Destabilization of Steroid Receptors by Heat Shock Protein 90-binding Drugs: A Ligand-independent Approach to Hormonal Therapy of Breast Cancer


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ABSTRACT

Steroid hormone receptors have become an important target in the management of breast cancers. Despite a good initial response rate, however, most tumors become refractory to current hormonal therapies within a year of starting treatment. To address this problem, we evaluated the effects of agents that bind the molecular chaperone heat shock protein 90 (Hsp90) on estrogen receptor function in breast cancer. Unstimulated estrogen and progesterone receptors exist as multimolecular complexes consisting of the hormone-binding protein itself and several essential molecular chaperones including Hsp90. We found that interaction of the Hsp90-binding drugs geldanamycin and radicicol with the chaperone destabilizes these hormone receptors in a ligand-independent manner, leading to profound and prolonged depletion of their levels in breast cancer cells cultured in vitro. Consistent with these findings, in vivo administration of the geldanamycin derivative 17-allylaminogeldanamycin (17AAG; NSC330507) to estrogen-supplemented, tumor-bearing SCID mice resulted in marked depletion of progesterone receptor levels in both uterus and tumor. Drug administration also delayed the growth of established, hormone-responsive MCF-7 and T47D human tumor xenografts for up to 3 weeks after the initiation of therapy. We conclude that in light of their novel mechanism of anti-hormone action, consideration should be given to examining the activity of 17AAG and other Hsp90-binding agents in patients with refractory breast cancer in future clinical trials, either alone or in combination with conventional hormone antagonists.

INTRODUCTION

Over the past two decades, steroid receptors have become increasingly prominent targets for the prevention and treatment of hormone-dependent cancers. In particular, anti-estrogens such as tamoxifen are now a cornerstone in the management of ERα-positive tumors (1). Unfortunately, most metastatic breast cancers eventually become refractory to hormonal therapy, often through acquired alterations in the structure, expression, or activity of the estrogen binding subunit of the receptor itself (2, 3). Extensive efforts have been directed at the development of selective estrogen receptor modulators that can repress estrogen-induced transcriptional activation of proliferation-associated genes while retaining agonist activity in relation to other estrogen-responsive target genes. Although they provide the potential for substantial improvements in selectivity and the avoidance of undesirable side effects, selective estrogen receptor modulators remain dependent on the high affinity interaction of antagonist with the hormone binding subunit of the receptor (4, 5). Because the frequent emergence of resistance to currently available antagonists limits their overall effectiveness as anticancer agents, the identification of compounds that inhibit receptor function in an alternative, ligand-independent manner could prove very useful.

Unstimulated steroid hormone receptors exist as multimolecular complexes containing the hormone binding protein itself and a number of essential chaperone proteins including Hsp90 (6). Inhibition of Hsp90 function prevents the assembly of the complexes required to maintain hormone receptors in their mature, ligand-binding configuration (7). In the past 5 years, the antitumor antibiotics GA and RD have become recognized as selective HBAs with a novel ability to alter the activity of many of the receptors, kinases, and transcription factors involved in cancer-associated signaling pathways. These drugs have now been shown by crystallographic (8, 9) and biochemical (10, 11) analyses to bind as nucleotide mimetics to an NH2-terminal ATP/ADP-binding domain within Hsp90, locking the chaperone in its ADP-bound conformation and compromising its function. Although GA and RD are active in vitro, derivatives of these parent compounds including 17AAG and the RD oxime derivative KF58333 have been developed which show greater in vivo efficacy at well-tolerated doses (12, 13). Fig. 1 provides a
simplified model summarizing previous work done by us and by others to elucidate the effects of drug interaction with Hsp90 on the structure and function of hormone receptor complexes. In their native state, steroid receptors consist of the relevant hormone binding protein itself, an Hsp90 dimer, and several cochaperones, such as p23, and immunophilins, such as CyP40 (Fig. 1A). When GA and the other known HBAs bind Hsp90, as illustrated in Fig. 1B, the conformation and function of Hsp90 are altered. The physical association of p23 and CyP40 is no longer detected, whereas that of other chaperones, such as Hsp70 and Hop, becomes apparent (7). In the case of the PR, androgen receptor, and GR, drug-mediated disruption of Hsp90 and maintenance of the receptor and maintains it in a conformation capable of high-affinity hormone binding. CyP40, cytochrome P-450. In B, the interaction of GA with Hsp90 alters its conformation and the composition of chaperone complexes found in association with the hormone-binding protein. In the case of GR, PR, and androgen receptor but not ER, these changes lead to a rapid loss of the high-affinity hormone binding conformation of the receptor. In C, drug-induced alterations in chaperone function led to the depletion of cellular hormone-binding protein levels via proteasome-mediated degradation.

MATERIALS AND METHODS

Cells and Reagents. MCF-7 and T47D cells were obtained from the American Type Culture Collection (Rockville, MD). Cells were cultured at 37°C under 6% CO2 in medium containing RPMI 1640 (Life Technologies, Inc.) supplemented with 10% fetal bovine serum (Irvine Scientific, Santa Ana, CA), 10 mM HEPES (Life Technologies, Inc.), and 2 mM l-glutamine (Life Technologies, Inc.). Cells were confirmed negative for Mycoplasma contamination by ELISA, and all experiments were performed within 10 serial passages. Viable cell numbers were quantitated by counting cells suspended in 0.2% trypan blue in a hemacytometer. RD and its derivative KF58333 were supplied by the Pharmaceutical Research Institute. GA and its derivative 17AAG were provided by the Developmental Therapeutics Program of the National Cancer Institute.

Metabolic Labeling and Receptor Immunoprecipitation. To examine the effects of drug treatment on receptor turnover, replicate dishes of MCF-7 cells were rinsed with methionine/cysteine-free DMEM supplemented with 10% dialyzed fetal bovine serum and incubated at 37°C for 1 h in the presence of GA (1.7 μM) or an equal volume of DMSO diluent (Sigma Chemical Co., St. Louis, MO). Cells were then labeled in the same medium supplemented with [35S]methionine/ [35S]cysteine (Translabel, 10.5 mCi/ml; ICN, Costa Mesa, CA) to yield 100 μCi/ml. Incubation was continued for an additional hour, and then cells were washed and refed with methionine-containing medium in the continued presence of GA or DMSO. Cell lysates were prepared at 0, 2, 4, and 8 h after washout. Immunoprecipitation was performed from metabolically labeled cell lysates using the monoclonal anti-ER antibody H-151 (Stressgen, Victoria, British Columbia, Canada) as described previously (14).

Immunoblotting. To evaluate cellular levels of ER and Hsp72, replicate dishes of MCF-7 and/or T47D cells were treated with drug or diluent and lysed in nonionic detergent buffer. Immunoblotting was performed using 100 μg of total protein/sample as described previously (16). Primary antibodies used included anti-Hsp72 (C-92) obtained from Stressgen and anti-PR (MC243) and anti-ER (ER17), both generously provided by David Toft (Mayo Clinic, Rochester, MN). Peroxidase-

Fig. 1 Schematic representation of steroid hormone receptor complexes and the effects of HBAs on receptor structure and stability. In A, the physical association of several molecular chaperones stabilizes the hormone-binding subunit of the receptor and maintains it in a conformation capable of high-affinity hormone binding. Cytochrome P-450, cytochrome P-450. In B, the interaction of GA with Hsp90 alters its conformation and the composition of chaperone complexes found in association with the hormone-binding protein. In the case of GR, PR, and androgen receptor but not ER, these changes lead to a rapid loss of the high-affinity hormone binding conformation of the receptor. In C, drug-induced alterations in chaperone function led to the depletion of cellular hormone-binding protein levels via proteasome-mediated degradation.
conjugated secondary antibodies, chemiluminescent substrate, and exposure to Kodak XAR-5 film were used for detection. Multiple exposure times were evaluated for each blot to ensure that the band intensities observed were within the dynamic response range of the film.

**Quantitation of Estrogen Binding.** MCF-7 cells were established in 24-well plates using phenol red-free RPMI 1640 supplemented with 10% charcoal-stripped fetal bovine serum. Cells were incubated for 72 h and then exposed for 1 h to 1 ml of medium containing tritiated 17β-estradiol (1 nM, 0.08 μCi/ml; NEN Life Science Products, Boston, MA) with or without 200-fold excess nonradioactive diethylstilbestrol (Sigma Chemical Co.). Wells were washed three times and extracted with ethanol for 20 min. Aliquots of the ethanolic solution were transferred to scintillation vials and counted. For each drug treatment condition, the protein content of replicate wells was determined by lysing the cells in nonionic detergent buffer and assaying for protein concentration using bicinchoninic acid reagent (BCA; Pierce, Rockford, IL). Specific hormone binding was calculated as the cpm per μg of cellular protein bound in the absence of excess nonradioactive steroid less the cpm/μg protein bound in its presence.

**In Vivo Studies.** Prior to all experimentation, SCID mice (Arizona Cancer Center breeding colony; C.B-17/IcrACCscid) were implanted s.c. with 17β-estradiol pellets (0.25 mg/21 day release; Innovative Research of America, Sarasota, FL). Non-tumor-bearing mice were treated with 50 mg/kg 17AAG formulated in DMSO and injected i.p. daily for 2 days. Control animals were treated with an equal volume of ethanol for 20 min. Aliquots of the ethanolic solution were transferred to scintillation vials and counted. For each drug treatment condition, the protein content of replicate wells was determined by lysing the cells in nonionic detergent buffer and assaying for protein concentration using bicinchoninic acid reagent (BCA; Pierce, Rockford, IL). Specific hormone binding was calculated as the cpm per μg of cellular protein bound in the absence of excess nonradioactive steroid less the cpm/μg protein bound in its presence.

**RESULTS**

HBAs Decrease ER Levels and Hormone Binding in Breast Cancer Cells. MCF-7 breast cancer cells were used to evaluate the effects of GA, the prototypic HBA, on ER stability and function in whole cells. A pulse-chase experiment performed after a 1-h labeling period demonstrated that although the intensities of the bands corresponding to the ER are equivalent at the start of the chase period, a more rapid decline in ER signal is observed over time in lysates prepared from GA-treated cells than in lysates from control cells (Fig. 2A). Synthesis of ER in treated and untreated cells thus appears to be approximately equivalent, whereas turnover of ER is clearly increased in the GA-treated cells. The identities of the slower migrating bands that coprecipitate with the receptor in this experiment are not certain, but based on their apparent molecular size and their induction by GA, they are most likely Hsp70 isofoms that as chaperones have a tendency to bind Sepharose beads nonspecifically. To determine whether accelerated ER turnover leads to alterations in total cellular levels of the receptor after GA exposure, immunoblotting of lysates from treated and untreated cells was performed. The level of ER detected in lysate from MCF-7 cells maintained for 24 h in GA-containing medium is markedly decreased compared with that seen in lysate from cells treated with drug vehicle alone (Fig. 2B). A comparable decrease in ER protein level is also seen in cells that were exposed to the HBAs for 1 h and then washed and cultured in drug-free medium for 24 h prior to lysis and immunoblotting. This finding indicates that a brief drug exposure can still result in sustained depletion of receptor. To assess the consequences of GA treatment on receptor function, we used a whole cell radioligand binding assay. Consistent with the depletion of ER protein levels seen in Fig. 2B, specific binding of 17β-estradiol is markedly decreased by GA exposure but only at later time points (Fig. 2C). This delay in loss of binding is consistent with depletion of hormone-binding protein rather than direct disruption of binding activity per se. It stands in marked contrast to our previously reported findings with the GR, where >80% of dexamethasone binding was lost within 10 min of drug application (14).

To examine whether the observed effects on ER level and function are unique to GA or can be attributed more generally to disruption of Hsp90 function, we used the chemically distinct compound RD which, like GA, has been shown by crystallographic and biochemical analyses to bind to Hsp90. Fig. 3 shows that treatment of MCF-7 cells with RD causes a dose-dependent decrease in the level of ER. Previous work in our laboratory has demonstrated that HBAs exposure results in a heat shock factor 1 (HSF1)-dependent increase in cellular Hsp levels in mammalian cells, and that changes in levels of these proteins can serve as a positive marker of HBA action (18). As expected, after treatment with RD, the decrease in ER protein is accompanied by a marked increase in Hsp72, a highly inducible isofoms of Hsp70. These data demonstrate that the decline in
receptor levels observed are not simply attributable to drug-induced cytotoxicity/cell death because the cells are still capable of mounting a stress response. As an internal control to allow comparison with the results in Fig. 2, cells were also treated with GA (1.7 μM), and the expected pattern of increase in Hsp72 and decrease in ER was observed. To determine whether these results are specific to the MCF-7 cell line, experiments were repeated using the T47D breast cancer cell line that expresses both ER and PR. Again, a dose-dependent decrease in ER level and an increase in Hsp72 are seen after exposure to RD and GA.

HBAs Decrease Cellular PR Levels. In preparation for whole animal studies, we examined the effects of HBA with activity in vivo on PR levels in T47D cells. It was important to validate the PR as a reliable end point for drug action in these experiments because of the difficulties associated with measuring ER levels in tissues from estrogen-supplemented mice (see “Discussion”). After overnight treatment of cells with KF58333, an oxime derivative of RD that is currently in preclinical development, lysates were analyzed by immunoblotting. Fig. 4A shows the expected induction of Hsp72 at drug concentrations >0.01 μM and a marked decrease in the level of ER, as well as a decrease in the A and B isoforms of the PR. Because we were concerned that HBA effects on receptor stability could be altered by the presence of ligand, we also examined receptor levels in cells cultured in hormone-supplemented medium. As shown in Fig. 4B (upper panel), supplementation with either 17β-estradiol or progesterone had little effect on the ability of KF58333 to deplete cellular PR levels. To confirm that this
effect is not specific to a single HBA, we also treated estrogen-supplemented T47D cells with 17AAG, a derivative of GA currently in Phase I clinical trial. The decrease in PR observed after exposure of cells to 17AAG (Fig. 4B, lower panel) is comparable with the change seen after treatment with KF58333 and only minimally altered by estrogen supplementation.

PR Depletion by HBAs Is Durable and Associated with a Decrease in Tumor Cell Growth. To simulate the type of bolus drug exposure that would be most relevant to clinical use, we exposed replicate cultures of T47D cells to GA for 1 h and then lysed cells at 24-h intervals after treatment. Brief exposure to GA resulted in a surprisingly durable induction of Hsp72, accompanied by persistent depletion of PR for up to 96 h after initial drug pulse (Fig. 5, left panel). As might be expected, the data also demonstrate that basal PR levels gradually increase over time in control cells as they grow to confluency. To assess whether the prolonged decrease in hormone receptor level observed after HBA exposure was simply a reflection of cytotoxicity, aliquots of the T47D cells exposed to GA or to diluent for 1 h were also counted in trypan blue at 24, 48, 72, and 96 h after treatment. As shown in Fig. 5 (right panel), control cells show rapid growth as expected, whereas drug-treated cells remain...
viable but fail to proliferate for at least 4 days after drug exposure. This type of experiment was also performed with KF58333 and 17AAG, and similar results were observed (data not shown), leading us to conclude that the sustained depletion of cellular PR levels observed after HBA exposure is not simply attributable to cytotoxicity/cell death.

Systemic Administration of HBA Decreases PR Levels in Target Tissues in Vivo. Non-tumor-bearing, estrogen-supplemented SCID mice were treated with 17AAG and then sacrificed 18 h after the last dose. Immunoblotting of lysates derived from uterine tissue demonstrated a marked increase in Hsp72 levels in tissue from the treated animals compared with controls (Fig. 6A). Analysis of PR isoforms shows that drug administration led to a marked decrease in levels of PR A and PR B in all animals treated with drug, with almost undetectable levels of PR seen in lysate from one animal. We next used animals bearing human tumor xenografts to assess changes in PR after administration of 17AAG. Estrogen supplemented SCID mice were injected with T47D tumor cells s.c. After the formation of palpable tumors, they were treated with 17AAG (75 mg/kg immunoprecipitation) daily for 2 days and then euthanized 18 h later. Fig. 6B shows immunoblots for PR and Hsp72 of lysates prepared from the uterus (left lanes) and tumor (right lanes) of three control and two drug-treated mice. Consistent with results in non-tumor-bearing mice, levels of Hsp72 are generally higher in uterus and tumor from drug-treated animals compared with tissues from controls. There does appear to be greater variability in Hsp72 levels in lysates from these animals, perhaps because of the stress of bearing tumor burdens. Nonetheless, a consistent decrease in the level of PR is seen in the lanes containing lysate from the uterus and tumor from drug-treated animals. The lysate from the tumor and uterus of a third drug-treated mouse in this experiment was not blotted because of excessive proteolytic degradation of the sample revealed by Coomassie staining (data not shown). In several experiments of similar design, lysates from a small but consistent minority of animals were also found to be degraded. Although this may have been a technical problem generated during preparation of lysates, the fact that degradation occurred only in tumor lysates from HBA-treated mice and never in lysates from uteri of control or drug-treated mice suggests that this finding may reflect the antitumor activity of the drug treatment itself.

Treatment with 17AAG Delays Growth of Human Tumor Xenografts. Given the demonstrated ability to modulate PR in vivo with administration of 17AAG, we next evaluated the effects of this drug on tumor growth. Estrogen-supplemented SCID mice bearing established tumors were treated with 17AAG, and tumor volumes were assessed using serial caliper measurements. Fig. 7 demonstrates that 17AAG treatment at systemically tolerated exposures significantly altered tumor growth in mice as determined by two-way ANOVA ($P < 0.0001$). Progression of T47D tumor growth is inhibited by HBA treatment for up to 3 weeks after a course of therapy.

DISCUSSION

The documented activity of hormonal therapies in the treatment and prevention of breast cancer has made the ER a well-validated therapeutic target in this common and often incurable malignancy. To date, hormonal therapies have been directed at blocking the ER (hormone antagonists such as tamoxifen) or reducing the synthesis of estrogens in postmenopausal women (aromatase inhibitors such as anastrozole). Although clinical trials have demonstrated a roughly 30% initial response rate (complete response + partial response) to such therapies in patients with advanced breast cancer patients (19), the responses are typically short-lived. A recent report found that median time to progression for postmenopausal women with advanced breast cancer treated with tamoxifen was 5.6 months (20). Patients whose tumors are ER$^+$ and/or PR$^+$ are

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**Fig. 6** Depletion of PR by 17AAG treatment of mice. Estrogen-supplemented SCID mice were injected i.p. with 17AAG or an equal volume of DMSO vehicle (50 µl) daily for a total of two doses. They were euthanized 18 h after the last dose, and tissues were resected and snap frozen for determination of relative PR and Hsp72. In A, four non-tumor-bearing mice/group were treated with 17AAG 50 mg/kg/dose or DMSO, and uterus lysates were analyzed by immunoblot. In B, three mice bearing established T47D tumors/group were treated with 17AAG (75 mg/kg/dose). Uterus and tumor lysates were analyzed by immunoblot. As a positive control for the blotting procedure, lysate prepared from T47D cells in culture (Cells lane) was also analyzed.
Each group consisted of 10 animals, and the means are depicted; time of initiation of tamoxifen therapy, time to progression was 7.8 months, and by 2 years from the introduction of DMSO (50 μl), and mean tumor volumes were measured serially. Each group consisted of 10 animals, and the means are depicted; bars, SE.

**T47D Tumors**

**Fig. 7** Inhibition of tumor growth by 17AAG. Estrogen-supplemented SCID mice bearing established breast tumor xenografts were injected with 17AAG (50 mg/kg/dose i.p. daily for 5 days) or an equal volume of DMSO (50 μl), and mean tumor volumes were measured serially. Each group consisted of 10 animals, and the means are depicted; bars, SE.

considered most likely to respond favorably to tamoxifen therapy, but investigators have shown that even in this group median time to progression was 7.8 months, and by 2 years from the time of initiation of tamoxifen therapy, >85% of patients had progressed (21). Clearly, alternative approaches to manipulate hormone signaling are needed if durable responses are to be achieved. To address this issue, we now report the feasibility of destabilizing steroid hormone receptors in breast cancer cells and human tumor xenografts using drugs that alter the function of the molecular chaperone, Hsp90 (Fig. 1).

Numerous studies have made clear that Hsp90 in conjunction with several other chaperones and cofactors modulates hormone binding and receptor stability but to different extents, depending on the specific steroid receptor and assay system being evaluated (22, 23). In the case of the ER, Hsp90 clearly forms complexes with the receptor, but its precise role in facilitating high-affinity hormone binding has remained controversial (24). Recently, the anticancer antibiotics GA and RD have been identified based on their ability to bind Hsp90 and alter its function (11, 25). Studies in our lab (7, 14) and those of several other investigators (reviewed in Refs. 26 and 27) have examined the molecular effects of these HBAs on steroid receptor structure, function, and stability. In this report, we show that unlike their effects on GR and PR, HBAs at low micromolar concentrations do not directly disrupt specific hormone binding by the ER but do destabilize the receptor, leading to its depletion in drug-treated cells (Figs. 2 and 3). On the basis of these findings in culture, we went on to examine the activity of HBAs in SCID mouse breast tumor xenografts models. To the best of our knowledge, this is the first published report demonstrating that depletion of a steroid hormone receptor can be achieved in tumor-bearing mice by using systemically tolerated doses of 17AAG (Fig. 6). It has been suggested recently that the novel “pure” antiestrogen ICI 182,780 causes increased degradation of ER (28). Unlike the ligand-independent HBA effect on ER, however, ICI 182,780 mediated ER depletion is dependent upon binding of this ligand to the receptor. HBAs, then, appear to possess a novel mechanism of action and therefore could prove useful either alone or in combination with receptor antagonists and aromatase inhibitors to achieve more effective blockade/ablation of estrogen action.

Although far from completely understood, acquired resistance to antiestrogens appears to involve multiple molecular mechanisms including: alterations in the metabolism of the antiestrogen itself, mutation of the ER hormone binding protein, alterations in the cross-talk between relevant signal transduction pathways, and alterations in the balance of nuclear coactivators and corepressors (Ref. 29 and references therein). Given the ligand-independent nature of HBA action (Fig. 4), however, these mechanisms are unlikely to impair the ability of drugs such as 17AAG and KF58333 to destabilize receptors and disrupt hormone action. Over time, alterations in drug metabolism and/or disposition may affect the efficacy of HBAs in patients with breast cancer, but mutation of the primary target of HBAs would seem unlikely. Hsp90 is a highly conserved molecular chaperone that plays an important role in many essential cellular functions in addition to its involvement with steroid receptors. As a result, mutations that alter its ability to bind HBAs would probably be quite deleterious to cell survival. In support of this contention, mutation of Hsp90 has not been reported in any cancers, although overexpression of certain chaperones, especially Hsp70, has been documented (30).

Hsp90 knock-out is known to be lethal in eukaryotes (31), and it has become clear that interaction of HBAs with their target is not the pharmacological equivalent of a knock-out. Instead, drug interaction with Hsp90 appears to alter some but not all of the cellular functions of this essential chaperone (32) and probably accounts for the observation that biological effects, such as destabilization of steroid receptors, can be achieved by drug exposures that are tolerable to cells in culture (Fig. 5) and whole animals (Fig. 6). Ongoing Phase I clinical trials have also found that micromolar peak concentrations of 17AAG can be achieved in human subjects without overt toxicity. Although quite selective in their interaction with Hsp90 class chaperones, the cellular effects of these agents are far from limited to destabilization of the ER and PR. They are known to disrupt the function of numerous Hsp90 client proteins, including receptor-linked kinases such as erbB-2 (33), and have shown in vivo activity in a colon cancer model (34). In an attempt to develop a GA derivative with greater selectivity for the ER, GA-estradiol conjugates have been reported that appear more active in stimulating the degradation of the ER than several other targets of GA in vitro, but no information on activity in animals has been reported (35). Although selectivity is often desirable, the fact that HBAs disrupt multiple cancer-associated targets may actually be of benefit therapeutically. Considerable cross-talk has been documented between the ER and PR pathways (36) and between the ER and erbB-2 pathways (37) in promoting breast cancer survival and growth. Simultaneous

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4 C. Takimoto, University of Texas San Antonio, personal communication.
destabilization of these three receptors (and undoubtedly others) by HBAs may well provide more effective antitumor activity than targeting the ER alone.

Our in vivo data demonstrate that marked depletion of PR can be achieved after well-tolerated exposures to 17AAG (Fig. 6) and KF58333 (not shown). We adopted PR as a pharmacodynamic end point for these studies because PR expression is regulated by estrogen, and there is considerable evidence for cross-talk between the ER and PR in promoting breast cancer progression (38). At a technical level, PR was the preferred marker as well because ER levels are low in highly estrogen-supplemented mice, making their reliable detection difficult. Furthermore, serum albumins migrate very closely with the M, 67,000 ER during SDS-PAGE electrophoresis and can interfere with its detection by immunoblotting. PR, on the other hand, is unregulated by estrogen supplementation, and its isoforms migrate well away from any interfering proteins. It is therefore a robust marker for drug effects on steroid receptor homeostasis in our animal model and in potential clinical trials in breast cancer patients in the future.

The activity demonstrated in Fig. 7 of 17AAG against established, hormone-responsive tumors is comparable with the activity reported for tamoxifen against MCF-7 tumors in another mouse model (39). The doses and schedules of 17AAG used for the experiments presented here were selected on the basis of preliminary work defining the maximum tolerated dose intensity in our SCID strain when bearing tumors. On the basis of our observations regarding the onset and duration of drug-induced effects in vitro (Fig. 5), a lower intensity dosing schedule spread over multiple weeks might be more appropriate if the agent is to be used more as a cytostatic modulator of hormone action than a direct cytotoxin. Although we have demonstrated that HBAs can effectively modulate steroid receptor levels, it is unlikely that the antitumor activity of HBAs resides solely in their destabilization of steroid receptors. Given the large number of intracellular Hsp90 clients altered by these drugs, other drug-sensitive substrates, such as erbB-2 or mutant p53 (40, 41), may well prove to be equally or more important to the overall anticaner activity of HBAs. Further work with hormone-independent breast tumors and recently described tamoxifen-resistant tumor models (42, 43) will be needed to define the best manner in which to exploit the novel biological activities of HBAs in the management of poor-prognosis breast cancer.

ACKNOWLEDGMENTS

We thank Marialouisa H. A. Lopez and Paul H. Cook for technical assistance. We thank Dan von Hoff for critical review prior to submission.

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