targeting to the nuclear proteasome. (A) Serum-starved PANC-1 cells were pretreated either with MG132 (10 μ M), leptomycin B (5 nM), or the combination MG132 + leptomycin B for 1 hour followed by the addition of vehicle (DMSO, 0.1%), AM251 (5 μ M), or XCT790 (2.5 μ M) for 16 hours. Cell lysates were analyzed by Western blot for the detection of ERR α and Hsp90. Bars represent the mean \pm S.E.M. ($n = 4$) of two independent experiments, each performed with two dishes per group. (B) PANC-1 cells were serum-depleted and then treated with or without AM251 for 16 hours. Nuclear extracts were prepared, subjected to immunoprecipitation (IP) with anti-ERR α , and then immunoblotted for SUMO-2,3 (upper panel). Reciprocal immunoprecipitation was carried out whereby anti-SUMO-2,3 immunoprecipitates were analyzed by Western blot with anti-ERR α (middle panel). Control immunoprecipitation (ctrl) was performed with protein G beads alone. Five percent of input (before immunoprecipitation) was loaded on the gel (bottom panel). Blots from a representative experiment are shown. Bars represent the immunoblot signals normalized to input. (C) Serum-depleted PANC-1 cells were treated with PMA (10 nM) or AM251 for 7 hours and then processed for Western blotting. Results are expressed as the mean \pm S.E.M. of three experiments, each performed in duplicate dishes. (D) Total RNA from PANC-1 cells treated with vehicle (DMSO, 0.1%), PMA (10 nM), or AM251 (5 μ M) for 7 hours was extracted and analyzed for ERR α and 18S by quantitative real-time PCR. Bars represent the mean \pm S.E.M. of two independent experiments, each performed in duplicate dishes. (E) Serum-depleted PANC-1 cells were treated with PMA or AM251 for 30 minutes followed by immunoblot analysis with antibodies against phosphorylated MARCKS and GAPDH, which served as a normalization control. Data represent the mean \pm S.E.M. ($n = 3$) of a representative experiment. Similar results were obtained in a second independent experiment. Different letters (a, b, c) indicate statistically significant differences at $P < 0.05$.

Our previous work showed that AM251 displays affinity and specificity for the ligand-binding domain of ERR α , which translates into selective reduction in ERR α protein levels without an effect on its mRNA levels (Fiori et al., 2011). In this study, the destabilization of ERR α by compounds structurally related to AM251 displayed a signature appropriate for this class of drugs. Interestingly, these effects appeared to be cell-type specific, as AM251, rimonabant, and SLV419 all promoted proteolytic degradation of ERR α in PANC-1 and ES-2 cells but not in the HepG2 cell line. Moreover, no alterations were found in protein levels of ERR γ or that of the coactivator PGC-1, regardless of cell type. However, a marked depletion in ERR α was observed in all cell lines after exposure to the potent ERR α -specific inverse agonist XCT790. These results, which suggest a model for cell-type-specific control of ERR α stability by biarylpyrazole compounds, are supported by findings in ERR α knockout mice, wherein gene induction was strongly dependent on the tissue type (Huss et al., 2004). Alternatively, the selective reduction of ERR α levels in different cell types might fine-tune ERR α signaling, for example, to modulate osteoblastic and adipogenic programs

(Ijichi et al., 2007; Delhon et al., 2009). These findings highlight the complexity and selectivity of ERR α regulation and suggest the involvement of additional players in ERR α proteolysis, for example, activation of the calpain proteases and the ubiquitin-proteasome complex.

To elucidate whether AM251-induced ERR α loss occurs through decreased protein synthesis and/or increase in proteasomal activity, specific inhibitors of each process were used. The rate of ERR α depletion by AM251 was significantly slower than that elicited by the protein synthesis inhibitor, cycloheximide, indicating that AM251 is likely to act through reduction of protein stability instead of impacting ERR α mRNA translation. Treatment with the proteasomal inhibitor MG132 abrogated AM251-induced ERR α loss, and led to an accumulation of ERR α within the nucleus as a multimeric complex whose DNA-binding ability was maintained in the presence of AM251 (Fig. 3). The lack of protection against the loss of ERR α in AM251-treated cells that were preincubated with leptomycin B (a CRM1 nuclear export inhibitor) implies the involvement of a nuclear proteasome complex in ERR α destabilization.

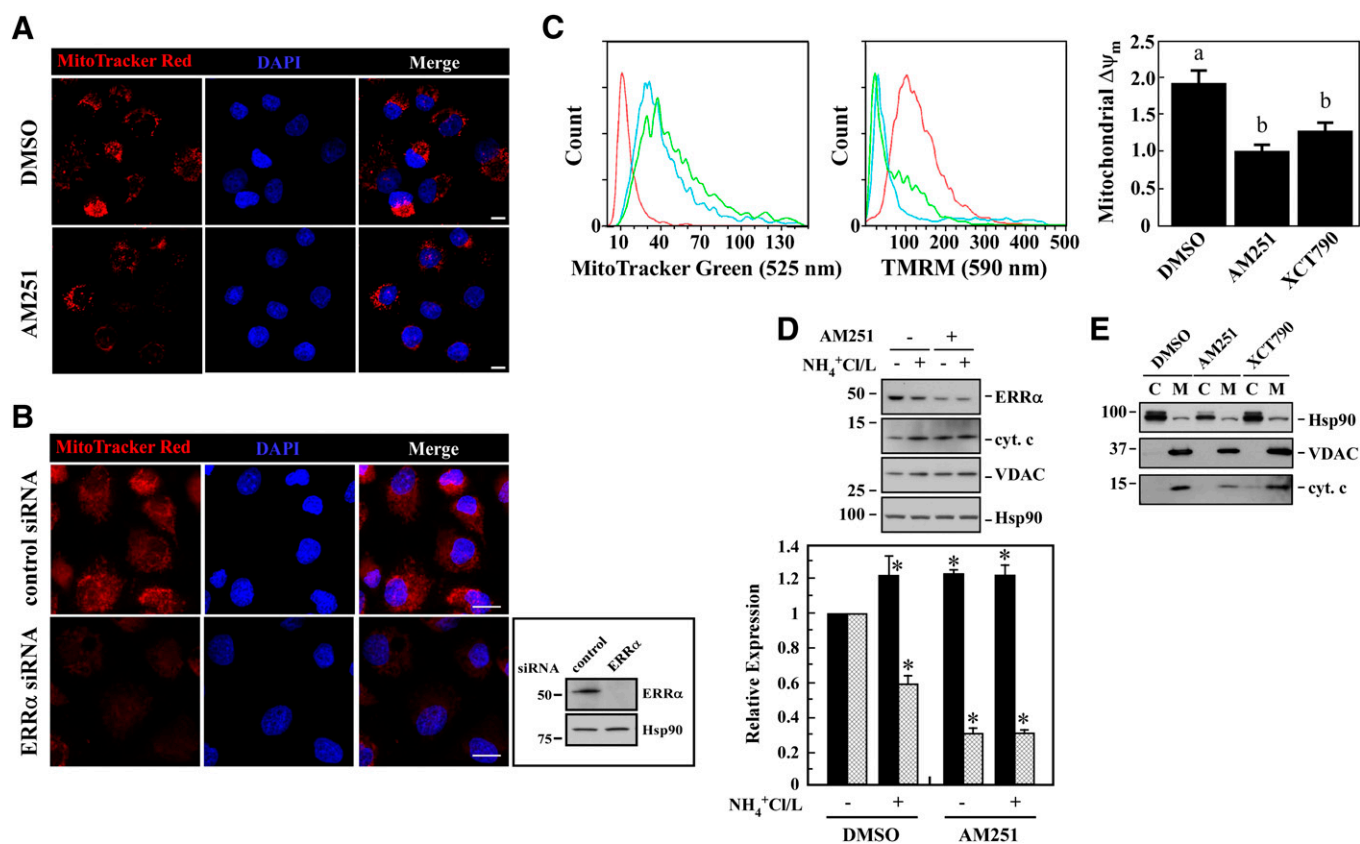


Fig. 5. ERR α depletion alters mitochondrial biogenesis and membrane potential. (A) Serum-depleted PANC-1 cells were treated with vehicle (DMSO) or AM251 (5 μ M) for 16 hours. Cells were incubated with MitoTracker Red CMXRos, rinsed with PBS, fixed, permeabilized, and then cell nuclei were counterstained with 4',6-diamidino-2-phenylindole (DAPI, blue). Cells were examined by fluorescence microscopy, as described in *Materials and Methods*. (B) PANC-1 cells were transfected with a control, nonsilencing siRNA, or ERR α siRNA for 48 hours followed by MitoTracker Red CMXRos staining. Mitochondria that have lost membrane potential are no longer visible after MitoTracker staining of the cells. Scale bar, 10 μ m. (C) Serum-depleted PANC-1 cells were treated with vehicle (DMSO, red), AM251 (5 μ M, blue), or XCT790 (2.5 μ M, green) for 16 hours. Cells were analyzed by flow cytometry after staining with Mitotracker Green and TMRM to differentiate intact mitochondria from cellular debris and determine $\Delta\psi_m$, respectively. Left panel: Representative Mitotracker-Green flow cytometric histograms (FITC channel). Middle panel: Representative TMRM flow cytometric histograms (red fluorescence). Right panel: Graphic representation of the pooled experiments. Relative $\Delta\psi_m$ is expressed as percentage of the mean fluorescence intensity of the Mitotracker Green-positive cell population, which was set at 100% in the DMSO control. Bars represent the mean \pm SD of two independent experiments, each performed in duplicate dishes ($n = 4$). In each analysis, 10,000 events were recorded. X-axis $\times 10^3$. (D) Determination of mitochondrial protein expression levels in the presence and absence of lysosomal inhibitors, NH $_4^+$ Cl/leupeptin, in control and AM251-treated PANC-1 cells. Serum-depleted cells were treated with DMSO or AM251 (5 μ M) for 12 hours followed by the addition of NH $_4^+$ Cl/leupeptin for the next 4 hours. Total cell extracts were analyzed by immunoblotting with the indicated antibodies, and Hsp90 was used as a loading control. Top panel: Representative immunoblots. Bottom panel: Densitometry of VDAC/porin and ERR α followed by normalization with Hsp90. Data represent the mean \pm S.E.M. of three separate experiments, each performed in duplicate. Filled bars, VDAC; hatched bars, ERR α . * $P < 0.05$. (E) Cytosolic (C) and mitochondrial (M) fractions were prepared from PANC-1 cells treated either with DMSO (0.1%), AM251 (5 μ M), or XCT790 (2.5 μ M) for 16 hours. Immunoblotting was performed with the indicated antibodies. Similar results were obtained in a separate experiment.

Proteasomal degradation typically involves posttranslational modifications of target proteins. ERR α has been shown to undergo numerous modifications including phosphorylation (Sladek et al., 1997; Lu et al., 2011), SUMOylation (Vu et al., 2007; Tremblay et al., 2008), ubiquitination (Ren et al., 2011), and acetylation (Wilson et al., 2010), many of which altering its transcriptional activity. In the current study, AM251 significantly increased SUMOylation of ERR α by SUMO-2,3 (Fig. 4B), a posttranslational modification associated with enhanced protein turnover (Miteva et al., 2010; Manente et al., 2011; Shimshon et al., 2011). Consistent with these findings, protein modifications with SUMO-2,3 have been associated with increased nuclear degradation (Anderson et al., 2012). Previous mutagenesis studies have identified the critical importance of residues Lys-14 and Lys-403 for ERR α SUMOylation (Vu et al., 2007; Tremblay et al., 2008) and found this modification to also occur in vivo (Tremblay

et al., 2008). SUMOylation has previously been linked to either the promotion (Manente et al., 2011) or inhibition (Anderson et al., 2012; Sharma et al., 2010) of protein ubiquitination. Despite ERR α being a target of ubiquitination by the E3 ligase Parkin (Ren et al., 2011), our preliminary findings failed to show any significant induction of ERR α ubiquitination by AM251 (data not shown).

Phosphorylation on Ser-19 enhances SUMOylation of ERR α on Lys-14 by SUMO2 (Vu et al., 2007; Tremblay et al., 2008). Because PKC ϵ is a known ERR α kinase (Lu et al., 2011), we next sought to determine whether AM251 alters PKC activity. Herein, the demonstration that phorbol ester stimulation can induce ERR α degradation paralleled the action of AM251. Similar with phorbol esters, AM251 also exhibited increased potency toward phosphorylation of an in vivo PKC substrate. This may support a role for PKC in triggering phosphorylation-dependent SUMOylation and

proteasomal degradation of nuclear ERR α by biarylpyrazole compounds. Moreover, the extent of ERR α phosphorylation could also influence subsequent posttranslational modification of this nuclear receptor, thereby altering the stability of ERR α -containing protein complexes. However, no differences were observed between AM251-treated and vehicle-treated cells in this respect (Fig. 3B, C). Nuclear extracts were resolved by NativePAGE gel electrophoresis, and a single 220-kDa complex was detected in both experimental conditions. In addition, the free monomeric form of ERR α did not exist, and no changes in these parameters were observed with cell treatment. Although ERR γ , PGC-1, and RIP140 are known interactors of ERR α , our data indicate that they are not integral members of the endogenous, nuclear ERR α -containing complex. In support of our findings, SUMOylation has no effect on either DNA-binding properties or coactivator recruitment to ERR α (Tremblay et al., 2008). A major effort is currently underway in our laboratory to identify the components of the 220-kDa complex.

Given the critical importance of ERR α in regulating expression of numerous mitochondrial genes (Eichner and Giguère, 2011), we hypothesized that AM251 would subsequently alter mitochondrial function through down-regulation of this orphan nuclear receptor. Recent findings have indicated that treatment with the AM251 analog rimonabant increased hepatic mitochondrial respiration in rats fed a high-fat diet (Flamment et al., 2009). However, no differences were observed in the quantity of mitochondrial DNA or the citrate synthase activity. The increase in mitochondrial activity would be expected to increase energy supply, but there was a reduction in ATP synthase activity consistent with an increase in mitochondrial proton leak (Flamment et al., 2009). Here, we found that treatment with AM251 or siRNA-mediated ERR α silencing exerted negative effects on mitochondrial staining with Mitotracker Red CMXRos. Different hypotheses may explain changes in mitochondrial function: 1) both approaches may interfere with mitochondrial electron transport; 2) mitochondrial activity may be impaired via depletion of NADH; or 3) the mitochondrial permeability transition pore complex may be compromised. It should also be noted that TMRM and mitotracker green assays were also performed and indicated a clear mitochondrial dysfunction in response to AM251 or XCT790 despite increased mitochondrial biogenesis. Moreover, our previous report found that AM251 decreased mRNA level of *PDK4*, an important mitochondrial gene (Fiori et al., 2011). Our observations, together with a recent investigation by Michel and colleagues (2012), provide examples of a putative retrograde response that enables cells to adapt to impaired mitochondrial activity.

In summary, we have demonstrated that the biarylpyrazole class of compounds reduces ERR α protein stability in association with altered mitochondrial dysfunction. We propose a molecular mechanism that contributes to ERR α degradation via increased PKC activity, leading to its SUMOylation and subsequent nuclear proteasomal degradation, which, in turn, leads to alterations in genes critical to mitochondrial biogenesis and function. The impairment in metabolic function for ERR α combined with recent reports of the significant effects of AM251 and rimonabant on GPR55, GABA receptors, and μ -opioid receptors (Sharir and Abood, 2010; Baur et al., 2012; Seely et al., 2012) are suggestive of drugs that in fact display significant off-target effects. Therefore, the findings demonstrated

herein may aid in the optimization of future therapeutics aimed at treating metabolic diseases with minimal side effects.

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Authorship Contributions

Participated in research design: Krzysik-Walker, González-Mariscal, Scheibye-Knudsen, Bernier.

Conducted experiments: Krzysik-Walker, González-Mariscal, Scheibye-Knudsen, Indig.

Contributed new reagents or analytic tools: Scheibye-Knudsen.

Performed data analysis: Krzysik-Walker, González-Mariscal, Scheibye-Knudsen, Indig, Bernier.

Wrote or contributed to the writing of the manuscript: Krzysik-Walker, Bernier.

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