

AD _____

Award Number: DAMD17-03-1-0674

TITLE: Structural Determination of Certain Novel ER Complexes

PRINCIPAL INVESTIGATOR: Ya-Ling Wu
Geoffrey L. Greene, Ph.D.

CONTRACTING ORGANIZATION: University of Chicago
Chicago, IL 60637

REPORT DATE: September 2006

TYPE OF REPORT: Annual Summary

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for Public Release;
Distribution Unlimited

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision unless so designated by other documentation.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 074-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503				
1. Agency Use Only (Leave blank)	2. Report Date 01 Sep 2006	3. Report Type and Period Covered (i.e., annual 1 Jun 00 - 31 May 01) Annual Summary 01 Sep 2003 - 31 Aug 2006		
4. Title and Subtitle Structural Determination of Certain Novel ER complexes		5. Award Number DAMD17-03-1-0674		
6. Author(s) Ya-Ling Wu; Geoffrey L. Greene				
7. Performing Organization Name (Include Name, City, State, Zip Code and Email for Principal Investigator) University of Chicago Chicago, IL 60637 E-Mail: yalingw@midway.uchicago.edu		8. Performing Organization Report Number (Leave Blank)		
9. Sponsoring/Monitoring Agency Name and Address U.S. Army Medical Research and Materiel Command Fort Detrick, Maryland 21702-5012		10. Sponsoring/Monitoring Agency Report Number (Leave Blank)		
11. Supplementary Notes (i.e., report contains color photos, report contains appendix in non-print form, etc.)				
12a. Distribution/Availability Statement (check one) ☒ Approved for public release; distribution unlimited ☐ Distribution limited to U.S. Government agencies only - report contains proprietary information			12b. Distribution Code (Leave Blank)	
13. Abstract (Maximum 200 Words) (<i>abstract should contain no proprietary or confidential information</i>) Tamoxifen is effective for the prevention and treatment of estrogen-dependent breast cancers, but is associated with an increased incidence of endometrial tumors. We completed the first aim of this proposal to solve the crystal structure of the estrogen receptor alpha ligand-binding domain (ER α LBD) bound to the structurally similar compound GW5638, which has therapeutic potential and does not stimulate the uterus. Like tamoxifen, GW5638 relocates the carboxy-terminal helix (H12) to the known coactivator-docking site in the ER α LBD. However, GW5638 repositions residues in H12 through specific contacts with the N-terminus of this helix. In contrast to tamoxifen, the resulting increase in exposed hydrophobic surface of ER α LBD correlates with a significant degradation of ER α in MCF-7 cells. Thus, the GW5638-ER α LBD structure reveals a unique mode of SERM-mediated ER antagonism, in which the stability of ER α is decreased through an altered position of H12. This dual mechanism of antagonism may explain why GW5638 can inhibit tamoxifen-resistant breast tumors. In addition, difficulties encountered with experiments under aim 2 and 3 were addressed along with alternative approaches proposed in this report.				
14. Subject Terms (keywords previously assigned to proposal abstract or terms which apply to this award) Steroid receptor; Endocrine and cell signaling; X-ray Hormone action; Selective estrogen receptor modulators;			15. Number of Pages (count all pages including appendices) 27	
			16. Price Code (Leave Blank)	
17. Security Classification of Report Unclassified	18. Security Classification of this Page Unclassified	19. Security Classification of Abstract Unclassified	20. Limitation of Abstract Unlimited	

Table of Contents

Introduction.....	page 4
Body.....	page 6
Key Research Accomplishments.....	page 10
Reportable Outcomes.....	page 10
Conclusions.....	page 10
References.....	page 12
Appendices.....	page 14

FINAL REPORT FOR SEP 01, 2003– JUN 30, 2005

INTRODUCTION

Breast cancers affect one in eight women in the United States. Despite the fact that estrogens are beneficial in various contexts including cognition, protective roles in the cardiovascular system and the control of reproductive functions, estrogen use has also been implicated as a risk factor in breast and uterine cancers. This suggests that a great degree of flexibility to control unwanted side effects would be desirable to target ER α for breast cancer treatment and prevention (Couse and Korach, 1999; Hunt, 1994; McGuire, 1978). Accordingly, endocrine therapy is the standard care for most women with hormone-dependent tumors in adjuvant and metastatic settings.

Selective estrogen receptor modulators (SERMs) with mixed characteristics as agonists or antagonists in a tissue-specific manner have been designed to bind ER and elicit distinct pharmacological profiles. These molecules behave like estrogen in bone and cardiovascular system but block its action in the mammary tissues. The mixed agonist/antagonist properties of SERMs and relatively mild side effects explain why drugs like tamoxifen and raloxifene are used for the treatment and prevention of breast cancer and for the prevention of osteoporosis, respectively. Tamoxifen is the standard endocrine treatment for ER α -positive primary and metastatic breast cancers. Unfortunately, most of these cancers become resistant within 2-5 years and the risk of uterine cancer increases in women who take tamoxifen. Available pharmacological data showed similar activities for raloxifene, but data on the activity of raloxifene in patients with advanced disease are limited (Buzdar et al., 1988; Gottardis and Jordan, 1987; Poulin et al., 1989). The commonly used second-line endocrine therapy for tamoxifen-refractory tumors includes aromatase inhibitors, gonadotrophin releasing hormone agonists or the pure ER α antagonist ICI (Fulvestrant, Faslodex). However, none of these agents has the beneficial agonist activities associated with tamoxifen.

GW5638 is a novel SERM that differs from tamoxifen in that the dimethylaminoethoxy group is replaced by an acrylate side chain (Willson et al., 1994). This compound exhibits beneficial estrogenic properties but unlike tamoxifen, it is a more potent antagonist in breast cancer cells and has no uterotrophic behavior. Because tamoxifen-resistant breast cancers are not cross-resistant to GW5638, this SERM has significant potential as a therapeutic agent. GW5638 and its 4-hydroxy metabolite (GW7604) can induce a unique conformational change in ER α that is recognized by synthetic peptides selected by phage display. These peptides recognize GW5638/GW7604-ER α complexes but not tamoxifen-ER α or other ligand-bound ER complexes, indicating that conformational changes elicited by GW5638 and tamoxifen are different (Connor et al., 2001). To better understand the pharmacology of GW5638, I proposed (1) to determine the structure of human ER α /ER β -LBD in complex with GW5638 (2) to determine

the structure of ER α -LBD/GW5638 associated with GW 7 α -16 and/or other CoRNR box peptides. In addition, we also propose to determine the structure of C through E domains of human ER α and to characterize the interactions among these functional domains, which may have important pharmacological significance in biology and drug design. Due to some technical difficulties while performing the original specific aims (2) and (3), I have revised my proposal to include alternative approaches in my last annual report. As I have completed my PhD studies in Jun, 2005, I will no longer pursue aim (3) in this proposal.

BODY

AIM 1: To determine the structure of human ER α / β -LBD in complex with GW5638 and to compare the conformational changes in ER α / β -LBD elicited by tamoxifen and GW5638

I have accomplished this specific aim, which includes (1) generating and purifying GW-ER α LBD for biochemical analysis and crystallization; (2) obtaining single, diffraction-quality crystals for x-ray analysis; (3) determining the x-ray structure of GW-ER α LBD and depositing the structure to the protein data bank.

The structure of ER α LBD bound to GW5638 was solved by molecular replacement with a modified raloxifene-ER α LBD structure to a resolution of 2.7 Å with an R factor of 0.208 and free R factor of 0.236 (Table 1, Appendix 1). The refined structure reveals clear electron density for GW5638 (Figure 1C, Appendix 1). Like other antagonist-bound ER structures, GW-ER α LBD folds into a canonical three-layered sandwich of twelve α -helices. GW5638 lies in an orientation similar to OHT or RAL inside the ligand-binding pocket (Figure 1D, Appendix 1). Unexpectedly, the carboxyl groups between GW5638 and Asp 351 form a hydrogen bond at the crystallization pH of 5.6 (Figure 2A), rather than repelling each other as predicted from molecular modeling studies of the 4-hydroxy metabolite GW7604 (Bentrem et al. 2001). It is likely that the hydrophobic environment of the pocket results in protonation of the weakly acidic acrylate, allowing for hydrogen bond formation with Asp351 (Urry et al., 1992). The acrylate side chain of GW5638 induces an unexpected conformation in H12, the C-terminal “activation function-2” (AF2) helix, which has not been observed in other antagonist-bound NR LBD structures. The electron density in this region was clearly revealed and the 2Fo-Fc map was shown in Figure 1C, right, Appendix 1. In the OHT and RAL ER α LBD structures, H12 binds to and occludes the coactivator-binding site by mimicking the hydrophobic interactions of coactivator NR box LXXLL motifs with the recognition groove formed by H3, H4 and H5 (Brzozowski et al., 1997; Shiau et al., 1998). This orientation of H12 is partially displaced from the hydrophobic cleft in the GW-ER complex, which can be attributed to the water-mediated hydrogen bonds that link one of the carboxyl oxygen atoms in GW5638 to the backbone NH group at the N-terminus of H12 (Figure 2C, Appendix 1). It is noteworthy that this ligand-protein interaction is very similar in every monomer in the asymmetric unit, as the rmsd values between main chains and side chains among three monomers are less than 1 Å.

Leu 536 mediates the N-terminal capping of H12, which is initiated by the water-mediated hydrogen bonds between the GW 5638 acrylate carboxyl group, Leu 536 and Tyr 537, bringing the N-terminus of H12 and the loop connecting H11 and H12 (L11-12) 6-7Å closer to the ligand (Figure 3, Appendix 1). Consequently, H12 relocates $\sim 10^\circ$ away from H11, compared to the OHT and raloxifene complexes, resulting in a $\sim 50^\circ$ difference in orientation for H12 in the

GW-ER α and OHT-ER α structures. This displacement disrupts the hydrophobic interactions between the AF-2 cleft and the H12 LLEML residues seen in the OHT-ER structure. In addition, a series of hydrogen bonds between H3/H5 and H12 in the OHT-ER structure are lost in the GW-ER structure (Figure 4, Appendix 1). Significantly, this unusual orientation induces a repositioning of hydrophobic residues in H12 (Leu-536, Leu-539, Leu-540 and Met-543), such that the side chains of these residues are no longer buried in the hydrophobic core but become solvent exposed on the protein exterior (Figure 3B, Appendix 1). Thus, GW5638 causes a nearly 27% increase in the exposed hydrophobic surface of H12 compared to the OHT-ER α structure. This surface is stabilized in part by contact with a neighboring LBD molecule in the crystal lattice.

I have also performed surface hydrophobicity of various ER α LBD complexes using bis-ANS probe. Endogenous ER α stability upon different ligand treatment was also monitored to confirm the structural information. In contrast to tamoxifen, the resulting increase in exposed hydrophobic surface of ER α LBD correlates with a significant degradation of ER α in MCF-7 cells (Figure 5 in Appendix 1), which may account for the ability of GW5638 to inhibit tamoxifen resistant MCF-7 breast tumor explants.

In short, the acrylate side chain of GW5638/7604, a tamoxifen analog, interacts with Leu-536 and Tyr-537 of the ER α LBD to induce capping of H12 and an unexpected conformation for this AF2 molecular switch. The resulting increase in ER α surface hydrophobicity correlates with a decrease in receptor stability, in sharp contrast to the increased stability observed for OHT-ER α . Notably, the ER α was significantly stabilized in the presence of GW7604 by replacement of Leu-536, Leu-539 and Leu-540 with Gln, which should reduce the surface hydrophobicity of H12. Thus, the GW5638-ER α structure adds another level of complexity to the observed conformational flexibility of H12 by showing that it not only controls the recruitment of cofactors but also influences the stability of ER α . Overall, our data suggest that antagonist-mediated increases in surface hydrophobicity can contribute to ER α instability.

The coordinates of this structure have been deposited in the Protein Data Bank (PDB ID: 1R5K). The technical details are given in the experimental procedure of Appendix 1.

AIM 2: To determine the structure of ER α /LBD/GW5638 associated with GW 7 α -16 and/or other CoRNR box peptides and to identify the specific interactions between GW5638 and ER that facilitate corepressor docking

The technical hurdles to obtain diffractable complex crystals as well substitutive approaches were detailed in my last annual report. Alternatively, we mapped the peptide-binding site by modeling and tested the predictions by mammalian two-hybrid assay coupled with mutagenesis. Based on the solved GW-ER structure and the sequence homology between GW-selective peptides and CoRNR box motif (Perissi et al., 1999), we proposed that GW-selective peptides bind to the putative CoRNR-binding region in the ER α LBD, which partially overlaps with the coactivator-binding site in the AF-2 cleft.

A few mutations that are known to enhance or reduce the interaction of TR α or RXR α with NCoR/SMRT (Hu and Lazar, 1999) were introduced into ER α at equivalent positions (Figure 6A, Appendix 1). ER α -peptide interaction was determined by the ability of wild-type or mutant ER α -VP16 to initiate transcription from the Gal4-responsive reporter in the presence of the GW compound. Deletion of H12 (ER α 537X or ER α 538X), which was previously shown to increase NCoR binding to ER α (Webb et al., 2003), enhanced the binding of GW-selective peptides to GW-ER α LBD (Figure 6B, Appendix 1). Although the L372R and V376R mutations did not have an overall effect on different GW-peptide binding, mutations L379R, at the base of H5, and K362A, at the H3/H4 boundary, significantly reduced all the interactions between ER and peptides (Figure 6C-D, Appendix 1). L379R is of interest because this residue was shown to be critical for NCoR recruitment to ER α (Webb et al., 2003). In the GW-ER α LBD crystal structure, H12 is partially displaced from the AF2 cleft, which may facilitate corepressor competition with H12 in the presence of GW5638/7604 compared to tamoxifen. The LBD structures correlate well with fluorescence-microsphere-binding data (Iannone et al., 2004), which showed that GW7604 and other compounds with the same acrylate or carboxylate side-chain are more effective recruiters of corepressor-like peptides to ER α . It is possible that the GW-selective peptides are affinity-optimized versions of the CoRNR box peptide motif for GW-ER α .

Transcriptional regulation by ER α is a complex process that involves the participation of coactivators and corepressors. While the interaction of coactivators with ER α is well established, the interaction and importance of corepressors is less clear (Dobrzycka et al., 2003). ER α is different from other NRs, such as retinoic acid receptor (RAR) and thyroid receptor hormone (TR), because it does not appear to actively repress transcription in the absence of ligand (Chen and Evans, 1995; Dobrzycka et al., 2003). However, evidence suggests that antagonist-mediated inhibition of ER α not only blocks coactivator recruitment but also facilitates the recruitment of

corepressors to form an actively repressed ER α complex (Cottone et al., 2001; Dobrzycka et al., 2003; Shang and Brown, 2002; Webb et al., 2003).

Most of the estrogen responsive breast cancers that are normally growth inhibited by tamoxifen therapy, become resistant to, and even stimulated by tamoxifen. Evidence has shown that this may due to a reduction in corepressor protein levels in breast cancer cells that have been chronically exposed to tamoxifen (Lavinsky et al., 1998). Our data indicated that drugs with acrylate or carboxylate side-chain may be more effective to recruit corepressor-(like) proteins, which could account for in part why tamoxifen-resistant cancers respond to GW5638.

In the absence of an ER α -corepressor structure, our structure data suggest how corepressor-like peptides might compete with the partially displaced H12 for the AF-2 cleft in the GW-ER α structure. Our mammalian-two hybrid data further support the structural information in that deletion of H12 as well as two ER α mutations L379R and K362A significantly alter the binding of GW-specific peptides. Notably, these peptides were obtained in the absence of any structural information. The fact that some of these peptides are homologous to the CoRNR box motif suggests that the ER α conformation induced by GW5638 favors the recruitment of corepressor-like proteins, implying that corepressors could play a critical role in the pharmacology of GW5638.

The technical details of performing mutagenesis and mammalian two-hybrid assay are given in the experimental procedure of Appendix 1.

AIM 3: To determine the structure of C through E domains of human ER α / β and to characterize the interactions among these functional domains, which may have important pharmacological significance in biology and drug design

I have attempted to express C through E domains of human ER α / β but it is problematic to purify the full-length of this region for further biochemical analysis and crystallization.

Because I have completed my PhD studies in June, 2005, I will no longer pursue aim 3 of this proposal.

KEY RESEARCH ACCOMPLISHMENTS

During the training period, I have crystallized, determined and refined the atomic structure of ER α LBD in complex with GW5638 and revealed the mechanism that may account for the ability of GW5638 to inhibit tamoxifen-resistant breast tumor explants. I have also accomplished the biochemical as well as functional characterizations with regard to GW-ER.

REPORTABLE OUTCOMES

1. The structure of GW-ER α LBD was deposited to the protein data bank (PDB ID: 1R5K)
2. The structure of GW-ER along with other functional characterizations has been published in *Molecule Cell*, vol 18, 413-424, 2005 (please refer to Appendix 1).
3. The structural study of GW-ER α LBD was presented as a poster at the Nuclear Receptor Keystone Symposia (02/28/04 – 03/04/04) supported by Keystone Symposia, held at Keystone Resort, Keystone, CO (please refer to Appendix 2 for the abstract).
4. The discoveries accomplished in the training period were presented as a poster at Era of Hope 2005 - Department of Defense Breast Cancer Research Program Meeting (06/08/05 – 06/11/05) hosted by U.S. Army Medical Research and Materiel Command, held at Philadelphia, PA (please refer to Appendix 3 for the abstract).
5. PhD thesis “Structural and Functional Characterization of Human Estrogen Receptor alpha Ligand-Binding Domain In Complex with GW5638”.

CONCLUSIONS

In summary, the GW5638-ER α LBD structure and supporting data may explain why GW5638/7604 is an effective inhibitor of tamoxifen-resistant MCF-7 tumor explants. GW5638/7604 shares some of the HRT benefits of tamoxifen but acts as a more potent antagonist in the breast and does not stimulate the uterus. The data presented here show that the distinct pharmacologies of tamoxifen and GW5638 are due, at least in part, to subtle changes in the respective ER α AF2 conformations. These data also suggest that an acidic side chain may be a useful substitute for drug design on the triphenylethylene scaffold. In addition to preventing coactivator recruitment by occlusion of the AF2 cleft, similar to other SERMs, GW5638/7604 also destabilizes ER α , although less so than the more potent ER antagonist ICI 164,380/182,780. Therefore GW5638/7604 belongs to a class of molecules that has mixed functions (SERM/SERD) (McDonnell, 2005). SERMs function either as agonists or antagonists, depending on the coregulator context. SERDs (selective estrogen receptor down-regulators) like

ICI and ZK-703 (Hoffmann et al., 2004), act as more potent antagonists by inducing receptor destabilization. If proven to be effective in clinical trials, molecules like GW5638/7604 could be used as a second-line therapy for patients whose breast cancers have become tamoxifen-resistant. Because no single endocrine agent is likely to prevent recurrent disease in ER-positive breast tumors, there continues to be a need for novel agents that differentially target estrogen/ER-signaling pathways.

REFERENCES

- Brzozowski, A. M., Pike, A. C., Dauter, Z., Hubbard, R. E., Bonn, T., Engstrom, O., Ohman, L., Greene, G. L., Gustafsson, J. A., and Carlquist, M. (1997). Molecular basis of agonism and antagonism in the oestrogen receptor. *Nature* **389**, 753-758.
- Buzdar, A. U., Marcus, C., Holmes, F., Hug, V., and Hortobagyi, G. (1988). Phase II evaluation of Ly156758 in metastatic breast cancer. *Oncology* **45**, 344-345.
- Chen, J. D., and Evans, R. M. (1995). A transcriptional co-repressor that interacts with nuclear hormone receptors. *Nature* **377**, 454-457.
- Connor, C. E., Norris, J. D., Broadwater, G., Willson, T. M., Gottardis, M. M., Dewhirst, M. W., and McDonnell, D. P. (2001). Circumventing tamoxifen resistance in breast cancers using antiestrogens that induce unique conformational changes in the estrogen receptor. *Cancer Res* **61**, 2917-2922.
- Cottone, E., Orso, F., Biglia, N., Sismondi, P., and De Bortoli, M. (2001). Role of coactivators and corepressors in steroid and nuclear receptor signaling: potential markers of tumor growth and drug sensitivity. *Int J Biol Markers* **16**, 151-166.
- Couse, J. F., and Korach, K. S. (1999). Estrogen receptor null mice: what have we learned and where will they lead us? *Endocr Rev* **20**, 358-417.
- Dobrzycka, K. M., Townson, S. M., Jiang, S., and Oesterreich, S. (2003). Estrogen receptor corepressors -- a role in human breast cancer? *Endocr Relat Cancer* **10**, 517-536.
- Gottardis, M. M., and Jordan, V. C. (1987). Antitumor actions of keoxifene and tamoxifen in the N-nitrosomethylurea-induced rat mammary carcinoma model. *Cancer Res* **47**, 4020-4024.
- Hoffmann, J., Bohlmann, R., Heinrich, N., Hofmeister, H., Kroll, J., Kunzer, H., Lichtner, R. B., Nishino, Y., Parczyk, K., Sauer, G., *et al.* (2004). Characterization of new estrogen receptor destabilizing compounds: effects on estrogen-sensitive and tamoxifen-resistant breast cancer. *J Natl Cancer Inst* **96**, 210-218.
- Hu, X., and Lazar, M. A. (1999). The CoRNR motif controls the recruitment of corepressors by nuclear hormone receptors. *Nature* **402**, 93-96.
- Hunt, K. (1994). Breast cancer risk and hormone replacement therapy: a review of the epidemiology. *Int J Fertil Menopausal Stud* **39**, 67-74.
- Iannone, M. A., Simmons, C. A., Kadwell, S. H., Svoboda, D. L., Vanderwall, D. E., Deng, S. J., Consler, T. G., Shearin, J., Gray, J. G., and Pearce, K. H. (2004). Correlation between in vitro peptide binding profiles and cellular activities for estrogen receptor-modulating compounds. *Mol Endocrinol* **18**, 1064-1081.

- Lavinsky, R. M., Jepsen, K., Heinzel, T., Torchia, J., Mullen, T. M., Schiff, R., Del-Rio, A. L., Ricote, M., Ngo, S., Gemsch, J., *et al.* (1998). Diverse signaling pathways modulate nuclear receptor recruitment of N-CoR and SMRT complexes. *Proc Natl Acad Sci U S A* 95, 2920-2925.
- McDonnell, D. P. (2005). The molecular pharmacology of estrogen receptor modulators: implications for the treatment of breast cancer. *Clin Cancer Res* 11, 871s-877s.
- McGuire, W. L. (1978). Hormone receptors: their role in predicting prognosis and response to endocrine therapy. *Semin Oncol* 5, 428-433.
- Perissi, V., Staszewski, L. M., McInerney, E. M., Kurokawa, R., Krones, A., Rose, D. W., Lambert, M. H., Milburn, M. V., Glass, C. K., and Rosenfeld, M. G. (1999). Molecular determinants of nuclear receptor-corepressor interaction. *Genes Dev* 13, 3198-3208.
- Poulin, R., Merand, Y., Poirier, D., Levesque, C., Dufour, J. M., and Labrie, F. (1989). Antiestrogenic properties of keoxifene, trans-4-hydroxytamoxifen, and ICI 164384, a new steroidal antiestrogen, in ZR-75-1 human breast cancer cells. *Breast Cancer Res Treat* 14, 65-76.
- Shang, Y., and Brown, M. (2002). Molecular determinants for the tissue specificity of SERMs. *Science* 295, 2465-2468.
- Shiau, A. K., Barstad, D., Loria, P. M., Cheng, L., Kushner, P. J., Agard, D. A., and Greene, G. L. (1998). The structural basis of estrogen receptor/coactivator recognition and the antagonism of this interaction by tamoxifen. *Cell* 95, 927-937.
- Urry, D. W., Peng, S. Q., and Parker, T. M. (1992). Hydrophobicity-induced pK shifts in elastin protein-based polymers. *Biopolymers* 32, 373-379.
- Webb, P., Nguyen, P., and Kushner, P. J. (2003). Differential SERM effects on corepressor binding dictate ERalpha activity in vivo. *J Biol Chem* 278, 6912-6920.
- Willson, T. M., Henke, B. R., Momtahan, T. M., Charifson, P. S., Batchelor, K. W., Lubahn, D. B., Moore, L. B., Oliver, B. B., Sauls, H. R., Triantafillou, J. A., and *et al.* (1994). 3-[4-(1,2-Diphenylbut-1-enyl)phenyl]acrylic acid: a non-steroidal estrogen with functional selectivity for bone over uterus in rats. *J Med Chem* 37, 1550-1552.

Structural Basis for an Unexpected Mode of SERM-Mediated ER Antagonism

Ya-Ling Wu,¹ Xiaojing Yang,² Zhong Ren,²
Donald P. McDonnell,³ John D. Norris,³
Timothy M. Willson,⁴ and Geoffrey L. Greene^{1,*}

¹The Ben May Institute for Cancer Research
and Department of Biochemistry
and Molecular Biology

University of Chicago
Chicago, Illinois 60637

²Renz Research, Inc.
Westmont, Illinois 60559

³The Department of Pharmacology
and Cancer Biology

Duke University Medical Center
Durham, North Carolina 27710

⁴GlaxoSmithKline
Research Triangle Park, North Carolina 27709

Summary

Tamoxifen is effective for the prevention and treatment of estrogen-dependent breast cancers, but is associated with an increased incidence of endometrial tumors. We report the crystal structure of the estrogen receptor α (ER α) ligand binding domain (LBD) bound to the structurally similar compound GW5638, which has therapeutic potential and does not stimulate the uterus. Like tamoxifen, GW5638 relocates the carboxy-terminal helix (H12) to the known coactivator-docking site in the ER α LBD. However, GW5638 repositions residues in H12 through specific contacts with the N terminus of this helix. In contrast to tamoxifen, the resulting increase in exposed hydrophobic surface of ER α LBD correlates with a significant destabilization of ER α in MCF-7 cells. Thus, the GW5638-ER α LBD structure reveals an unexpected mode of SERM-mediated ER antagonism, in which the stability of ER α is decreased through an altered position of H12. This dual mechanism of antagonism may explain why GW5638 can inhibit tamoxifen-resistant breast tumors.

Introduction

Breast cancers affect one in eight women in the United States. Many of these cancers respond to hormonal therapy and the presence of human estrogen receptor- α (ER α) is associated with a more favorable response and short-term prognosis (Hunt, 1994). ER α is a ligand-activated transcription factor that has important functions in many tissues and plays a critical role in the etiology of breast cancer (Couse and Korach, 1999; Hunt, 1994; McGuire, 1978). Because ER α is an important target for breast cancer treatment and prevention, numerous molecules have been designed to bind ER α and elicit distinct pharmacological profiles. Tamoxifen or 4-hydroxytamoxifen (OHT) is part of a growing family of molecules called selective estrogen receptor modulators (SERMs)

that can behave as agonists or antagonists in different tissue and environmental contexts. It has been widely used for breast cancer treatment and shows considerable potential as a preventive agent. Tamoxifen has protective benefits in bone and cardiovascular tissues as an ER α agonist and displays antagonistic activity in most ER-positive breast tumors. Unfortunately, advanced breast cancers that initially respond well to tamoxifen eventually become refractory to this compound. Its uterotrophic activity also restricts its utility in a prevention setting (Graham et al., 2000; McDonnell et al., 2002; Ravdin et al., 1992).

GW5638, 3-[4-(1,2-Diphenylbut-1-enyl)phenyl]acrylic acid, is a SERM with clinical potential that was identified in a screen for compounds that are mechanistically distinct from tamoxifen and raloxifene (Willson et al., 1994). In contrast to tamoxifen, the dimethylaminoethoxy group is replaced by an acrylate side chain (Figure 1A). This compound exhibits beneficial estrogenic properties, but unlike tamoxifen, it is a more potent antagonist in breast cancer cells and has no uterotrophic behavior (Willson et al., 1997). Because tamoxifen-resistant breast cancers are not cross resistant to GW5638, this SERM has significant potential as a therapeutic agent. GW5638 and its 4-hydroxy metabolite (GW7604) can induce a unique conformational change in ER α that is recognized by synthetic peptides (Figure 1B) selected by phage display (Connor et al., 2001). These peptides recognize GW5638/GW7604-ER α complexes but not tamoxifen-ER α or other ligand bound ER complexes (Willson et al., 1994; Willson et al., 1997), indicating that conformational changes elicited by GW5638 and tamoxifen are different. To better understand the pharmacology of GW5638, we solved the crystal structure of ER α ligand binding domain (LBD) bound to GW5638. The crystal structure reveals a new LBD conformation in which AF2 H12 is repositioned by direct contacts between the carboxyl side chain of GW5638 and the N terminus of H12. The associated decrease in ER α stability may account for the ability of GW5638 to inhibit tamoxifen-resistant MCF-7 breast tumor explants.

Results

GW5638 Induces a Distinct Conformation in H12 and L11-12 through Specific Interactions with H12

The structure of ER α LBD bound to GW5638 was solved by molecular replacement with a truncated raloxifene-ER α LBD structure to a resolution of 2.7 Å with an R factor of 0.208 and free R factor of 0.236 (Table 1). The refined structure contains three GW5638-ER α LBD complexes in one asymmetric unit and reveals clear electron density for GW5638 (Figure 1C, left). Like other known ER LBD structures, GW-ER α LBD folds into a canonical three-layered sandwich of twelve α helices. GW5638 lies in an orientation similar to OHT inside the ligand binding pocket (Figures 2A and 2B). Surprisingly, the carboxyl groups between GW5638 and Asp 351

*Correspondence: ggrene@uchicago.edu

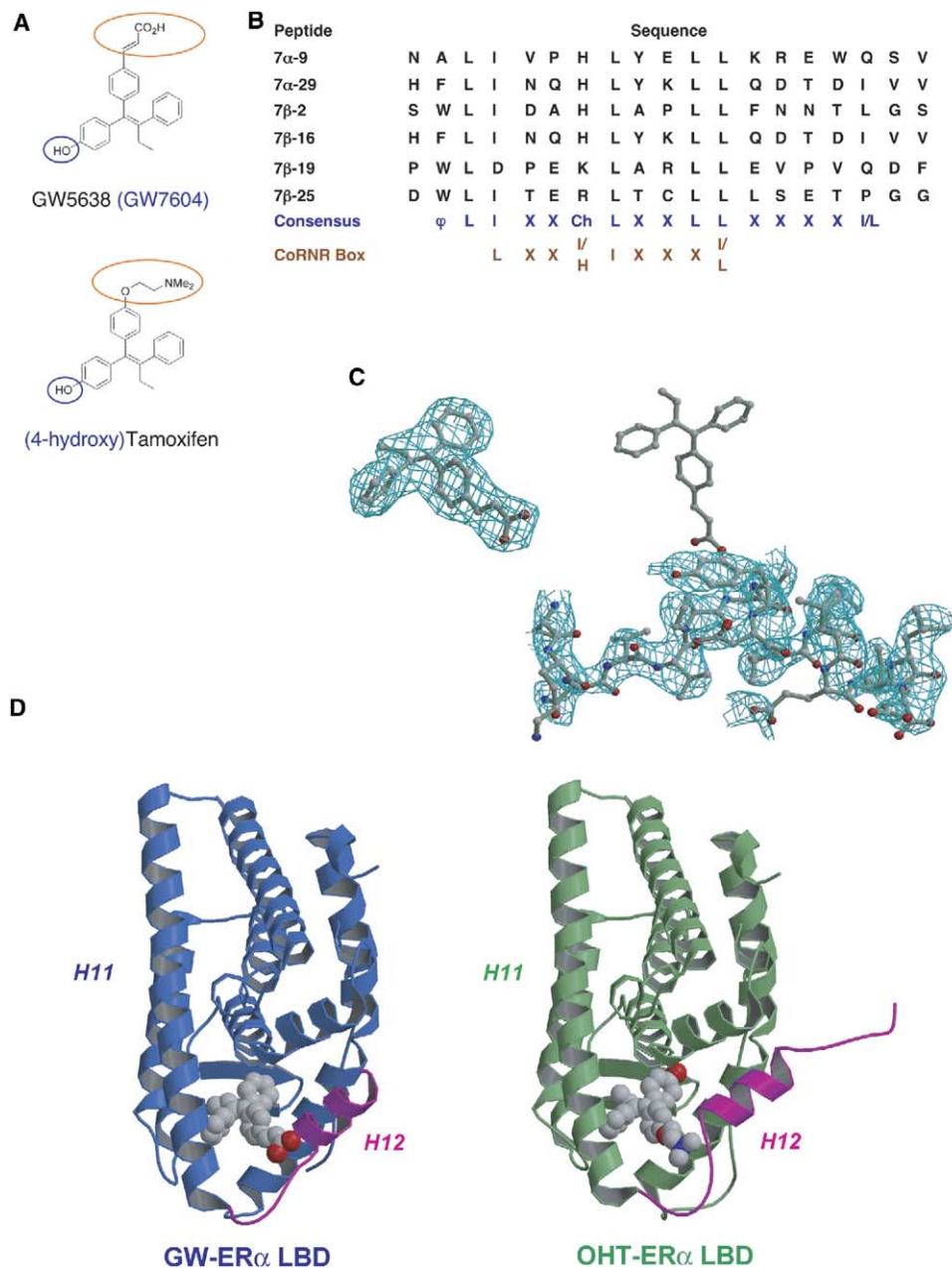


Figure 1. Overall Structure of GW5638-ER α LBD Compared to OHT-ER α LBD

(A) Structures of tamoxifen and GW5638 (OHT and GW7604 with a hydroxyl group at the fourth position). The side chains of both compounds are highlighted in orange.

(B) Sequence alignment of the GW-selective peptides and CoRNR box motif. Abbreviations and symbols used are as follows: ϕ , hydrophobic residue; Ch, charged residue; X, any amino acid.

(C) Two Fo-Fc electron density maps of GW5638, H12, and L11-12 calculated at the resolution of 2.7 Å and contoured at 1.0 σ .

(D) Equivalent views of GW-ER α LBD (left) and OHT-ER α LBD (right). H12 in the two structures is colored magenta.

form a hydrogen bond at the crystallization pH of 5.6 (Figure 2A), rather than repelling each other as predicted from molecular modeling studies of the 4-hydroxy metabolite GW7604 (Bentrem et al., 2001). It is likely that the hydrophobic environment of the pocket results in protonation of the weakly acidic acrylate, allowing for hydrogen bond formation with Asp351 (Urry et al., 1992). Interestingly, the acrylate side chain of GW5638 in-

duces an unexpected conformation in H12, the C-terminal "activation function-2" (AF2) helix, which has not been observed in other antagonist bound NR LBD structures (Figure 1D). The electron density in this region was clearly revealed in the initial omit map and the final 2Fo-Fc map is shown at the right section of Figure 1C. In the OHT and RAL ER α LBD structures, H12 binds to and occludes the coactivator binding site by mimick-

Table 1. Statistics for GW5638-ER α LBD Structure Determination

Data Collection Details	
Wavelength	$\lambda = 0.9$
Space group	P6(1)22
Unit cell dimension	a = b = 136.031 Å; c = 357.626 Å
Processing Statistics	
Resolution range	100-2.70 Å
Observations	408320
Unique reflections ^a	53588 (5227)
Completeness ^a	97.3% (96.8%)
I/ σ (last shell)	26.2 (2.1)
R _{merge} ^b	7.2%
Refinement Statistics	
Resolution range (Å)	27.95-2.70 (2.77-2.70)
Reflections used (R _{free} set)	45583 (5160)
Total nonhydrogen atoms	5756
R _{cryst} (%) ^{a,c}	20.8 (34.8)
R _{free} (%) ^{a,c}	23.6 (35.5)
Rmsd deviation	
Bonds (Å)	0.014
Angles (°)	1.34
Average B factor (Å ²)	45.9

^a The value in parentheses corresponds to the highest resolution shell (2.77-2.70 Å).

^b $R_{\text{merge}} = 100 \times \sum |I - \langle I \rangle| / \sum \langle I \rangle$.

^c $R_{\text{cryst}} = \sum |F_{\text{obs}} - F_{\text{calc}}| / \sum |F_{\text{obs}}|$, where F_{obs} and F_{calc} are observed and calculated amplitudes, respectively. R_{free} is calculated similarly using a test set (10.2%) of reflections.

ing the hydrophobic interactions of coactivator NR box LXXLL motifs with the recognition groove formed by H3, H4 and H5 (Brzozowski et al., 1997; Shiao et al., 1998). This orientation of H12 is partially displaced from the hydrophobic cleft in the GW-ER complex, which can be attributed to the water-mediated hydrogen bonds that link one of the carboxyl oxygen atoms in GW5638 to the backbone NH groups at the N terminus of H12 (Figure 2C).

GW5638 Induces a Relocation of Hydrophobic Residues in H12

Leu-536 mediates the N-terminal capping of H12, which is initiated by the water-mediated hydrogen bonds between the GW 5638 acrylate carboxyl group, Leu-536 and Tyr-537, bringing the N terminus of H12 and the loop connecting H11 and H12 (L11-12) 6-7 Å closer to the ligand (Figure 2C). Consequently, H12 relocates ~10° away from H11, compared to the OHT and raloxifene complexes, resulting in a ~50° difference in orientation for H12 in the GW-ER α and OHT-ER α structures (Figure 3A). This displacement disrupts the hydrophobic interactions between the AF-2 cleft and the H12 LLEML residues in the OHT-ER structure (Figure 4A). In addition, a series of hydrogen bonds between H3/H5 and H12 in the OHT-ER structure are lost in the GW-ER structure (Figure 4B). Significantly, this unusual orientation induces a repositioning of hydrophobic residues in H12 (Leu-536, Leu-539, Leu-540, and Met-543) such that the side chains of these residues are no longer buried in the hydrophobic core but become relocated to the protein exterior (Figure 3B). Thus, GW5638

causes a nearly 27% increase in the exposed hydrophobic surface of H12 compared to the OHT-ER α structure. This surface is stabilized in part by contact with a neighboring LBD molecule in the crystal lattice.

Analysis of the Surface Hydrophobicity of ER α LBD

A bis-ANS probe that fluoresces strongly in hydrophobic environments (Rosen and Weber, 1969; Slavik, 1982) was used to determine if structure-predicted surface hydrophobicity is reflected in the solution conformations of ER α LBD in the presence of different ligands. Based on peptide phage-display and mammalian two-hybrid data, GW7604 and GW5638 should induce nearly identical conformations in the ER α LBD (Connor et al., 2001). Because GW7604 has a significantly higher affinity for ER α than GW5638 (Willson et al., 1997) and is more like the OHT structure, we used GW7604, OHT, ICI 182,780, and the natural ER α agonist 17 β -estradiol (E2) in bis-ANS experiments. The binding of bis-ANS to ER α LBD was monitored by the enhancement of bis-ANS fluorescence intensities (Rosen and Weber, 1969; Slavik, 1982). Consistent with the structure-based prediction (see Figure 5A), the fluorescence intensity for GW7604-ER α LBD was ~20% greater than for OHT-ER α LBD. The ligand-mediated steady-state surface hydrophobicity of ER α LBD in solution was ICI > E2 > GW7604 > OHT. (Figure 5B). For ICI-ER β LBD (Brzozowski et al., 1997; Pike et al., 2001), the bulky ICI side chain blocks the association between H12 and the rest of the LBD (Figure 5A). Thus, ICI-ER LBD should have the most open hydrophobic interior. E2-ER LBD has an agonist bound conformation (Brzozowski et al., 1997) that also exposes a hydrophobic binding site for coactivator NR box domains (Shiao et al., 1998).

Instability of ER α Is Associated with Surface Hydrophobicity

Several studies have shown that ER α protein degradation is mediated through the ubiquitin-proteasome pathway. Agonist-induced ER α protein turnover is concomitant with transcriptional activation and coactivator recruitment (Dace et al., 2000; Nawaz et al., 1999a; Shao et al., 2004), whereas degradation induced by the potent antagonist ICI 164,380/182,780 presumably occurs through a different mechanism and OHT appears to stabilize ER α . Surface hydrophobicity has long been associated with other destabilizing modifications such as oxidation, arginylation, and ubiquitination, and this property is recognized as an important determinant of protein stability (Bohley, 1996). Our data suggest that ER α LBD surface hydrophobicity elicited by various antagonists (Figure 5B) may correlate with ER α stability. We therefore inspected the protein level of ER α by Western blot analysis after 4 hr of ligand treatment. As reported elsewhere, GW7604 and ICI 182,780 differentially reduce ER α steady-state levels, whereas OHT stabilizes ER α , despite the structural similarity between GW5638/7604 and tamoxifen (Figure 5C). Our data show an inverse correlation between the surface hydrophobicity and ER α protein levels after short-term ligand treatment (Figure 5D). ICI 182,780, which has the most profound effect on ER α degradation, induces a conformation that exposes the most surface hydrophobicity

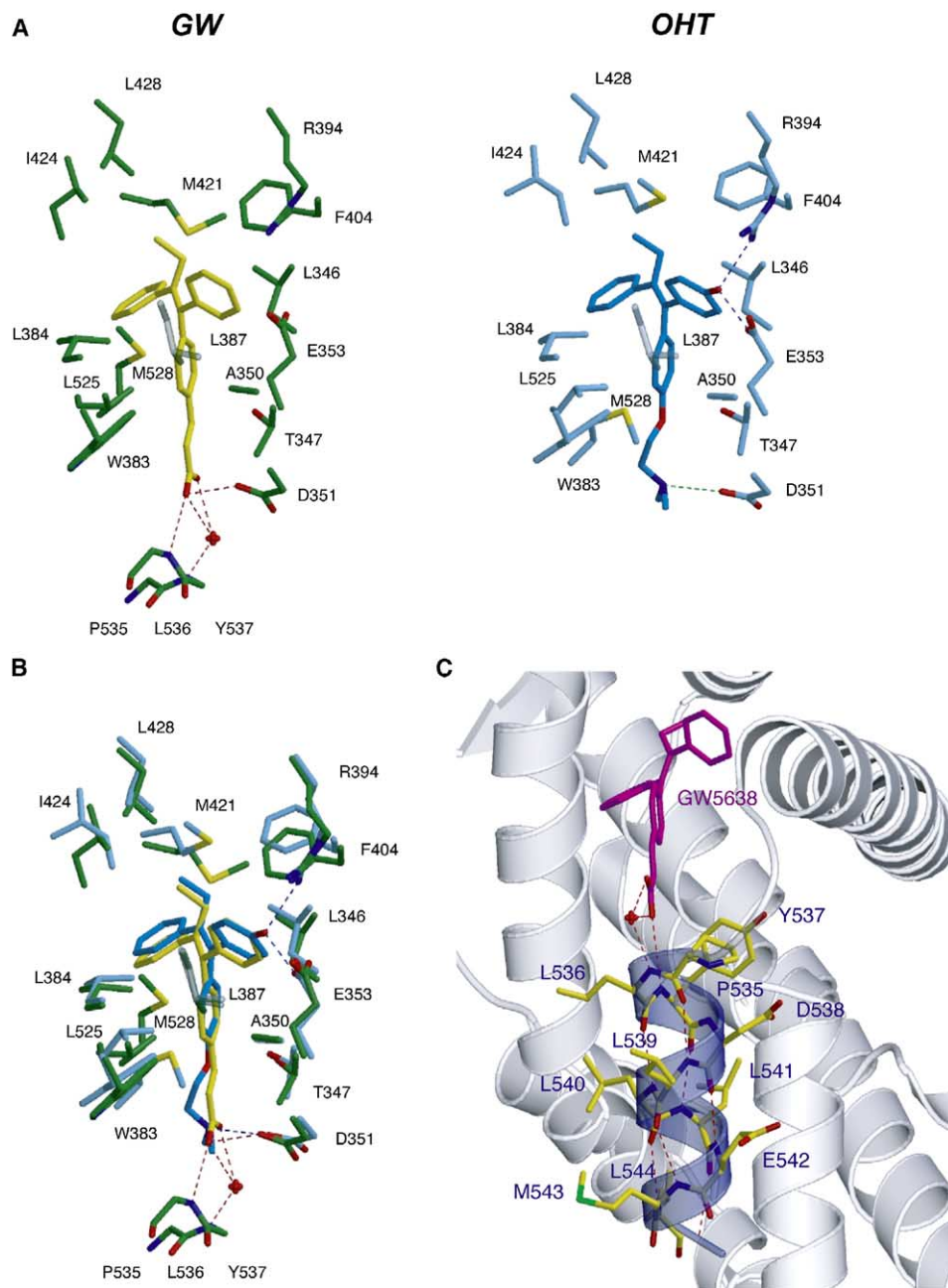


Figure 2. Ligand-LBD Interactions in GW5638-ER α LBD and OHT-ER α LBD

(A) Interactions of GW5638 or OHT and the ligand binding pocket of ER α LBD (4.0 Å cutoff). GW5638 is colored yellow, and OHT is colored blue. Atoms of residues are colored by atom type (carbon [GW], green; carbon [OHT], light blue; nitrogen, dark blue; oxygen, red; sulfur, yellow). Side chains of all residues are shown except that main chains of residues P535, L536, and Y537 in GW-ER are illustrated. For clarity, the side chain of M343 is not shown. Hydrogen bonds are depicted as dashed red lines in GW-ER and dashed blue lines in OHT-ER. The weak salt bridge between the dimethylamino group of the OHT side chain and the carboxylate side chain of D351 is colored green.

(B) An overlay of GW5638-ER α LBD and OHT-ER α LBD in the ligand binding pocket.

(C) The side chain of GW5638 initiates N-terminal capping of H12. Hydrogen bonds are depicted as dashed red lines. GW5638 is colored magenta. Residues in H12 are colored by atom type (carbon, yellow; nitrogen, dark blue; oxygen, red; sulfur, green).

compared to other ligands (Figures 5B and 5D). OHT, which decreases ER α turnover, has the least exposed hydrophobic surface, whereas GW7604 induces a conformation that is intermediate in exposed hydrophobic surface, consistent with its effect on ER α stability (Fig-

ure 5D). Although E2 appears to induce an exposed hydrophobic surface that correlates with its effect on ER α stability, this surface is presumably occupied by coactivator in vivo, which appears to be essential for agonist-mediated degradation of ER α . Overall, these results

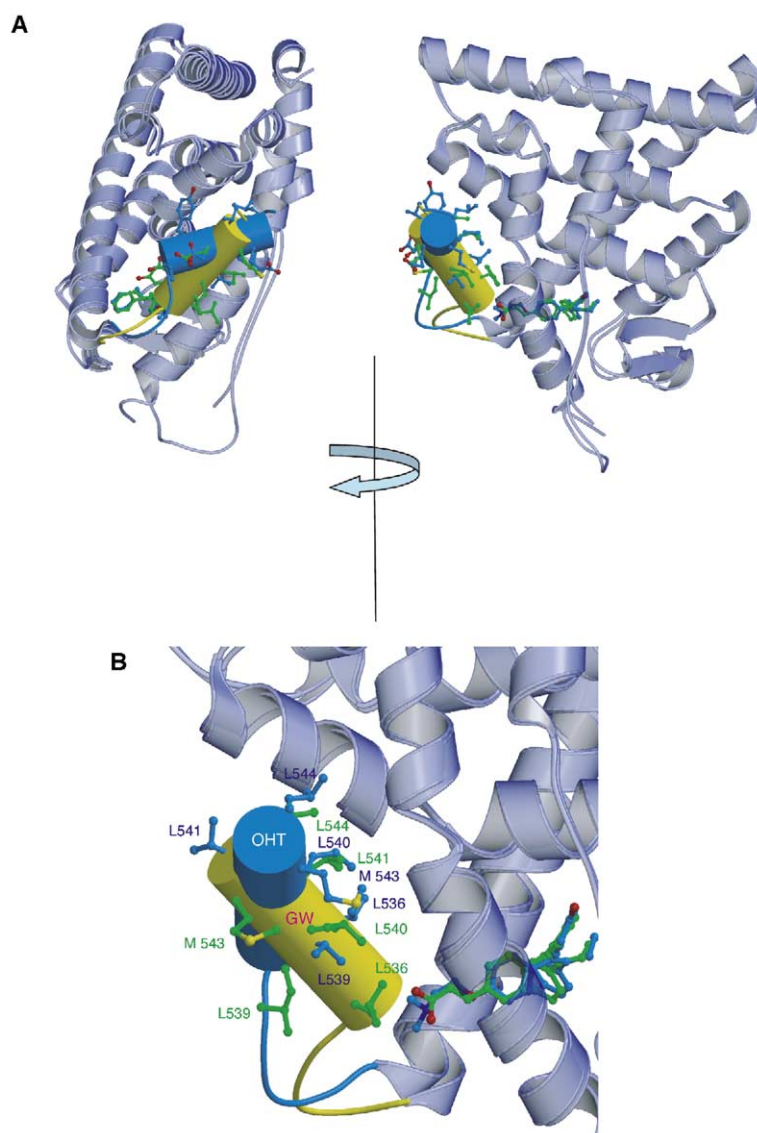


Figure 3. Superimposed Structures of GW5638-ER α LBD and OHT-ER α LBD

(A) Two orthogonal views of the orientations and positions of H12 and L11-12. H12 is shown as cylinder presentation, yellow in the GW complex and blue in the OHT complex. Side chains in H12 are colored by atom type (carbon [GW], green; carbon [OHT], blue; nitrogen, dark blue; oxygen, red; sulfur, yellow).

(B) A closer look of the superimposed GW and OHT-ER α LBD structures. Only hydrophobic residues in H12 are shown. Side chains and ligands are colored by atom type (carbon [GW], green; carbon [OHT], blue; nitrogen, dark blue; oxygen, red; sulfur, yellow).

suggest that antagonist-mediated increases in surface hydrophobicity can contribute to ER α instability. Consistent with this hypothesis, replacement of Leu-536, Leu-539, and Leu-540 with Gln, which should reduce the surface hydrophobicity of H12, increased ER α stability from 68% to 85% in the presence of GW7604 (Figure 5E).

Mutations in the Putative CoNR Box-Interacting Region of ER α Affect the Binding of GW-Specific Peptides

GW-selective peptides, which were obtained from a phage library that contained the "LXXLL" motif, share homology with the NR box-related consensus corepressor nuclear receptor-interacting motif (CoNR box: LXXI/HIXXXI/L) (Perissi et al., 1999) (Figure 1B). To test if these peptides bind to the putative CoNR binding region in the ER α LBD, which partially overlaps with the coactivator binding site in the AF-2 cleft, we used a

mammalian two-hybrid approach. Peptides were fused to the DNA binding domain of Gal4 and the ER α LBD was fused to the VP16 activation domain. Several mutations that are known to enhance or reduce the interaction of thyroid hormone receptor (TR) or retinoic X receptor (RXR) with NCoR/SMRT (Hu and Lazar, 1999) were introduced into ER α at equivalent positions (Figure 6A). ER α -peptide interaction was determined by the ability of the wild-type or mutant ER α -VP16 to activate transcription from the Gal4-responsive reporter in the presence of the GW compound. Deletion of H12 (ER α 537X or ER α 538X), which was previously shown to increase NCoR binding to ER α (Webb et al., 2003), enhanced the binding of GW-selective peptides to GW-ER α LBD (Figure 6B). Although the L372R and V376R mutations did not significantly affect peptide binding (data not shown), mutations L379R, at the base of H5, and K362A, at the H3/H4 boundary, significantly reduced these interactions (Figures 6C and 6D). L379R is

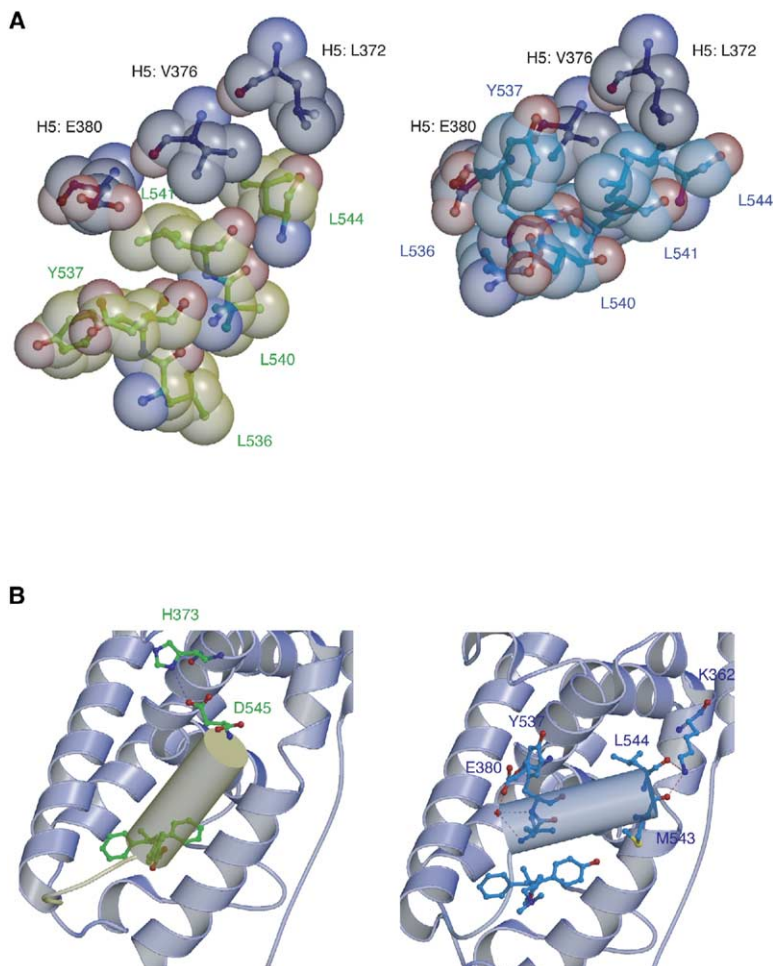


Figure 4. Interactions between H12 and H3/H5 in GW5638-ER α LBD and OHT-ER α LBD (A) van der Waals contacts between H5 and H12 in the GW-ER (left) and OHT-ER (right). Residues are colored by atom type (carbon [H5], dark blue; carbon [H12 in GW], green; carbon [H12 in OHT], light blue; nitrogen, blue; oxygen, red). (B) Illustrations of GW and OHT-ER α LBD showing the interactions between H3/H5 and H12. The hydrogen bonds in the OHT-ER structure are depicted as dashed red lines. The weak salt bridge in the GW-ER structure is depicted as blue dashed line. Side chains and ligands are colored by atom type (carbon [GW], green; carbon [OHT], blue; nitrogen, dark blue; oxygen, red; sulfur, yellow).

of interest because this residue was shown to be critical for NCoR recruitment to ER α (Webb et al., 2003). In the GW-ER α LBD crystal structure, H12 is partially displaced from the AF2 cleft, which may facilitate corepressor competition with H12 in the presence of GW5638/7604 compared to tamoxifen (Figures 3 and 4). The LBD structures correlate well with fluorescence-microsphere binding data (Iannone et al., 2004), which showed that GW7604 and other compounds with the same acrylate or carboxylate side chain are more effective recruiters of corepressor-like peptides to ER α . Although we did not detect a significant interaction between SMRT/NCoR and ER α in the mammalian two-hybrid assay (data not shown), it is possible that the GW-selective peptides are affinity-optimized versions of the CoRNR box peptide motif for GW-ER α .

Discussion

In total, the GW5638-ER α LBD structure and supporting data may explain how GW5638/7604 is an effective inhibitor of tamoxifen-resistant MCF-7 tumor explants. Clearly, relatively subtle ligand modifications can significantly alter the conformation of the H12 molecular switch. In addition to preventing coactivator recruit-

ment by occlusion of the AF2 cleft, similar to OHT and RAL, GW5638/7604 also destabilizes ER α , although less so than the more potent ER antagonist ICI 164,380/182,780. This effect is associated with a rotation of H12, induced by the tethering of Leu-536 and Tyr-537 to the carboxyl moiety on GW5638/7604, which leads to an increase in the surface hydrophobicity of the ER α LBD. This increased surface hydrophobicity is associated with a decrease in ER α stability. Therefore, GW5638/7604 is a more potent growth inhibitor than OHT and RAL because it also downregulates ER α .

The Conformation of H12 Plays a Role in the Stability of ER α

The acrylate side chain of GW5638/7604, a tamoxifen analog, interacts with Leu-536 and Tyr-537 of the ER α LBD to induce capping of H12 and an unexpected conformation for this AF2 molecular switch. The resulting increase in ER α surface hydrophobicity correlates with a decrease in receptor stability, in sharp contrast to the increased stability observed for OHT-ER α . Notably, the ER α was significantly stabilized in the presence of GW7604 (Figure 5E) by replacement of Leu-536, Leu-539, and Leu-540 with Gln, which should reduce the surface hydrophobicity of H12. Thus, the GW5638-ER α

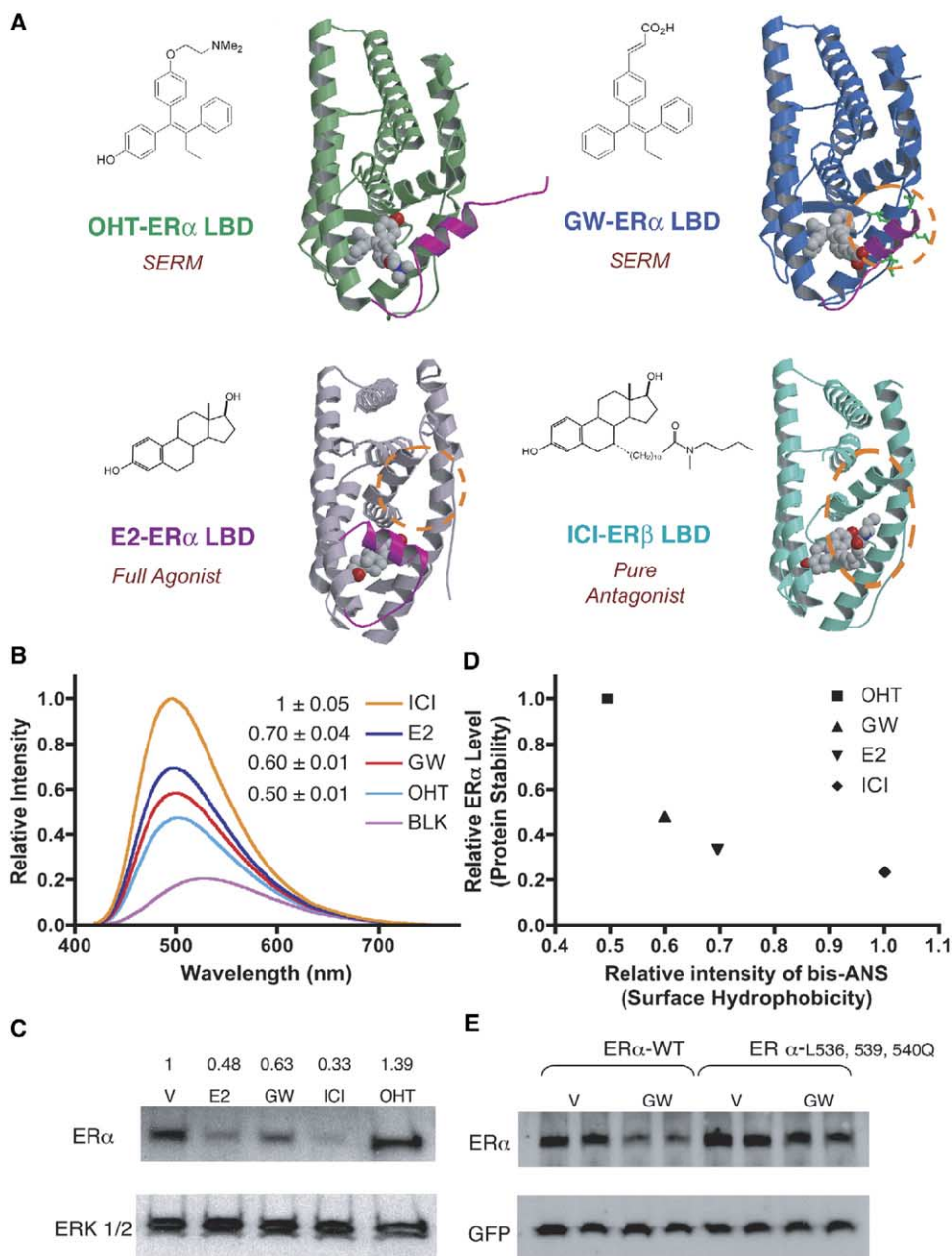


Figure 5. Surface Hydrophobicity Contributes to the Stability of Antagonist Bound ER α .

(A) Overall structures of E2- (Brzozowski et al., 1997), OHT- (Shiau et al., 1998), GW-ER α LBD, and ICI-ER β LBD (Pike et al., 2001). The regions that contribute to the altered surface hydrophobicity are circled in orange. H12 and L11-12 in the structures are colored magenta.

(B) The fluorescence intensity of bis-ANS in the presence of buffer alone (BLK), ER α LBD bound to E2, OHT, GW7604, or ICI. The relative fluorescence intensities of triplicate samples after normalized to BLK are expressed in numerical values as mean $\pm$ standard deviation compared to ICI.

(C) Protein levels of ER α in MCF-7 cells after 4 hr of ligand induction. The Western blot signals of ER α were normalized to the internal control ERK1/2 protein expression and the relative quantification is shown in numerical values (V, ethanol; E2, 17 β -estradiol; GW, GW7604; ICI, ICI 182,780; OHT, 4-hydroxytamoxifen).

(D) Correlation between the surface hydrophobicity and the protein level of ER α after short-term ligand treatment.

(E) The Western blot showing the expression levels of the wild-type or mutant ER α . Ishikawa cells were cotransfected with the wild-type or mutant ER α and a control green fluorescence protein expression vector (V, ethanol; GW, GW7604).

structure adds another level of complexity to the observed conformational flexibility of H12 by showing that it not only controls the recruitment of cofactors but also

influences the stability of ER α . Overall, our data suggest that antagonist-mediated increases in surface hydrophobicity can contribute to ER α instability.

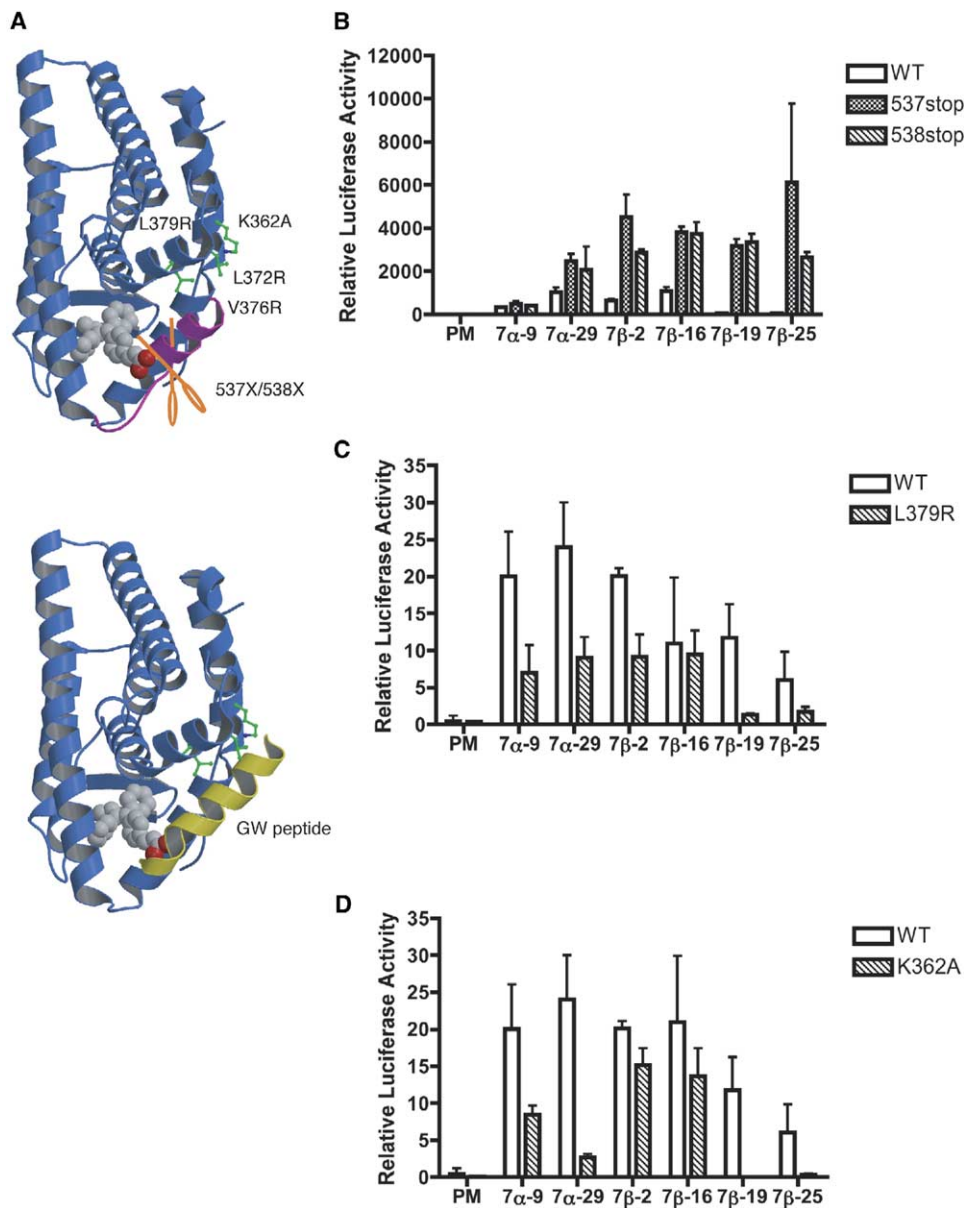


Figure 6. Mammalian Two-Hybrid Data Showing How Mutations in the Putative CoRNR Box-Interacting Region of ER α Affect the Binding of GW-Specific Peptides

(A) The upper section shows mutations introduced in this study; the lower section shows GW 7 β -16 peptide binding to GW-ER α LBD. H12 is omitted for clarity. The model of GW 7 β -16 peptide was generated using SwissPDB viewer (Guex and Peitsch, 1997) by replacing the sequence of a canonical α -helix to GW 7 β -16. The position of GW 7 β -16 peptide is superimposed on H12 in the OHT-ER structure.

(B) H12 ER α truncations increase the binding of GW-selective peptides to GW-ER α . COS-7 cells were transfected with VP16-ER α , VP16-ER α 537X or VP16-ER α 538X, Gal4-DBD-peptide fusion, and 5xGal4-TATA-Luc. The error bars indicate the standard deviation of triplicate samples.

(C) ER α mutant L379R reduces the binding of GW-selective peptides to GW-ER α . COS-7 cells were transfected with VP16-ER α , VP16-ER α L379R, Gal4-DBD-peptide fusion, and 5xGal4-TATA-Luc. The error bars indicate the standard deviation of triplicate samples.

(D) The ER α mutant K362A reduces the binding of GW-selective peptides to GW-ER α . COS-7 cells were transfected with VP16-ER α , VP16-ER α K362A, Gal4-DBD-peptide fusion, and 5xGal4-TATA-Luc reporter. The error bars indicate the standard deviation of triplicate samples.

The exposed hydrophobic surface of H12 is partly stabilized via crystal contacts with an adjacent GW5638-ER α LBD monomer. Other published ER α LBD structures, such as the OHT-ER LBD complex (Shiau et al., 1998), also show similar packing arrangements. In the absence of a solution structure, it is difficult to determine the net contribution of such contacts to the ob-

served conformation. However, the bis-ANS data (Figure 5B) support the conclusion that GW-ER has a larger exposed hydrophobic surface than OHT-ER.

It is also unlikely that the acidic pH (5.6–5.7) at which GW5638-ER α LBD crystallized contributed significantly to the observed structure. OHT-ER α LBD (Shiau et al., 1998) and RAL-ER α LBD (Brzozowski et al., 1997) have

very similar structures, even though the former crystallized under acidic conditions (pH 6.5) and the latter crystallized at pH 8.5. The biochemical and cell-based experiments (Figures 5 and 6), which were carried out at pH 7–8, are consistent with the behavior predicted by the GW5638-, OHT-, E2-, and ICI-ER α LBD structures (Figure 5A).

Estradiol-mediated ER α degradation has been linked to coactivator recruitment and transcriptional activation, which is not involved in GW- or ICI-mediated ER α degradation and inactivation (Lonard et al., 2000; Lonard and Smith, 2002; Nawaz et al., 1999a; Reid et al., 2003; Shao et al., 2004; Wijayaratne and McDonnell, 2001). The mechanisms for agonist- and antagonist-regulated ER α degradation appear to be distinct (Shao et al. 2004), although ubiquitin-mediated targeting of ER to the 26S proteasome is undoubtedly essential for both, and receptor stability and the level of ER α ubiquitination have been linked (Wijayaratne and McDonnell, 2001).

Hydrophobic clusters are considered to be important recognition motifs for ubiquitin E3 ligases, (Bohley, 1996). One of the unexpected findings in this study was the correlation between ER α LBD surface hydrophobicity in solution and subtle alterations in the conformation of H12 induced by different ligands. Surface hydrophobicity is not only important for E3 ligase recognition and ubiquitination but also for the targeting of multiubiquitinated proteins to the 26S proteasome (Bohley, 1996). We propose that the degree of LBD surface hydrophobicity observed for different ligands may correlate with differential levels of ER α ubiquitination. Ubiquitin can also function as a “chaotropic” signal by unfolding target molecules and exposing more hydrophobic residues, thereby amplifying the degradation process. Several components of the ubiquitin-proteasome system, including E3 ligases, are reported to be involved in the degradation of steroid receptors, such as uba3 (Fan et al., 2002), Ubc9 (Poukka et al., 1999), RSP5/RPF1 (Imhof and McDonnell, 1996), MDM2 (Saji et al., 2001), SUG1/Trip1 (Lee et al., 1995; vom Baur et al., 1996), and E6-AP (Nawaz et al., 1999b). It is unlikely that GW- and ICI-mediated ER α degradation involves the same E3 ligase(s) as estradiol, although it is possible that the same E3 ligase targets GW- and ICI-ER α . However, since the conformations and transcriptional responses triggered by these two ligands are not the same in different tissue contexts, it is reasonable that different E3 ligases are involved. Experiments are ongoing to identify the ligases and other components that participate in the GW- and ICI-mediated ER α degradation.

Corepressor Recruitment and Antiestrogen Action

Transcriptional regulation by ER α is a complex process that involves the participation of coactivators and corepressors. While the interaction of coactivators with ER α is well established, the interaction and importance of corepressors is less clear (Dobrzycka et al., 2003). ER α is different from other NRs, such as retinoic acid receptor (RAR) and thyroid hormone receptor (TR) because it does not appear to actively repress transcription in the absence of ligand (Chen and Evans, 1995; Dobrzycka et al., 2003). However, evidence suggests that

antagonist-mediated inhibition of ER α not only blocks coactivator recruitment but also facilitates the recruitment of corepressors to an actively repressed ER α complex (Cottone et al., 2001; Dobrzycka et al., 2003; Shang and Brown, 2002; Webb et al., 2003).

In the absence of an ER α -corepressor structure, our structural data suggest the possibility that corepressor-like peptides could compete with the partially displaced H12 for the AF-2 cleft in the GW-ER α structure. Our mammalian two-hybrid data (Figure 6) further support the structural information, in that deletion of H12 as well as two ER α mutations L379R and K362A significantly alter the binding of GW-specific peptides.

The mammalian two-hybrid data showed that the GW compound is more effective in recruiting corepressor-like peptides, suggesting that the distinctively oriented H12 might be more flexible in GW-ER. We do not rule out the possibility that the unusual H12 orientation in the observed GW-ER structure is a transitory instead of the equilibrium structure. While this structure reflects the accessible ER conformation in solution, a larger hydrophobic surface may imply the instability of H12 conformation upon GW binding. This may also explain why the GW compound is a more successful drug in recruiting corepressor-like peptides than OHT. Notably, these peptides were obtained in the absence of any structural information. The fact that some of these peptides are homologous to the CoRNR box motif suggests that the ER α conformation induced by GW5638 favors the recruitment of corepressor-like proteins, implying that corepressors could play a critical role in the pharmacology of GW5638.

GW5638 As a Prototype Drug for Tamoxifen-Resistant Breast Cancers

The mixed agonist/antagonist properties of SERMs and relatively mild side effects explain why drugs like tamoxifen and raloxifene are used for the treatment or prevention of breast cancer and for the prevention of osteoporosis, respectively. Tamoxifen is the standard endocrine treatment for ER α -positive primary and metastatic breast cancers. Unfortunately, most of these cancers become resistant within 2–5 years, and the risk of uterine cancer increases in women who take tamoxifen. Available pharmacological data show similar activities for raloxifene, but data on the activity of raloxifene in patients with advanced disease are limited (Buzdar et al., 1988; Gottardis and Jordan, 1987; Poulin et al., 1989). The commonly used second-line endocrine therapy for tamoxifen-refractory tumors includes aromatase inhibitors, gonadotrophin releasing hormone agonists, or the pure ER α antagonist ICI (Fulvestrant, Faslodex). However, these agents do not have the beneficial agonist activities associated with tamoxifen.

GW5638/7604 belongs to a class of molecules that has mixed function (SERM/SERD) (McDonnell, 2005). SERMs function either as agonists or antagonists, depending on the coregulator context. SERDs (selective estrogen receptor downregulators), like ICI and ZK-703 (Hoffmann et al., 2004), act as more potent antagonists by inducing receptor turnover. ICI is the only FDA-approved SERD for treating postmenopausal women with ER-positive metastatic breast cancers that no

longer respond to tamoxifen. Interestingly, GW5638/7604 shares some similarities with ICI besides its effect on ER stability. ICI and GW5638/7604 derive from pre-existing ER ligands (estradiol and tamoxifen). They both induce different ER conformations than their parent ligands, through side chain modifications. In addition, the destabilization of ER induced by ICI and GW5638/7604 is brought about, at least in part, by an increase in the surface hydrophobicity of ER.

GW5638/7604 shares some of the HRT benefits of tamoxifen but acts as a more potent antagonist in the breast and does not stimulate the uterus. The data presented here show that the distinct pharmacologies of tamoxifen and GW5638 are due, at least in part, to subtle changes in the respective ER α AF2 conformations. These data also suggest that an acidic side chain may be a useful substitute for drug design on the triphenylethylene scaffold. If proven to be effective in clinical trials, molecules like GW5638/7604 that could be used as a second-line therapy for patients whose breast cancers have become tamoxifen resistant. Because no single endocrine agent is likely to prevent recurrent disease in ER-positive breast tumors, there continues to be a need for novel agents that differentially target estrogen/ER-signaling pathways.

Experimental Procedures

Chemicals, Materials, and Plasmids

GW5638 and GW7604 were synthesized at GlaxoSmithKline (Research Triangle Park, North Carolina) by using the published procedure (Willson et al., 1994). 17 β -Estradiol and 4-hydroxytamoxifen were obtained from Sigma-Aldrich (St. Louis, Missouri). ICI 162,780 was purchased from Tocris (Ellisville, Missouri). Bis-ANS was from Molecular Probes, Inc. (Eugene, Oregon). The generation of plasmids including the wild-type VP16-ER α , mutants VP16-ER α (K362A, L372R, and V376R), as well as Gal4-DBD-peptide fusion was described previously (Huang et al., 2002). Mutant receptor VP16-ER α L379R as well as the triple mutant receptor VP16-ER α L536, 539, 540Q were generated using QuikChange site-directed mutagenesis kit (Stratagene, La Jolla, California) with the wild-type VP16-ER α as template. VP16-ER α 537X and VP16-ER α 538X were constructed by PCR using the wild-type ER α as template with primers containing a stop codon at ER α 537 or ER α 538 and were subsequently subcloned into the EcoRI sites of the pVP16 vector.

Protein Expression and Purification

The human ER α LBD (residues 297–554) was expressed in BL21(DE3)pLysS as described previously (Shiau et al., 1998). The amount of ER α LBD in each bacterial extract was determined by saturation analysis with ³H-estradiol using a controlled pore glass-bead (CPG) assay. Protein purification was carried out on an estradiol-Sepharose affinity column (E-SepH) (Greene et al., 1980), followed by FPLC ion exchange purification (Resource Q, Pharmacia, Sweden). While still bound to the E-SepH beads, ER α LBD was carboxymethylated with 5 mM iodoacetic acid (Hegy et al., 1996). GW5638-containing buffer was used to elute ER α LBD from the affinity column. Protein samples were analyzed by native gel electrophoresis. FPLC fractions containing the purest protein were collected and concentrated to 5–10 mg/ml for crystallization.

Crystallization and Data Collection

The crystals of GW5638-ER α LBD were grown at 4°C by hanging drop vapor diffusion. Samples (2 μ l) of 5 mg/ml protein were mixed with 2 μ l of the reservoir buffer consisting of 1.5%–2% ethylene imine polymer, 100 mM trisodium citrate (pH 5.6–5.7), 0.5 M sodium chloride, and 9% of Yttrium chloride hexahydrate. Crystals that grew up to the size of >0.1 mm were harvested and transferred to a cryoprotectant solution containing 2% ethylene imine polymer,

100 mM trisodium citrate (pH 5.6), 1M of sodium chloride, and 25%–40% glycerol and stored in liquid nitrogen. Data were collected at BioCARS 14BMC beamline (λ = 0.9 Å) station, Advanced Photon Source, Argonne National Laboratory. Diffraction data were recorded on an ADSC Quantum-4 detector. The images of data sets were processed with Denzo and Scalepack programs in the HKL 1.96 package.

Structure Determination and Refinement

Our initial efforts to determine the structure utilized a low-resolution (3.3 Å) data set. The three ligand binding domains in the asymmetric unit were located by molecular replacement with EPMR version 2.5 (Kissinger et al., 1999) using a modified raloxifene-ER α LBD (1ERR.pdb) as the search probe. The crystals of the GW5638-ER α LBD lie in the space group of P6₁22. The unit cell parameters are $a = b = 136.031$ Å and $c = 357.626$ Å. The R factor and correlation coefficient (CC) after rigid body refinement are 43.1% and 0.65, respectively. The model was refined initially with CNS 1.0 (Brunger et al., 1998) and later with Refmac5.1.24 (Murshudov et al., 1997). TLS (Schomaker and Trueblood, 1968) in Refmac was applied to correct for anisotropic displacements of each monomer in the asymmetric unit. Model building of the GW5638-ER α LBD structure that was not included in the original search probe from molecular replacement was done by Xtalview (McRee, 1999). The R_{free} set contains a random sample of 10.2% of all data. The structure of GW5638-ER α LBD using data up to 2.7 Å was refined to a crystallographic R factor of 20.8% and an R_{free} factor of 23.6%. The statistics of the structure and data sets are summarized in Table 1.

Structural Analysis and Illustrations

The angles between the aligned H12 from different complex structures (OHT-ER and GW-ER) were calculated using a python script developed in-house based on CCL (<http://renzresearch.com>). The angle between any two helices is defined as the spatial angle between the axes of the two helices. Illustrations of structures were generated using Molscript (Kraulis, 1991) or Bobscript (Esnouf, 1999), which were further rendered by Raster3d (Merritt, 1994).

bis-ANS Probing of Receptor Surface Hydrophobicity

All ligand bound ER α LBD samples were prepared as described above. Samples of ER α -LBD were purified on E-SepH to separate ligand bound from unliganded receptor. Eluted protein samples were dialyzed against 25 mM of Tris (pH 8.1) and 25mM of sodium chloride buffer overnight in order to remove DTT and excess ligand that could potentially interfere with the bis-ANS binding study. 1.2 μ M of protein sample were incubated with 25 mM of bis-ANS at room temperature for 1 hr. An aliquot (200 μ l) of the solution was transferred into a 3 $\times$ 3 mm quartz fluorescence cuvette and placed in the sample chamber of fluorolog Tau-2 Fluorescence Spectroscopy System (Spex industries, Inc., Edison, New Jersey). The samples were excited at 395 nm, and the emission spectra were scanned from 420–750 nm. The data were normalized to the blank and averaged from triplicate results. The peak intensity of each spectrum was normalized to the height of ICI-ER α LBD sample.

Cell Culture and Transient Transfections

COS-7 cells were cultured in DMEM (Mediatech, Inc., Herndon, Virginia) supplemented with 10% fetal bovine serum (Atlanta Biologicals, Lawrenceville, Georgia) and maintained in the 37°C incubator with 5% CO₂. The cells were plated into 48-well plates 24 hr before transfection. DNA was delivered to the cells by transient transfection using PolyFect. (Qiagen, Inc., Valencia, California). 100 nM of ligands were added to the cells 18–24 hr before the cell harvest. For mammalian two-hybrid assay, 200 ng 5xGal4-TATA-Luc reporter plasmid, 200 ng VP16-receptor fusion, 200 ng Gal4-DBD-peptide fusion, and 20 ng normalization plasmid pRL-TK or pCMV- β gal were used. 100 nM of GW7604 were added to the cells 18–24 hr before the cell harvest. Luciferase activities were normalized to either Renilla luciferase or β -galactosidase activities by Dual-Luciferase Reporter Assay or β -galactosidase Enzyme Assay System (Promega Corp., Madison, Wisconsin).

Western Blot Analyses

MCF-7 cells were maintained in phenol-free medium containing 10% charcoal-filtered serum at least 24 hr before the assay. 100 nM of ligands were added to the cells for 4 hr before harvest. Ishikawa cells were cultured in DMEM F12 HAM (Sigma-Aldrich) supplemented with 10% fetal bovine serum (Atlanta Biologicals). The cells were plated into 12-well plates 24 hr before transfection. DNA was delivered to the cells by transient transfection using Effectene according to the manufacturer's protocol. (Qiagen, Inc.). 10 μ M of ligands were added to the cells 18 hr before the cell harvest. Proteins (20 μ g samples) from the cell extracts were separated on SDS-PAGE and transferred to Hybond-ECL nitrocellulose membrane (Amersham Biosciences Corp., Piscataway, New Jersey). The receptors were detected with the monoclonal antibody H222 (Greene et al., 1980). Total ERK1/2 were detected with p44/42 MAP kinase antibody (Cell Signaling Technology, Beverly, Massachusetts). The GFP expression was detected with polyclonal GFP (FL) antibody (Santa Cruz Biotechnology, Inc., Santa Cruz, California). Immunoreactive bands were visualized by enhanced chemiluminescence using Western Lightning Chemiluminescence reagent (PerkinElmer, Wellesley, Massachusetts) as described by the manufacturer.

Acknowledgments

We would like to thank Huey-Jing Huang for providing some of the plasmids critical to this work, Mohammed Yousef for assisting in the bis-ANS experiments, and Michelle S. Jansen, Shohei Koide, Anthony A. Kossiakoff, and Shawn Williams for helpful comments. We would also like to thank the BioCARS staff scientists for the assistance in data collection. The authors would especially like to thank Phoebe A. Rice for invaluable discussions and manuscript editing. This work has been supported by funds from the Ludwig Fund for Cancer Research (to G.L.G.) and the National Institutes of Health (P30CA14599-29, RO1 CA89489 [to G.L.G.], and RO1 DK48807 [to D.P.M.]). Y.L.W. was supported by a Department of Defense predoctoral training grant (DAMD17-03-1-0674). Duke University holds certain rights to GW5638 as a therapeutic agent, and consequently, the University, and Drs. McDonnell and Norris, could financially benefit if this drug is commercialized.

Received: October 1, 2004

Revised: April 7, 2005

Accepted: April 26, 2005

Published: May 12, 2005

References

- Bentrem, D., Dardes, R., Liu, H., MacGregor-Schafer, J., Zapf, J., and Jordan, V. (2001). Molecular mechanism of action at estrogen receptor α of a new clinically relevant antiestrogen (GW7604) related to tamoxifen. *Endocrinology* 142, 838–846.
- Bohley, P. (1996). Surface hydrophobicity and intracellular degradation of proteins. *Biol. Chem.* 377, 425–435.
- Brunger, A.T., Adams, P.D., Clore, G.M., DeLano, W.L., Gros, P., Grosse-Kunstleve, R.W., Jiang, J.S., Kuszewski, J., Nilges, M., Pannu, N.S., et al. (1998). Crystallography & NMR system: A new software suite for macromolecular structure determination. *Acta Crystallogr. D Biol. Crystallogr.* 54, 905–921.
- Brzozowski, A.M., Pike, A.C., Dauter, Z., Hubbard, R.E., Bonn, T., Engstrom, O., Ohman, L., Greene, G.L., Gustafsson, J.A., and Carlquist, M. (1997). Molecular basis of agonism and antagonism in the oestrogen receptor. *Nature* 389, 753–758.
- Buzdar, A.U., Marcus, C., Holmes, F., Hug, V., and Hortobagyi, G. (1988). Phase II evaluation of LY156758 in metastatic breast cancer. *Oncology* 45, 344–345.
- Chen, J.D., and Evans, R.M. (1995). A transcriptional co-repressor that interacts with nuclear hormone receptors. *Nature* 377, 454–457.
- Connor, C.E., Norris, J.D., Broadwater, G., Willson, T.M., Gottardis, M.M., Dewhirst, M.W., and McDonnell, D.P. (2001). Circumventing

tamoxifen resistance in breast cancers using antiestrogens that induce unique conformational changes in the estrogen receptor. *Cancer Res.* 61, 2917–2922.

Cottone, E., Orso, F., Biglia, N., Sismondi, P., and De Bortoli, M. (2001). Role of coactivators and corepressors in steroid and nuclear receptor signaling: potential markers of tumor growth and drug sensitivity. *Int. J. Biol. Markers* 16, 151–166.

Couse, J.F., and Korach, K.S. (1999). Estrogen receptor null mice: what have we learned and where will they lead us? *Endocr. Rev.* 20, 358–417.

Dace, A., Zhao, L., Park, K.S., Furuno, T., Takamura, N., Nakanishi, M., West, B.L., Hanover, J.A., and Cheng, S. (2000). Hormone binding induces rapid proteasome-mediated degradation of thyroid hormone receptors. *Proc. Natl. Acad. Sci. USA* 97, 8985–8990.

Dobrzycka, K.M., Townson, S.M., Jiang, S., and Oesterreich, S. (2003). Estrogen receptor corepressors—a role in human breast cancer? *Endocr. Relat. Cancer* 10, 517–536.

Esnouf, R.M. (1999). Further additions to MolScript version 1.4, including reading and contouring of electron-density maps. *Acta Crystallogr. D Biol. Crystallogr.* 55, 938–940.

Fan, M., Long, X., Bailey, J.A., Reed, C.A., Osborne, E., Gize, E.A., Kirk, E.A., Bigsby, R.M., and Nephew, K.P. (2002). The activating enzyme of NEDD8 inhibits steroid receptor function. *Mol. Endocrinol.* 16, 315–330.

Gottardis, M.M., and Jordan, V.C. (1987). Antitumor actions of keoxifene and tamoxifen in the N-nitrosomethylurea-induced rat mammary carcinoma model. *Cancer Res.* 47, 4020–4024.

Graham, J.D., Bain, D.L., Richer, J.K., Jackson, T.A., Tung, L., and Horwitz, K.B. (2000). Nuclear receptor conformation, coregulators, and tamoxifen-resistant breast cancer. *Steroids* 65, 579–584.

Greene, G.L., Nolan, C., Engler, J.P., and Jensen, E.V. (1980). Monoclonal antibodies to human estrogen receptor. *Proc. Natl. Acad. Sci. USA* 77, 5115–5119.

Guex, N., and Peitsch, M.C. (1997). SWISS-MODEL and the Swiss-PdbViewer: an environment for comparative protein modeling. *Electrophoresis* 18, 2714–2723.

Hegy, G.B., Shackleton, C.H., Carlquist, M., Bonn, T., Engstrom, O., Sjöholm, P., and Witkowska, H.E. (1996). Carboxymethylation of the human estrogen receptor ligand-binding domain-estradiol complex: HPLC/ESMS peptide mapping shows that cysteine 447 does not react with iodoacetic acid. *Steroids* 61, 367–373.

Hoffmann, J., Bohlmann, R., Heinrich, N., Hofmeister, H., Kroll, J., Kunzer, H., Lichtner, R.B., Nishino, Y., Parczyk, K., Sauer, G., et al. (2004). Characterization of new estrogen receptor destabilizing compounds: effects on estrogen-sensitive and tamoxifen-resistant breast cancer. *J. Natl. Cancer Inst.* 96, 210–218.

Hu, X., and Lazar, M.A. (1999). The CoRNR motif controls the recruitment of corepressors by nuclear hormone receptors. *Nature* 402, 93–96.

Huang, H.J., Norris, J.D., and McDonnell, D.P. (2002). Identification of a negative regulatory surface within estrogen receptor α provides evidence in support of a role for corepressors in regulating cellular responses to agonists and antagonists. *Mol. Endocrinol.* 16, 1778–1792.

Hunt, K. (1994). Breast cancer risk and hormone replacement therapy: a review of the epidemiology. *Int. J. Fertil. Menopausal Stud.* 39, 67–74.

Iannone, M.A., Simmons, C.A., Kadwell, S.H., Svoboda, D.L., Vanderwall, D.E., Deng, S.J., Consler, T.G., Shearin, J., Gray, J.G., and Pearce, K.H. (2004). Correlation between in vitro peptide binding profiles and cellular activities for estrogen receptor-modulating compounds. *Mol. Endocrinol.* 18, 1064–1081.

Imhof, M.O., and McDonnell, D.P. (1996). Yeast RSP5 and its human homolog hRPF1 potentiate hormone-dependent activation of transcription by human progesterone and glucocorticoid receptors. *Mol. Cell. Biol.* 16, 2594–2605.

Kissinger, C.R., Gehlhaar, D.K., and Fogel, D.B. (1999). Rapid automated molecular replacement by evolutionary search. *Acta Crystallogr. D Biol. Crystallogr.* 55, 484–491.

- Kraulis, P.J. (1991). MOLSCRIPT: A Program to Produce Both Detailed and Schematic Plots of Protein Structures. *J. Appl. Crystallogr.* 24, 946–950.
- Lee, J.W., Ryan, F., Swaffield, J.C., Johnston, S.A., and Moore, D.D. (1995). Interaction of thyroid-hormone receptor with a conserved transcriptional mediator. *Nature* 374, 91–94.
- Lonard, D.M., Nawaz, Z., Smith, C.L., and O'Malley, B.W. (2000). The 26S proteasome is required for estrogen receptor- α and coactivator turnover and for efficient estrogen receptor- α transactivation. *Mol. Cell* 5, 939–948.
- Lonard, D.M., and Smith, C.L. (2002). Molecular perspectives on selective estrogen receptor modulators (SERMs): progress in understanding their tissue-specific agonist and antagonist actions. *Steroids* 67, 15–24.
- McDonnell, D.P. (2005). The molecular pharmacology of estrogen receptor modulators: implications for the treatment of breast cancer. *Clin. Cancer Res.* 11, 871s–877s.
- McDonnell, D.P., Connor, C.E., Wijayaratne, A., Chang, C.Y., and Norris, J.D. (2002). Definition of the molecular and cellular mechanisms underlying the tissue-selective agonist/antagonist activities of selective estrogen receptor modulators. *Recent Prog. Horm. Res.* 57, 295–316.
- McGuire, W.L. (1978). Hormone receptors: their role in predicting prognosis and response to endocrine therapy. *Semin. Oncol.* 5, 428–433.
- McRee, D.E. (1999). XtalView/Xfit—A versatile program for manipulating atomic coordinates and electron density. *J. Struct. Biol.* 125, 156–165.
- Merritt, E.A. (1994). Raster3D Version 2.0. A program for photorealistic molecular graphics. *Acta Crystallogr. D Biol. Crystallogr.* 50, 869–873.
- Murshudov, G.N., Vagin, A.A., and Dodson, E.J. (1997). Refinement of macromolecular structures by the maximum-likelihood method. *Acta Crystallogr. D Biol. Crystallogr.* 53, 240–255.
- Nawaz, Z., Lonard, D.M., Dennis, A.P., Smith, C.L., and O'Malley, B.W. (1999a). Proteasome-dependent degradation of the human estrogen receptor. *Proc. Natl. Acad. Sci. USA* 96, 1858–1862.
- Nawaz, Z., Lonard, D.M., Smith, C.L., Lev-Lehman, E., Tsai, S.Y., Tsai, M.J., and O'Malley, B.W. (1999b). The Angelman syndrome-associated protein, E6-AP, is a coactivator for the nuclear hormone receptor superfamily. *Mol. Cell. Biol.* 19, 1182–1189.
- Perissi, V., Staszewski, L.M., McInerney, E.M., Kurokawa, R., Krone, A., Rose, D.W., Lambert, M.H., Milburn, M.V., Glass, C.K., and Rosenfeld, M.G. (1999). Molecular determinants of nuclear receptor-corepressor interaction. *Genes Dev.* 13, 3198–3208.
- Pike, A.C., Brzozowski, A.M., Walton, J., Hubbard, R.E., Thorsell, A.G., Li, Y.L., Gustafsson, J.A., and Carlquist, M. (2001). Structural insights into the mode of action of a pure antiestrogen. *Structure* 9, 145–153.
- Poukka, H., Aarnisalo, P., Karvonen, U., Palvimäki, J.J., and Janne, O.A. (1999). Ubc9 interacts with the androgen receptor and activates receptor-dependent transcription. *J. Biol. Chem.* 274, 19441–19446.
- Poulin, R., Merand, Y., Poirier, D., Levesque, C., Dufour, J.M., and Labrie, F. (1989). Antiestrogenic properties of keoxifene, trans-4-hydroxytamoxifen, and ICI 164384, a new steroidal antiestrogen, in ZR-75-1 human breast cancer cells. *Breast Cancer Res. Treat.* 14, 65–76.
- Ravdin, P.M., Green, S., Dorr, T.M., McGuire, W.L., Fabian, C., Pugh, R.P., Carter, R.D., Rivkin, S.E., Borst, J.R., Belt, R.J., et al. (1992). Prognostic significance of progesterone receptor levels in estrogen receptor-positive patients with metastatic breast cancer treated with tamoxifen: results of a prospective Southwest Oncology Group study. *J. Clin. Oncol.* 10, 1284–1291.
- Reid, G., Hubner, M.R., Metivier, R., Brand, H., Denger, S., Manu, D., Beaudouin, J., Ellenberg, J., and Gannon, F. (2003). Cyclic, proteasome-mediated turnover of unliganded and liganded ER α on responsive promoters is an integral feature of estrogen signaling. *Mol. Cell* 11, 695–707.
- Rosen, C.G., and Weber, G. (1969). Dimer formation from 1-amino-8-naphthalenesulfonate catalyzed by bovine serum albumin. A new fluorescent molecule with exceptional binding properties. *Biochemistry* 8, 3915–3920.
- Saji, S., Okumura, N., Eguchi, H., Nakashima, S., Suzuki, A., Toi, M., Nozawa, Y., and Hayashi, S. (2001). MDM2 enhances the function of estrogen receptor α in human breast cancer cells. *Biochem. Biophys. Res. Commun.* 281, 259–265.
- Schomaker, V., and Trueblood, K.N. (1968). Original description of TLS. *Acta Crystallogr.* B24, 63–76.
- Shang, Y., and Brown, M. (2002). Molecular determinants for the tissue specificity of SERMs. *Science* 295, 2465–2468.
- Shao, W., Keeton, E.K., McDonnell, D.P., and Brown, M. (2004). Coactivator AIB1 links estrogen receptor transcriptional activity and stability. *Proc. Natl. Acad. Sci. USA* 101, 11599–11604.
- Shiau, A.K., Barstad, D., Loria, P.M., Cheng, L., Kushner, P.J., Agard, D.A., and Greene, G.L. (1998). The structural basis of estrogen receptor/coactivator recognition and the antagonism of this interaction by tamoxifen. *Cell* 95, 927–937.
- Slavik, J. (1982). Anilino-naphthalene sulfonate as a probe of membrane composition and function. *Biochim. Biophys. Acta* 694, 1–25.
- Urry, D.W., Peng, S.Q., and Parker, T.M. (1992). Hydrophobicity-induced pK shifts in elastin protein-based polymers. *Biopolymers* 32, 373–379.
- vom Baur, E., Zechel, C., Heery, D., Heine, M.J., Garnier, J.M., Vivat, V., Le Douarin, B., Gronemeyer, H., Chambon, P., and Losson, R. (1996). Differential ligand-dependent interactions between the AF-2 activating domain of nuclear receptors and the putative transcriptional intermediary factors mSUG1 and TIF1. *EMBO J.* 15, 110–124.
- Webb, P., Nguyen, P., and Kushner, P.J. (2003). Differential SERM effects on corepressor binding dictate ER α activity in vivo. *J. Biol. Chem.* 278, 6912–6920.
- Wijayaratne, A.L., and McDonnell, D.P. (2001). The human estrogen receptor- α is a ubiquitinated protein whose stability is affected differentially by agonists, antagonists, and selective estrogen receptor modulators. *J. Biol. Chem.* 276, 35684–35692.
- Willson, T.M., Henke, B.R., Momtahan, T.M., Charifson, P.S., Batchelor, K.W., Lubahn, D.B., Moore, L.B., Oliver, B.B., Sauls, H.R., Triantafyllou, J.A., et al. (1994). 3-[4-(1,2-Diphenylbut-1-enyl)phenyl]acrylic acid: a non-steroidal estrogen with functional selectivity for bone over uterus in rats. *J. Med. Chem.* 37, 1550–1552.
- Willson, T.M., Norris, J.D., Wagner, B.L., Asplin, I., Baer, P., Brown, H.R., Jones, S.A., Henke, B., Sauls, H., Wolfe, S., et al. (1997). Dissection of the molecular mechanism of action of GW5638, a novel estrogen receptor ligand, provides insights into the role of estrogen receptor in bone. *Endocrinology* 138, 3901–3911.

Accession Numbers

Coordinates of the GW5638-ER α LBD structure were deposited in the Protein Data Bank under the ID code 1R5K.

APPENDIX 2. Keystone Nuclear Receptor Symposia poster abstract

Structural Characterization of hER α -LBD in Complex with GW5638

Yaling Wu,^{*} Xiaojing Yang,[†] Zhong Ren,[†] and Geoffrey Greene^{*}

^{*}Department of Biochemistry and Molecular Biology, University of Chicago, USA

[†]Renz Research, Inc.

Breast cancers affect one in eight women in the United States. Many of these cancers respond to hormonal therapy and the presence of estrogen receptor (ER α) is associated with a more favorable response and short-term prognosis. Tamoxifen is a selective estrogen receptor modulator (SERM) that acts through ER α and is effective in the prevention and treatment of estrogen-dependent breast cancer. However, tamoxifen is estrogenic in the uterus and is associated with an increased incidence of endometrial cancers. In addition, advanced breast cancers invariably become resistant to tamoxifen. Here we report the crystal structure of a complex containing the estrogen receptor ligand-binding domain (ER α LBD) bound to a structurally similar compound, GW5638, which has clinical potential and exhibits no adverse effects in the uterus. Notably, tamoxifen resistant MCF-7 breast tumor explants still respond to GW5638. Although GW5638 induces a characteristic antagonist-ER LBD structure, it elicits a distinct conformation in the carboxyl-terminal activation (AF-2) helix (H12) through direct interactions with the N-terminus of H12, which has not been observed in any of the previously solved nuclear receptor LBD structures. Similar to 4-hydroxytamoxifen (OHT), GW5638 induces an autoinhibitory conformation of ER that prevents the binding of coactivators. However, in contrast to OHT, GW5638 repositions hydrophobic residues in H12, thereby increasing the exposed hydrophobic surface of ER, which correlates with a significant degradation of ER α in MCF-7 cells. Thus, the GW5638-ER α LBD structure reveals a novel mode of SERM-mediated ER antagonism in which the stability of ER is decreased through an altered position of H12. This dual mechanism may account for the ability of GW5638 to inhibit tamoxifen-resistant breast tumor explants.

This research is funded by DAMD17-03-1-0674

APPENDIX 3. Era of Hope 2005 poster abstract

STRUCTURAL BASIS FOR A NOVEL MODE OF SERM-MEDIATED ER ANTAGONISM

Ya-Ling Wu,¹ Xiaojing Yang,² Zhong Ren,² Donald P. McDonnell,³ John D. Norris,³ Timothy M. Willson,⁴ And Geoffrey L. Greene,*

¹The Ben May Institute for Cancer Research and Department of Biochemistry and Molecular Biology, the University of Chicago, Chicago, Illinois, 60637, ²Renz Research, Inc., Westmont, Illinois, 60559, ³The Department of Pharmacology and Cancer Biology, Duke University Medical Center, Durham, North Carolina, 27710, ⁴GlaxoSmithKline, Research Triangle Park, North Carolina, 27709

Breast cancers affect one in eight women in the United States. Many of these cancers respond to hormonal therapy and the presence of estrogen receptor (ER α) is associated with a more favorable response and short-term prognosis. Tamoxifen is part of a growing family of molecules called selective estrogen receptor modulators (SERMs) that can behave as agonists or antagonists in different tissue and environmental contexts. It has been widely used for breast cancer treatment and shows considerable potential as a preventive agent. Unfortunately, advanced breast cancers that initially respond well to tamoxifen eventually become refractory to this compound. Its uterotrophic activity also restricts its utility in a prevention setting. We report the crystal structure of the estrogen receptor α (ER α) ligand-binding domain (LBD) bound to the structurally similar compound GW5638, which has therapeutic potential and does not stimulate the uterus. Like tamoxifen, GW5638 relocates the carboxy-terminal helix (H12) to the known coactivator-docking site in the ER α LBD. However, GW5638 repositions residues in H12 through specific contacts with the N-terminus of this helix. In contrast to tamoxifen, the resulting increase in exposed hydrophobic surface of ER α LBD correlates with a significant degradation of ER α in MCF-7 cells. Thus, the GW5638-ER α LBD structure reveals a unique mode of SERM-mediated ER antagonism, in which the stability of ER α is decreased through an altered position of H12. This dual mechanism of antagonism may explain why GW5638 can inhibit tamoxifen-resistant breast tumors.

The US Army Medical Research and Material Command under DAMD17-03-1-0674 supported this work.