The mechanisms and managements of hormone-therapy resistance in breast and prostate cancers

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Abstract

Breast and prostate cancer are the most well-characterized cancers of the type that have their development and growth controlled by the endocrine system. These cancers are the leading causes of cancer death in women and men, respectively, in the United States. Being hormone-dependent tumors, antihormone therapies usually are effective in prevention and treatment. However, the emergence of resistance is common, especially for locally advanced tumors and metastatic tumors, in which case resistance is predictable. The phenotypes of these resistant tumors include receptor-positive, ligand-dependent; receptor-positive, ligand-independent; and receptor-negative, ligand-independent. The underlying mechanisms of these phenotypes are complicated, involving not only sex hormones and sex hormone receptors, but also several growth factors and growth factor receptors, with different signaling pathways existing alone or together, and with each pathway possibly linking to one another. In this review, we will discuss the potential mechanisms of antihormone-therapy resistance in breast and prostate cancers, especially focusing on the similarities and differences of these two cancers. We will also discuss novel agents that have been applied in clinical practice or with clinical potential in the future.

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Introduction

The endocrine system is critical for growth, maturation, and coordination of the human body. However, malignancies can also arise from the organs influenced by endocrine-system-secreted hormones. Among these malignancies, the most widely studied are breast cancer and prostate cancer. Apart from skin cancers, breast cancer and prostate cancer are the primary diagnosed cancer and secondary cause of cancer death in women and men, respectively, in the United States (Jemal et al. 2004). These two types of cancer are not only similar in their epidemiological patterns but also possess similar pathological entities. Both of them are hormone-related cancers. They depend on specific steroid hormone receptors, such as estrogen receptor (ER), progesterone receptor (PR), and androgen receptor (AR), to mediate hormone effects on the initiation and progression of diseases. With the improvement of diagnostic methodologies, the incidence of both cancer types have increased, which is most likely attributed to early diagnosis, but the cancer death rate of breast and prostate cancers has continued to decline since 1992 and 1995, respectively (Jemal et al. 2003). However, to date curative treatments for both advanced cancers have not yet been established. Understanding the underlying pathogenesis of disease progression is the pivotal prerequisite for developing effective therapeutic and preventive strategies of these two cancers.

Since ER and AR mediate the hormone effect on tumor initiation and progression in breast and prostate cancer, several selective ER modulators (SERMs;
Katzenellenbogen and Katzenellenbogen 2002, Jordan 2003a, 2003b) and selective AR modulators (SARMs) that specifically inhibit receptor function by means of hormone deprivation or hormone blockade have been applied in clinics as both therapeutic and preventive strategies. Tamoxifen (TAM), the most commonly used SERM, competes with estrogen having a higher binding affinity to ER. Although TAM-binding ER can also translocate into the nucleus, the TAM–ER transcription complex is incomplete and insufficient to initiate downstream target gene transcription which is required for estrogen-dependent tumor growth (Piccart et al. 2003). Flutamide (FLU) and bicalutamide are both pure antiandrogen agents; they inhibit androgen from binding to AR and its subsequent translocation (Brogden & Chrisp 1991). In order to get maximal androgen blockade, antiandrogen agents usually combine gonadotropin-releasing hormone (GnRH) agonist androgen blockade, antiandrogen agents usually combine gonadotropin-releasing hormone (GnRH) agonist to suppress the compensatory-elevated luteinizing hormone (LH) and follicular-stimulating hormone (FSH; Labrie et al. 1993).

About 75% of breast cancer patients are ER- or PR-positive. TAM is the most frequently used drug as an adjuvant therapy for ER- and/or PR-positive breast cancer patients (Kiang & Kennedy 1977, Early Breast Cancer Trialists’ Collaborative Group 1998, Fisher et al. 1998, Schiff et al. 2000).

After a 5-year administration of adjuvant TAM, the proportional recurrence reduction was 47%, and the corresponding mortality reduction was 26% (Early Breast Cancer Trialists’ Collaborative Group 1998). TAM can also be used as a first-line therapy for metastatic breast cancer patients if their tumors are hormone receptor-positive and can be used as a chemoprevention agent for high-risk patients (Fisher et al. 1998). Although TAM is effective as an adjuvant and chemopreventive agent, there is still a significant proportion of patients who develop breast cancer or relapse breast cancer even after taking TAM, and the emergence of resistance in metastatic breast cancers is usually not preventable (Muss 1992). In prostate cancer, the majority of cases are AR-positive and androgen-ablation therapy by surgery, medicine, or combination is mandatory to those patients with locally advanced prostate cancer or metastatic disease. However, the response to hormone therapy is temporary and relapse is eventually inevitable. Chemoprevention is considered to be particularly important to reduce incidence of prostate cancer because of its diagnosis in elderly men, and even a modest delay in the neoplastic development could result in a substantial reduction in the incidence of this clinically detectable disease. Unlike breast cancer, chemoprevention for prostate cancer has just emerged and under evaluation. A recent prostate cancer prevention trial has been done to show that finasteride, a 5α-reductase inhibitor that inhibits the conversion of testosterone to a more potent androgen, dihydrotestosterone, has a chemopreventive effect for prostate cancer development (Thompson et al. 2003).

However, in this study they point out that finasteride also increases the risk of high-grade prostate cancer. This result implies that hormone deprivation for prostate cancer may promote the phenotypic progression of those tumor cells that are able to survive the acute period of the therapy. The selection pressure driven by hormone therapy seems play the same roles in both breast and prostate cancer.

The phenotypes of these resistant/relapsed tumors can be roughly categorized into: (1) receptor-positive, hormone-dependent, but resistant to or even stimulated by the first-line antihormone agents; (2) receptor-negative, hormone-independent; and (3) receptor-negative, hormone-independent. Several mechanisms have been proposed for these phenotypes. However, a common scenario is that once the tumor develops resistance to antihormone therapy it will become more aggressive and correlate with poor prognosis. Therefore understanding the mechanism of resistance emergence and the methods to overcome the resistance is critical for the treatment of hormone-therapy-resistant tumors. In this review, we will discuss the similarities and differences between breast cancer and prostate cancer in the development of hormone resistance and the therapeutic options (Table 1).

### Sex hormone — sex hormone receptor-modulating mechanisms

In human beings, secretion of sex hormones is controlled by the hypothalamus-pituitary-gland axis. For premenopausal women, ovaries produce almost all of the estrogen, and the primary estrogen produced is 17β-estradiol; for postmenopausal women, peripheral tissues, such as the adrenal gland, peripheral adipose tissue, and even the breast itself are the main organs producing estrogen. In men, the testes produce the majority of circulating testosterone, which is converted into the more powerful dihydrotestosterone (DHT) by 5α-reductase in target organs. A small portion of testosterone is produced by adrenal glands. Although the secretion of testosterone will decrease during aging, testes are still the major source of androgen in the elderly (Table 2).

Both ER and AR belong to the steroid nuclear receptor superfamily. The basic domain structures of
Table 1 Resistance mechanism and corresponding therapeutic countermeasures

<table>
<thead>
<tr>
<th>Receptor</th>
<th>Ligand dependence</th>
<th>Resistance mechanism</th>
<th>Therapeutic countermeasures</th>
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<tbody>
<tr>
<td>ER-/AR-positive</td>
<td>Positive</td>
<td>Receptor amplification</td>
<td>Total hormone ablation by antihormone agent and GnRH agonist</td>
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<td></td>
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<td>Increased circulating hormone</td>
<td>Aromatase inhibitor (BC)</td>
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<td>Increased endogenous hormone</td>
<td>Fulvestrant (BC)</td>
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<td>Receptor hypersensitivity</td>
<td>MAPK-pathway inhibitors</td>
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<td>Changing ratio of coregulators</td>
<td>Chemotherapy</td>
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<td>SERM, SARM</td>
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<td>Hsp90 inhibitor</td>
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<td>Anti-EGFR antibodies (IMC-C225, ABX-EGF)</td>
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<td>Anti-Her-2 antibodies (trastuzumab, 2C4)</td>
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<td></td>
<td>Tyrosine kinase inhibitors</td>
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<td>(gefitinib, OSI-774, CI-1033, PKI166, GW572016)</td>
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<td></td>
<td>Emodin, E1A</td>
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<td></td>
<td></td>
<td></td>
<td>Bcl-2 antisense</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Chemotherapy</td>
</tr>
<tr>
<td>ER-/AR-negative</td>
<td>Negative</td>
<td>Loss of receptors</td>
<td>BC, breast cancer</td>
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<td></td>
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<td></td>
<td>EFGR, epidermal growth factor receptor</td>
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<td>Hsp, heat-shock protein</td>
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<td></td>
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<td>MAPK, mitogen-activated protein kinase</td>
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Table 2 The major hormone source and antihormone therapy agents of breast cancer and prostate cancer

<table>
<thead>
<tr>
<th></th>
<th>Breast cancer</th>
<th>Prostate cancer</th>
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</thead>
<tbody>
<tr>
<td>Major sex hormone</td>
<td>17β-Estradiol</td>
<td>DHT</td>
</tr>
<tr>
<td>Major source of sex hormone</td>
<td>Premenopause: ovary</td>
<td>Majority: testis</td>
</tr>
<tr>
<td></td>
<td>Postmenopause: peripheral adipose tissue, adrenal gland, breast</td>
<td>Minority: adrenal gland</td>
</tr>
<tr>
<td>First-line antihormone agents</td>
<td>TAM</td>
<td>FLU</td>
</tr>
<tr>
<td>Chemoprevention agents</td>
<td>TAM</td>
<td>GnRH agonist</td>
</tr>
<tr>
<td></td>
<td>Aromatase inhibitor</td>
<td>Finasteride</td>
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</table>

the nuclear receptor superfamily include an N-terminal region with the activation function 1 (AF-1) domain, a DNA-binding domain (DBD) with two zinc-finger structures, and a hinge region and ligand-binding domain (LBD) at the C-terminus (Fu et al. 2003). The LBD includes the activation function 2 (AF-2) domain and 12 α-helices that project away from the hormone-binding groove in the absence of ligand. Without ligand binding, ER/AR associates with chaperone proteins, heat-shock proteins (Hsps), and the immunophilin complex. After ligand binding, receptors dissociate from chaperone proteins, and form homodimers or heterodimers that can bind to the estrogen- and androgen-response elements in the promoter regions of target genes. This will release corepressors and recruit coactivators, thereby forming a transcriptional complex and initiating target gene transcription (Feldman & Feldman 2001, Osborne et al. 2001, Isaacs et al. 2003). There are two ER genes on different chromosomes, ER-α on chromosome 6q25.1, and ER-β on chromosome 14q22-25. ER-α is usually the dominant isoform and correlates with most of the prognostic factors in breast cancers (Fuqua et al. 2003). Both proteins have compatible binding affinities for estradiol and similar binding domains for ligand and DNA; they also have two transcriptional domains, AF-1 and AF-2. The transcriptional function of AF-1 and AF-2 is tissue- and promoter-specific. The transcription function of AF-1 is ligand-independent, and it is closely related to the phosphorylation status of ER, and can be induced by mitogen-activated protein kinases (MAPKs), growth factors and oncogenes (Fu et al. 2003), while
AF-2 is completely ligand-dependent (Kato et al. 2000). AF-1 and AF-2 of ER can activate transcription independently or synergistically. ER-α and ER-β have opposite effects on transcription initiated by AP-1, SP-1, or cAMP-response elements (CREs; Paech et al. 1997, Castro-Rivera et al. 2001, Liu et al. 2002). Especially in a low-estrogen environment such as in cases of aromatase-inhibitor treatment, the inhibitory effect of ER-β could become more prominent as an antitumor mechanism (Jordan 2003). Thus compounds that are antagonists for ER-α may be agonists for ER-β at these sites. However, the function and prognostic significance of ER-β is still not clear (Hall & McDonnell 1999, Palmieri et al. 2004, Speirs et al. 2004). For those breast cancer cells with ER expression, the ratio between ER-α and ER-β may change during carcinogenesis, it may also serve as an important marker in predicting the response to certain kinds of specific selective estrogen-modulator therapy (Dotzlaw et al. 1999). In contrast to ER, no AR isoform has been found to date. Without ligand binding, ER mainly stays in nucleus but the majority of AR stays in cytoplasm. Upon ligand binding, the AR homodimer will translocate into the nucleus. In addition, androgens can stabilize AR protein level 6-fold compared to the level without ligand binding. However, estrogen binding will accelerate ER degradation. These biological differences between ER and AR could be used as different targeting strategies (Table 3).

**Mechanisms of resistance**

There are several mechanisms that have been proposed to be responsible for the emergence of hormone resistance in breast cancers and prostate cancers. These resistance mechanisms can occur at the pre-receptor level, such as a change in the hormone level, at the receptor level, or at the post-receptor level. Based on the three major phenotypes mentioned above, we summarize several possible mechanisms for the development of resistance (Figure 1). These events can occur alone or together, dependent on the individual case, and therefore the next step of therapy after the emergence of resistance should depend on the underlying mechanism for the resistance.

**Receptor-positive, ligand-dependent**

**Enhancing receptor expression**

Long-term hormone deprivation may select for cancer cell clones that enhance the expression of receptors to compensate for the low-level ligand environment. In long-term estrogen deprivation of MCF-7 cells, ER-α was found to be upregulated 4–10-fold (Santen et al. 2003). The same situation was reported for ER-β from clinical samples (Speirs et al. 1999). In prostate cancer AR gene amplification is rarely found in primary cancer; after androgen-ablation therapy, approximately 30% of tumors become androgen independent due to an increase of AR expression (Feldman & Feldman 2001). Additionally, the gain of AR gene copies in primary prostate cancer due to X-chromosome polysomy was observed (Ropke et al. 2004). This may due to the selective effect that comes from the low level of androgen after androgen ablation, which favors clonal expansion of cancer cells expressing a higher level of AR. These tumors are still hormone-dependent, and they may respond to second-line therapy with total hormone ablation.

**Increased circulating hormone**

TAM binds to ER, and FLU binds to AR to antagonize sex hormones in the tumors; however, they also bind to the receptors in pituitary gland and hypothalamus, which may interrupt the negative-feedback pathways of sex hormones. As a result GnRH is secreted continuously, ultimately producing a hyperstimulatory effect on the ovaries or testes resulting in oversecretion of estrogen or androgen. This may explain the elevated estradiol levels that were noted in some premenopausal breast cancer patients after TAM administration (Ravdin et al. 1988). To overcome this problem, GnRH analogues can be combined with antihormone agents to reach total estrogen or androgen ablation (Robertson & Blamey 2003).

<table>
<thead>
<tr>
<th>Table 3 Comparison of ER and AR</th>
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<tbody>
<tr>
<td><strong>Expression before treatment</strong></td>
</tr>
<tr>
<td>ER</td>
</tr>
<tr>
<td>AR</td>
</tr>
<tr>
<td><strong>Mutation as the cause of resistance</strong></td>
</tr>
<tr>
<td>ER-α</td>
</tr>
<tr>
<td>AR</td>
</tr>
<tr>
<td><strong>Location before ligand binding</strong></td>
</tr>
<tr>
<td>ER-α</td>
</tr>
<tr>
<td>AR</td>
</tr>
<tr>
<td><strong>Isoform</strong></td>
</tr>
<tr>
<td>ER-α/ER-β</td>
</tr>
<tr>
<td>Homo-/heterodimer</td>
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<tr>
<td><strong>Dimer formation after ligand binding</strong></td>
</tr>
<tr>
<td>Accelerated degradation</td>
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</tbody>
</table>
Increased endogenous hormone

In females, estrogen production can be converted from androgen by aromatase in the breast. The transcriptional control of aromatase is different between normal tissue and breast cancer tissue (Harada et al. 1993). Increased aromatase expression and activity have been noted in breast tumors compared to peritumor tissues (Goss & Strasser 2002). This increased production of aromatase comes from the interaction between breast cancer cells and associated fibroblasts and inflammatory cells in the adjacent stroma. Breast cancer cells synthesize prostaglandin \( E_2 \), and inflammatory cells produce not only prostaglandin \( E_2 \) but also interleukin 6 (IL-6), IL-11, and tumor necrosis factor \( \alpha \) (TNF\( \alpha \)), all of which stimulate fibroblasts to produce aromatase. This mechanism is related closely to cyclooxygenase 2 (COX-2; Johnston & Dowsett 2003). Also in long-term estrogen-deprived breast cancer cells, aromatase activity increases adaptively (Yue et al. 1999). Both of these cases lead to higher local estrogen concentration and can overcome the effect of anti-estrogen agents. This may explain in part why aromatase inhibitors elicit a better clinical response than TAM in clinical studies (Wong & Ellis 2004).

In males, long-term androgen-ablation therapy may select prostate cancer cells with higher \( 5\alpha \)-reductase activity, which can produce more DHT from adrenal androgen, thus providing a higher intracellular DHT level to compensate for the low level of circulating testosterone (Navarro et al. 2002). Men of African descent, who have the highest incidence of a polymorphism in the gene of \( 5\alpha \)-reductase in which a valine residue at codon 89 is substituted by a leucine, have been reported to have higher \( 5\alpha \)-reductase activity and...
have a particularly high incidence of prostate cancer with poor prognosis (Ruijter et al. 1999).

**Receptor hypersensitivity**

Receptors may have congenital or acquired mutations that change their sensitivity to ligands. A study of a typical breast hyperplasia found that a mutation of ER-α (Ala-908→Gly) affects the border of the hinge and hormone-binding domains of ER-α and shows increased sensitivity to estrogen. This mutation may promote or accelerate the development of cancer from premalignant breast lesions (Fuqua et al. 2000). Long-term deprivation of estrogen, for instance with TAM treatment, can induce hypersensitivity of breast cancer cells to estradiol (Berstein et al. 2004). Such adaptive hypersensitivity may go through a rapid, nongenomic plasma membrane receptor-mediated pathway: estradiol binds to ER-α, then phosphorylates Shc, Shc then binds to Grb-2 and SoS, resulting in the rapid activation of MAPK through Ras, Raf, and MAPK/ extracellular-signal-regulated kinase (ERK) kinase (MEK), and then the phosphorylation of AF-1 on ER-α (Santen et al. 2003). Several agents can block this pathway, including: aromatase inhibitors, which block the estrogen production from the peripheral tissue; the pure anti-estrogen fulvestrant (Howell 2001); farnesylthiosalicylic acid, an inhibitor of GTP-Ras binding to pure anti-estrogen fulvestrant (Howell 2001); farnesylthiosalicylic acid, an inhibitor of GTP-Ras binding to pure anti-estrogen fulvestrant (Howell 2001); farnesylthiosalicylic acid, an inhibitor of GTP-Ras binding to pure anti-estrogen fulvestrant (Howell 2001). Although the crystal structure of AR suggests that ligand-binding induced LBD conformations similar to ER and potentially generates a similar coregulator interaction surface, functional analyses of the full-length receptors suggest that distinct differences exist between the coregulator interaction domains of AR and ER. This may be because the interaction between the AR N-terminus and the LBD generates a potential coregulator in interaction structure that differs from that of ER. Since different target cells express different levels of coactivators and corepressors, which accounts for cell-specific regulation of responsive gene expression, increased activity of coactivators can lead to the emergence of resistance. Additionally, coactivators can interact with other transcriptional factors (Lee et al. 1998), and as a result they also enhance transcription without ligand binding. Several coactivators are important both in breast cancer and prostate cancer for the development of hormone independence. Disruption of SRC-1 results in partial hormone resistance, particularly to thyroid hormone (Xu et al. 1998).
# Table 4 The common AR and ER coregulators

<table>
<thead>
<tr>
<th>Transcriptional coregulator</th>
<th>Other nuclear receptor targets</th>
<th>Functions</th>
<th>Selected references</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRC-1 (NcoA-1)</td>
<td>GR, PR, TR, RXR</td>
<td>Unlike ER and other receptors, which interact with SRC-1 through their LBD, AR interacts through its N-terminal and DBDs. Interacts with CBP/p300 and possesses weak acetyltransferase activity.</td>
<td>Bevan et al. 1999, He et al. 1999, Spencer et al. 1997</td>
</tr>
<tr>
<td>AIB1/SRC-3 (Rac3, ACTR, TRAM1, p/CIP)</td>
<td>PR, TR, RAR</td>
<td>Interact with CBP/p300 and possess acetyltransferase activity.</td>
<td>Anzick et al. (1997), Chen et al. (1997), Yeh et al. (1998).</td>
</tr>
<tr>
<td>RIP140</td>
<td>PPARγ, PPARα</td>
<td>Influences the transcriptional activity of PPARγ and PPARα. May recruit histone deacetyltransferases. Functions as an RNA transcript and associated with an SRC-1-containing coregulator complex.</td>
<td>Bevan et al. (1999), Treuter et al. (1998)</td>
</tr>
<tr>
<td>SRA</td>
<td>PR, GR</td>
<td>Enhances transactivation through AF-1 domain of GR and PR. Functions as a general coregulator for nuclear receptors.</td>
<td>Lanz et al. (1999)</td>
</tr>
<tr>
<td>Src</td>
<td>ERβ</td>
<td>Src tyrosine kinase activity stimulated by E2 and DHT for non-genomic steroid action.</td>
<td>Kousteni et al. (2001), Migliaccio et al. (2002)</td>
</tr>
<tr>
<td>TIF2 (GRIP1, NcoA2)</td>
<td>TR, VDR, RAR, GR, PR</td>
<td>Interacts with CBP and functions as a general coregulator for nuclear receptors.</td>
<td>Berrevoets et al. (1998), He et al. (1999),</td>
</tr>
<tr>
<td>Tip60</td>
<td>PR</td>
<td>Interacts with AR through Hing LBD domain. A member of the MTST/SAS family of histone acetyltransferases. Also functions as coactivator for PR.</td>
<td>Hong et al. (1997), Brady et al. (1999)</td>
</tr>
<tr>
<td>Zac-1</td>
<td>TR, GR</td>
<td>Interacts with AR through LBD domain. In Hela cells, coactivation is synergistic with TIF2.</td>
<td>Huang &amp; Stallcup (2000)</td>
</tr>
<tr>
<td>ARA267 (NSD1)</td>
<td>TR, RAR, RXR</td>
<td>Interacts with AR through both N- and C-terminal domains. Contains SET and PHD domains.</td>
<td>Huang et al. (1998), Wang et al. (2001)</td>
</tr>
<tr>
<td>ARA70 (RFG, ELE1)</td>
<td>PPARγ, GR</td>
<td>Enhances the transactivation of both wild-type AR and AR (T877A) in response to DHT and E2. Functions as a bridge factor for TFIIB and p/CAF.</td>
<td>Heinlein et al. (1999), Yeh &amp; Chang (1996), Yeh et al. (1998)</td>
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PPAR, peroxisome proliferator-activated receptor; RAR, retinoic acid receptor; RXR, retinoid X receptor; GR glucocorticoid receptor, TR thyroid receptor, VDR Vitamin D receptor, CBP, cAMP-response-element-binding protein-binding protein; E2: 17 beta-estradiol; MYST/SAS: (M02, Ybf2/Sas3, Sas2, and TIP 60)/(something about silencing) domain; SET (Su(var)3-9, Enhancer-of-zeste, trithorax) methyl transferase domain; PAD: plant homeodomain.
addition, results from different groups indicated that SRC-1 is involved in the progression of prostate cancers. Using reverse transcriptase PCR, Fujimoto and colleagues (2001) found that the expression levels of SRC-1 were higher in higher-grade prostate cancers or cancers with a poor response to endocrine therapy. At the same time, it has been reported that SRC-1 expression was elevated, together with the expression of AR, in recurrent prostate cancers (Gregory et al. 2001). Previous studies found that SRC-2 is also overexpressed in recurrent prostate cancers. Overexpression of SRC-1 and SRC-2 confers on AR an increased sensitivity to the growth-stimulating effects of low-androgen concentrations. This change may contribute to prostate cancer recurrence after androgen-deprivation therapy. High levels of SRC-1 in uterus and breast are known to enhance the agonistic effect of TAM (Katzenellenbogen & Katzenellenbogen 2002); SRC-1 can also interact synergistically with CRE-binding protein to activate ER-mediated transcription in a ligand-independent manner (Jackson et al. 1997), and this activity can be inhibited by corepressor SMRT (Smith et al. 1997).

In TAM-treated breast cancer patients, high AIB1/SRC-3 expression was associated with worse disease-free survival, which is indicative of TAM resistance (Osborne et al. 2003). Compared with the widespread expression of SRC-1 and SRC-2, expression of AIB1/SRC-3 is restricted to few tissues, including the uterus, the mammary gland and the testis (Suen et al. 1998). Disruption of AIB1/SRC-3 gene in mice causes severe growth and reproductive defects, such as the retardation of mammary gland development (Xu et al. 2000). Amplification and overexpression of AIB1/SRC-3 in human breast and ovarian cancers have been observed (Anzick et al. 1997, Chen et al. 1997, Yeh et al. 1998). It has been reported that the AIB1/SRC-3 amplification/overexpression was correlated with ER and PR positivity (Bautista et al. 1998).

Breast cancer (BRCA1) is a breast cancer-susceptibility gene, and its mutations are correlated with an increased risk of breast and ovarian cancers (Martin et al. 2001). Interestingly, BRCA1 was shown to function as a ligand-independent corepressor for ER and PR and enhance the ligand-dependent AR transactivation in the presence of exogenous SRC family members (Miki et al. 1994, Yeh et al. 2000, Fan et al. 2001). Thus, it is reasonable to speculate that the normal expression of BRCA1 probably protects the breast from tumorigenesis by suppressing the ER and PR signaling pathway and promoting AR activity in prostate cancer development. The ARAs, AR-associated proteins, is a group of factors that can bind to AR and modulate its transcriptional activity. Based on their molecular masses, these factors were named ARA70, ARA160, ARA54, ARA55, ARA267 and ARA24 (Kang et al. 1999, Yeh et al. 1999). Studies on the expression patterns of ARA70 in different cell lines and human cancer samples showed that the expression of ARA70 was decreased in prostate cancer (Yeh et al. 1999) and breast cancer (Kollara et al. 2001). In breast, loss of ARA70 protein expression was found in 60% of Human Epidermal growth factor receptor (HER)-positive breast cancers, whereas only 33% of HER2-negative breast cancer samples lost the expression (Kollara et al. 2001). Since androgen plays an inhibitory role for breast cancer cell growth, and HER2 stimulates the growth of breast cancers, loss of the expression of AR and/or ARA70 in breast might confer a growth advantage to these cells. In prostate, ARA70 mRNA is highly expressed in the normal epithelial cells, while benign prostatic hyperplasic and cancer cell lines express either lower or no ARA70 (Kollara et al. 2001).

Receptor-positive, ligand-independent

Receptor mutations

Mutations of receptors can occur during the initiation of tumor formation, or can develop after therapy begins. Mutations in the ligand-binding domains of receptors may change not only their binding affinity and sensitivity to circulating ligands, but also the specificity of the receptors to their ligands. In this case receptors are able to bind substitutes such as other circulating steroid hormones, or even antihormone agents such as TAM or FLU to stimulate cell growth.

In breast cancer, ER mutation is not a major cause of hormone resistance since it is seen in fewer than 10% of TAM-resistant breast cancer patients (Achuthan et al. 2001). However, in prostate cancer, AR mutations are found in about 30% of the metastases that are resistant to hormone therapy (Navarro et al. 2002). In addition, the mutation rate is significantly increased in metastatic sites compared to primary tumors (Marcelli et al. 2000), especially after androgen-ablation therapy (Taplin et al. 1995). Many of the mutations are gain of function and are located in the ligand-binding domain, which results in inappropriate activation of AR by steroid hormones other than androgen and AR antagonists (Buchanan et al. 2001). For instance, several mutant ARs such as Thr-877→Ala, Leu-701→His, and Leu-701→His/Thr-877→Ala have a broadened spectrum of ligand responsiveness, and bicalutamide works as an agonist for these mutants (Hara et al. 2003). These mutations are considered to be responsible for the phenomenon
of ‘antiandrogen withdrawal syndrome’ (Nelson et al. 2003).

**ER/AR crosstalk with other growth factors**

During the progression from hormone-dependent to independent cancers, the crosstalk between ER/AR and other growth factor pathways is a complicated issue. There are several growth factors and their receptors involved in this process. The crosstalk between growth factor pathways and ER/AR occurs at multiple levels and is bidirectional with different importance in breast and prostate cancers. Novel therapies against these growth factors are emerging as alternative choices for the prevention and treatment of hormone-resistant breast cancer or prostate cancer.

Many of the estrogen-responsive genes code for peptide growth factors, membrane-bound tyrosine kinase receptors (TKRs), and several cellular signaling molecules, and usually their transcription is inversely correlated with ER expression (Schiff et al. 2004). On the contrary, the genotropic activity of ER is enhanced by several growth factor signaling pathways, including epidermal growth factor (EGF), insulin-like growth factor type I (IGF-1), and transforming growth factor-α (TGF-α), which enhance the phosphorylation of AF-1 on Ser-118 of ER by MAPK. This phosphorylation enhances the nuclear localization of coactivators and their interaction with nuclear ER, producing ligand-independent transcriptional activity of AF-1, even in the presence of TAM, and is related to antihormone resistance (Kato et al. 1995, Schiff et al. 2003). Thus, increasing the expression of growth factors or upregulation of their receptors or the downstream signaling elements can promote antihormone-therapy resistance.

Membrane ERs can also function like growth factor receptors by binding to p85, a regulatory subunit of phosphoinositide 3-kinase (PI3K) at the cell membrane, leading to activation of the protein kinase Akt and the subsequent downstream signaling (Migliaccio et al. 2002). Therefore, membrane ER enhances the transcriptional activity of nuclear ER through a nongenotropic pathway. Both genotropic and nongenotropic actions seem to be complementary, even synergistic, not only for cellular growth but also for the emergence of hormone resistance in a low-estrogen environment (Schiff et al. 2003). In summary, ER may suppress the expression of other growth factor receptors and long-term estrogen suppression can reactivate the expression of membrane TKRs. This results in increased growth factor signaling, and ERK1/2 MAPK, and PI3K/Akt activities, alteration of ER subcellular localization and enhancement of the nongenotropic action, stimulating the malignant phenotype (Kumar et al. 2002, Schiff et al. 2004). More and more evidence suggests that the crosstalk between ER and these signaling pathways is upregulated or activated in endocrine-resistant breast cancers, and may be the major cause of endocrine resistance (Johnston et al. 2003). In an in vitro study, dual inhibition of MAPK with U-0126 and PI3K with Ly294002 have been found to decrease the sensitivity of ER to estradiol (Yue et al. 2003).

Among all the growth factors and growth factor receptors, the EGF receptor (EGFR) family seems to play a major role in promoting hormone refractory transition, in particular HER-2/neu is well known to associate with poorer prognostic phenotypes including high-grade histology, high proliferation rate, and ER negativity. There is also a tendency for HER-2/neu-overexpressed breast cancer to be less responsive to anti-estrogen therapies (Revillion et al. 1998). Introducing HER-2/neu cDNA into breast cancer cells promotes ligand-independent downregulation of ER, and converts cancer cells from estrogen-dependent to estrogen-independent (Pietras et al. 1995). Its signaling pathway can also disrupt the TAM-induced interaction of ER with the transcriptional corepressor N-CoR (Kurokawa et al. 2000, Kurokawa & Arteaga 2001). High HER-2/neu expression constitutively activates PI3K/Akt. Active Akt renders MCF-7 cells from estrogen-dependent to -independent, and treating these cells with TAM actually stimulates instead of inhibiting their growth (Faridi et al. 2003). Since HER-2/neu overexpression is closely related with MAPK hyperactivity and TAM resistance, inhibiting MAPK can reverse TAM resistance in HER-2/neu-overexpressed breast cancer cells (Kurokawa et al. 2000).

The crosstalk between AR and growth factor signaling pathways of prostate cancer is very similar to that of breast cancer (Nelson et al. 2003). EGF, IGF-I, and keratinocyte growth factor all activate AR, especially IGF-1, and the AR antagonist casodex blocks this activation completely (Culig et al. 1994). This indicates that the activation is AR-dependent. Membrane-bound TKRs, especially HER-2/neu, were also observed to be involved in the progression to AIPC, as overexpression of HER-2/neu increases MAPK and Akt activities, phosphorylates AR, and then turns on downstream target genes in a ligand-independent manner (Lin et al. 2001).

The cytokine IL-6 is also related to the growth of breast and prostate cancers and the emergence of hormone resistance through its interaction with TKRs and intracellular signaling pathways. In both breast cancer and prostate cancer, elevated circulating levels
of IL-6 are associated with worse prognosis, especially in AIPC (Drachenberg et al. 1999, Salgado et al. 2003). Serum IL-6 levels are significantly elevated in hormone-refractory prostate cancer patients as compared with earlier stages of the disease or with benign prostate hyperplasia (Drachenberg et al. 1999). In breast cancer, IL-6 increases intracellular aromatase activity (Honma et al. 2002). IL-6 also facilitates the formation of bone metastasis of both breast cancer and prostate cancer by stimulating osteoclasts (Roodman 2001). In prostate cancer, IL-6 is the most potent nonsteroidal regulator of AR activity. It alone causes the activation of AR to approximately 50% of the maximal activity induced by androgen (Culig 2003). IL-6 regulation of AR activity and prostate cancer growth occurs through MAPK and signal transducer and activator of transcription 3 (STAT3; Chen et al. 2000, Culig et al. 2002). It can also stimulate the autophosphorylation of HER-2/neu in prostate cancer cells and subsequently activate the downstream kinase signaling pathways (Qiu et al. 1998). Thus, IL-6 is important in mediating and enhancing the transition from hormone-dependent to hormone-independent of breast and prostate cancer cells.

Since long-term estrogen deprivation induces the expression of growth factors and growth factor receptors, and overexpressed growth factors and growth factor receptors facilitate the emergence of antihormone resistance, the question arises as to whether it is possible to not only treat antihormone-resistant cancer, but also to prevent the development of resistance by early treatment with anti-growth factor agents, either alone or in combination with anti-estrogen agents. Several experiments using such combinations have been reported, and have shown promising results (Schiff et al. 2004).

Receptor-positive, receptor/ligand-independent (bypass pathway)

The mechanisms involved in hormone-refractory transition are complicated. Several complementary or alternative pathways may occur simultaneously, some of which are capable of bypassing receptors completely. Inhibition of genotrophic or nongenotrophic pathways can lead to apoptosis in breast and prostate cancer cells. Blocking the apoptotic cascades by enhancing antiapoptotic genes, decreasing proapoptotic genes or through mutations in oncogenes or tumor-suppressor genes all are possible mechanisms for the bypass pathway.

The antiapoptotic gene Bcl-2 is overexpressed in more than half of all human cancers. Overexpression of Bcl-2 occurs in 40–80% of human breast tumors (Nahta & Esteva 2003) and also occurs frequently in prostate cancers. Overexpression of Bcl-2 is associated with the resistance to hormonal therapy and chemotherapy in both breast cancers and prostate cancers. This phenotype may come from the selection effect of antihormone agents. Treatment with Bcl-2 antisense in a prostate cancer animal model delays the emergence of androgen independence (Gleave et al. 1999). Transcriptional factor nuclear factor κB (NF-κB) modulates the expression of genes involved in cell proliferation, differentiation, apoptosis, and metastasis. Constitutive activation of NF-κB is noted in ER-negative breast cancer cells, in TAM-resistant MCF-7 cells (Gu et al. 2002), and during breast cancer progression to hormone-independent growth (Nakshatri et al. 1997).

Mutation or decreased expression of tumor-suppressor genes is also an alternative pathway. Tumor-suppressor genes are involved in the DNA-repair process to maintain genomic integrity, cell-cycle control, and induction of apoptosis in damaged cells and regulation of transcription. Failure of tumor-suppressor genes increases the probability of accumulation of replication errors and genomic instability, making cells less responsive to apoptotic signals, and contributing to an increase in hormone-independence and tumor aggressiveness. The most common mutated tumor-suppressor gene is p53 (Levine et al. 1991). In hormone-refractory prostate cancers p53 was positively increased during hormonal therapy from 17% of untreated primary tumors to 40% of hormone-refractory recurrences. The percentage of mutations was significantly higher in cases of AR gene amplification (Koivisto & Rantala 1999). PTEN (phosphatase and tensin homologue deleted on chromosome 10) is another tumor-suppressor gene that has been noted to be mutated in both breast cancer and prostate cancer (Li et al. 1997). In breast cancer, BRCA1 and BRCA2 mutations are well known for hereditary and sporadic breast cancers (Wooster & Weber 2003). Recently these two genes were found to be related to prostate cancer development (Rosen et al. 2001).

Receptor-negative, hormone-independent

Since ER/AR are responsible for the ligand-induced signal transduction, ER/AR are also the main targets of antihormone agents. With decreased expression of ER/AR these therapeutic agents lose their targets, which may be a cause of resistance. In fact, absence of ER expression is the most common mechanism of de novo resistance in breast cancers, whereas a complete loss of
ER expression is not common in acquired resistance (Clarke et al. 2003). Decreased expression of receptors usually comes from hypermethylation of the responsible genes. DNA hypermethylation of the AR promoter region leading to AR downregulation has been identified in 30% of hormone-refractory prostate cancers, compared with only 10% in untreated primary tumors (Suzuki et al. 2003). Reverse DNA hypermethylation by cytosine DNA methyltransferase inhibitors restores androgen responsiveness in androgen-refractory prostate cancer cells, making them sensitive to growth inhibition by antiandrogen agents (Izbicka et al. 1999). Hypermethylation of a CpG island in the 5′ region of the ER gene is seen in ER-negative breast cancer cells; demethylation of this site reactivates ER gene expression (Ferguson et al. 1995). The same condition has also been reported in AR-negative prostate cancer cells (Jarrard et al. 1998).

Novel agents targeting sex hormone receptors in hormone-resistant breast and prostate cancers

In recent years, there has been growing interest in the development of nonsteroidal modulators for steroid hormone receptors as therapeutic agents. SERMs, SARMs, and nonsteroidal modulators for progesterone receptor have been successfully developed (Zhi et al. 1998, 2000, Hamann et al. 1999, Mitlak & Cohen 1999, Weryha et al. 1999). These modulators are well characterized for their better receptor specificity and selectivity than steroidal ligands, and are more flexible in structural modification for pharmacologic properties. More importantly, with these nonsteroidal chemicals, it may achieve tissue-selective actions and thus generate compounds with diverse purpose suitable for specific therapeutic needs.

SERMs

Estrogens are widely used clinically to control reproduction and for hormone therapy and the treatment of menopausal symptoms in women. Although beneficial in these contexts, estrogen use has also been implicated as a risk factor in breast and uterine cancer, particularly since the first published report from the Women’s Health Initiative (Rossouw et al. 2002), suggesting that a greater measure of flexibility to control unwanted side effects would be desirable. Consequently, the recognition of SERMs as agents able to elicit estrogenic effects in a tissue-specific manner has expanded the potential population that could benefit from ER ligand therapies. The prototypic SERM is the trans isomer of TAM (Gottardis & Jordan 1987, Gottardis et al. 1988). Although it was first proposed to use for regulating fertility, it has been applied primarily as a drug to treat breast cancer (Harper & Walpole 1967, Williamson & Ellis 1973). The ability of TAM to inhibit ER action has long been considered integral to its utility in the breast cancer arena, and this is consistent with numerous studies and clinical trials demonstrating an effect of TAM in ER-positive cells or breast tumors and an absence of any significant activity in those lacking ER expression (Early Breast Cancer Trialists’ Collaborative Group 1998). The subsequent observation of the estrogen-like effects of TAM in the human skeleton (Love et al. 1992) was important to the conceptualization of SERMs as potential drugs for indications other than breast cancer. The success of TAM as a SERM has been a driving force in the search for new SERMs as well as selective modulators for other nuclear/steroid receptors. Raloxifene, like TAM, exhibits anti-estrogen activity in the breast and estrogen activity in the skeleton. However, raloxifene lacks the significant uterotrophic activity associated with TAM and therefore represents an improved agonist/antagonist profile (Delmas et al. 1997, Ettinger et al. 1999). In addition, a number of other compounds, including lasofoxifene, arzoxifene, and bazedoxifene, are under development, which may one day be of clinical use for chemoprevention of breast cancer or treatment and prevention of osteoporosis (Baracat et al. 1999, Suh et al. 2001). Consequently, the recognition of SERMs as agents able to elicit estrogenic effects in a tissue-specific manner has expanded the potential population that could benefit from ER ligand therapies.

SARMs

Chemicals that regulate the transcriptional activity of AR can be further categorized into structural (steroidal and nonsteroidal) and functional (androgenic and antiandrogenic) classes. Steroidal androgens, mainly testosterone and its derivatives, have been used clinically as replacement therapies for androgen deficiency (Bagatell & Bremner 1996). Antiandrogens are used to counteract the undesirable actions of excessive androgens (e.g. to treat acne, hirsutism, male-pattern baldness, and androgen-dependent prostate cancer; Neumann 1982, McLeod et al. 1993). Nonsteroidal antiandrogens, such as FLU (Eulexin), nilutamide (Anadron), and bicalutamide (Casodex), bind to the AR LBD and, therefore, are devoid of antagonadotropic, anti-estrogenic, and progestational effects. These agents are advantageous over

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steroidal antiandrogens (e.g. megestrol acetate, cyproterone acetate) in terms of specificity and selectivity (Cockshott et al. 1990, Teutsch et al. 1994). Whereas steroidal antiandrogens have been used clinically for a long period of time, nonsteroidal androgens were not conceptualized until very recently. Although androgen therapies are currently available, they are based primarily on delivery of testosterone or its derivatives by injections or skin patches (Negro-Vilar 1999). Neither approach is optimal because injections result in undesirable fluctuations in serum testosterone levels, and skin patches are associated with irritation and rashes. Oral preparations of currently available androgens are not recommended because of their relatively low efficacy, fluid retention, liver toxicity, prostatic hypertrophy, and gynecomastia. Therefore, the goal of preservation of positive androgen effects in some tissues, while minimizing negative side effects in other tissues, has stimulated a search for SARMs. Recently, a group of nonsteroidal androgens that are electrophilic derivatives of bicalutamide and hydroxyflutamide was discovered (Dalton et al. 1998). Also, several analogs of quinoline-based AR antagonists, notably tricyclic pyridinodihydroquinoline derivatives, showed promising anabolic effects without any significant action on the prostate and seminal vesicles (Edwards et al. 1999, Hamann et al. 1999, Higuchi et al. 1999, Zhi et al. 1999). The selective action of these compounds on muscle and bone tissues implies important clinical applications for these androgen analogs in the treatment of elderly men and patients with wasting diseases. These studies marked the emergence of a novel category of pharmacological agents with potential applications in androgen therapy. Assessments of the in vivo SARM activity of these compounds are underway in animals as well as in humans, and they show a promising tissue-selective activity profile. Animal experiments with one such SARM, LGD2226, revealed that it prevented loss of bone mineral density associated with orchidectomy in rats; in contrast, LGD2226 did not stimulate prostate weights above those observed for intact rats (Negro-Vilar 1999). The discovery of nonsteroidal androgens provides an opportunity to identify agents with superior pharmacokinetic profiles to steroidal androgens and implicates the possibility to obtain tissue-selective AR modulators.

**Fulvestrant**

To overcome crosstalk between ER and other growth factors, several novel agents have been evaluated, some of which are currently in clinical practice. The most straightforward method is to diminish functional ER. Fulvestrant (Faslodex; ICI 182,780), is a pure anti-ER agent which competes with estrogen for binding to ER, with much higher affinity (89 versus 2.5% binding affinity of estriodiol; Wakeling et al. 1991, Morris & Wakeling 2002). Fulvestrant reduces the rate of ER dimerization, increases ER degradation (Fawell et al. 1990), and reduces ER shuttling from the membrane to the nucleus by blocking its nuclear uptake (Dauvois et al. 1993). The loss of ER not only abrogates the transcriptional effect of estrogen, but also blocks the activation of ER by other growth factors. More importantly fulvestrant blocks the agonistic effects of both estrogen and TAM without a demonstrable estrogen-agonistic effect (Wakeling & Bowler 1988, Howell 2001). A single dose of fulvestrant has been shown to decrease ER, PR, and Ki-67 levels significantly in the primary breast cancers of postmenopausal women compared to TAM (Robertson et al. 2001). For the treatment of postmenopausal women with receptor-positive breast cancers, fulvestrant was at least as effective as aromatase inhibitors and TAM (Howell et al. 2002, 2004, Osborne et al. 2002). The long-term efficacy and side effects of fulvestrant still need to be followed.

**Hsp90 inhibitors**

As a chaperone protein, Hsp90 binds to over 100 kinds of proteins that are involved in multiple signaling pathways utilized by cancer cells for growth and survival. These proteins include steroid hormone receptors (ER, AR, PR), growth factor receptors (EGFR, HER-2), several kinases (Akt, c-RAF-1), transcriptional factors, and mutated or chimeric signaling proteins (mutated p53, p210Bcr-Abl; Isaacs et al. 2003). Hsp90 serves as an important regulator to control the folding, intracellular disposition, and proteolytic turnover of many key regulatory proteins of cell growth, differentiation, and survival. It is constitutively expressed at 2–10-fold higher levels in tumor cells compared to normal cells (Isaacs et al. 2003), its protective effect allows tumor cells to tolerate the mutation of multiple critical signaling molecules that would otherwise be lethal. Therefore it may be important for cancer cell development and survival (Bagatell & Whitesell 2004). Hsp90 inhibitors including geldanamycin, the derivative product of geldanamycin–17-allylamino geldanamycin (17-AAG), help to degrade several oncogenic proteins, and block several oncogenic pathways (Workman 2004). More surprisingly, the Hsp90 that is derived from tumor cells has a 100-fold-higher binding affinity for 17-AAG than
the Hsp90 from normal cells (Kamal et al. 2003). This information suggests that Hsp90 is a good target of 17-AAG for treating cancers. In breast cancer and prostate cancer, Hsp90 inhibitors can effectively downregulate ER and AR protein levels (Segnitz & Gehring 1997, Bagatell et al. 2001). Hsp90 inhibitors downregulate HER-2/neu, inhibit Akt activation, and enhance paclitaxel-induced apoptosis in HER-2/neu-overexpressed breast cancer cells (Basso et al. 2002, Solit et al. 2003). Thus Hsp90 inhibitors can be used to target hormone-dependent and -independent breast and prostate cancers with high activities of growth factor signaling pathways. A clinical trial combining 17-AAG and paclitaxel together against HER-2/neu-overexpressed breast cancer and prostate cancer is currently ongoing.

**Novel agents targeting tyrosine kinase receptor in hormone-resistant breast and prostate cancers**

Since crosstalks with other growth factors and their receptors — especially tyrosine kinase receptors — are important mechanisms for the emergence of antihormone resistance, an alternative method to block or reverse this resistance is targeting the growth factors and receptors themselves. Tyrosine kinases are tightly regulated enzymes that play an important role in the control of most fundamental cellular processes, including cell proliferation, differentiation, metabolism, migration, and survival. There are several potentially effective interventions of the signaling pathways of tyrosine kinase receptors, including agents targeting growth factors; anti-growth factor receptor antibodies such as trastuzumab (Herceptin), which target HER-2/neu-overexpressed breast cancer, and pertuzumab (2C4), which binds to a different epitope of HER-2/neu ectodomain than trastuzumab; monoclonal antibodies against EGFR such as IMC-C225 and a fully humanized anti-EGFR monoclonal antibody ABX-EGF; low-molecular-mass EGFR-specific tyrosine kinase inhibitors, such as gefitinib (ZD1839 or Iressa), which works by competing at the ATP-binding site on the tyrosine kinase domain of EGFR; OSI-774 (Tarceva), which specifically blocks the kinase activity of EGFR and EGFR autophosphorylation; CI-1033, which acts as a pan-EGFR tyrosine kinase inhibitor, and PKI-166, which is a reversible tyrosine kinase inhibitor and can block the enzymatic activity of HER-2/neu. All of these agents are presently in clinical trials or clinical practices and have been reviewed extensively (Johnston et al. 2003, Normanno et al. 2003, Madhusudan & Ganesan 2004). Thus, we will not discuss these agents here. Instead, we will describe a couple of novel agents that may have potential to interfere tyrosine kinase receptors.

**Emodin**

Emodin (3 methyl-1,6,8-trihydroxyanthraquinone), isolated from *Polygonum uspidatum*, is an inhibitor of protein tyrosine kinases (Jayasuriya et al. 1992). Emodin also initiates apoptotic pathways in cancer cells, such as hepatoma (Jing et al. 2002), cervical cancer (Srinivas et al. 2003), and leukemia cells (Chen et al. 2002). Emodin suppresses the autophosphorylation and transphosphorylation activities of HER-2/neu tyrosine kinase, resulting in tyrosine hypophosphorylation of p185neu in HER-2/neu-overexpressing breast cancer cells and non-small cell lung cancer (Zhang et al. 1995, Zhang & Hung 1996), suppressing their growth and sensitizing these tumors to several chemotherapeutic agents including paclitaxel, doxorubicin, etoposide, and cisplatin. In vivo Emodin also represses the growth of HER-2/neu-overexpressed breast cancer cells and sensitizes these cells to paclitaxel (Zhang et al. 1999). Since emodin inhibits tyrosine kinase activity, suppresses HER-2/neu phosphorylation, and enhances chemosensitivity of breast cancers, it has the potential to be an alternative therapy for HER-2/neu-overexpressed, hormone-resistant breast cancers.

**Type 5 adenovirus early region 1A (E1A) protein**

The E1A of human adenovirus type 5 encodes the proteins that activate viral transcription, thus permitting viral replication in infected cells (Flint & Shenk 1989). E1A was reported to have an antitumor growth effect and anti-metastasis effect (Pozzatti et al. 1988a, b, Frisch 1991, Chinnadurai 1992, Frisch & Mymryk 1991, 1993). There are several molecular mechanisms that may contribute to this anti-cancer effect of E1A: E1A can suppress HER-2/neu gene expression; E1A inhibits activation of NF-kB through suppression of 1xkB kinase (IKK) activity and 1xB phosphorylation, rendering cells to be more sensitive to environmental stress (Shao et al. 1997, 1999, 2001); E1A also negatively regulates the expression of Axl, which is a transforming receptor tyrosine kinase essential for tumor cell growth (Lee et al. 2009). When combined with chemotherapeutic agents, E1A can sensitize cells to the cytotoxic effect of drugs (Lowe et al. 1993, Ueno et al. 1997). This sensitizing effect,
K-M Rau, H-Y Kang et al.: Hormone-therapy resistance in breast and prostate cancers

which can be observed in a preclinical gene therapy setting using an orthotopic breast cancer animal model, may, through E1A, activate p38 and inactivate Akt (Liao & Hung 2003, Liao et al. 2004).

The first clinical trial of E1A gene therapy was initiated in 1996, which was the first gene-therapy trial focused on breast cancers and ovarian cancers (Hortobagyi et al. 2001). In this trial, E1A was delivered by a specific liposome into the thoracic cavity of breast cancer patients with pleural effusion, or into the peritoneal cavity of ovarian cancer patients with ascites. After E1A treatment, HER-2/neu expression in cancer cells derived from patients with HER-2/neu-overexpressing cancers decreased significantly. In addition, the local concentration of TNFα increased. E1A was known to sensitize TNFα-induced apoptosis; thus the enhanced TNFα may help E1A-mediated anti-cancer activity (Wold 1993, Shao et al. 1999). There are other clinical trials focused on breast, ovarian, and head and neck cancer that have been reported indicating the feasibility of the E1A gene therapy (Yoo et al. 2001, Villaret et al. 2002, Madhusudan et al. 2004).

In summary, E1A as a therapeutic gene can be used in several kinds of cancer. Its function is through not only downregulating HER-2/neu expression, but also interfering with mitogenic signaling pathways. These effects may work on hormone-dependent or -independent breast cancers, and may reverse hormone resistance.

Conclusion

The endocrine system controls the long-term coordination of whole body organs. A dysregulated response to hormones, in some cases, leads organs to receive the hormone as a growth stimulant and results in malignancy. Breast cancer and prostate cancer are the most well-known and well-studied examples of this. Although in most cases the cancers are initially sex-hormone-positive and responsive to antihormone therapy, the complicated interactions in these cells eventually will make the resistance inevitable. From previous reviews we know the emergence of resistance is composed of several mechanisms, which can work alone or in cooperation with each other, making treatment more complicated and difficult. However, the more we know about the mechanisms, the better we can predict the prognosis of patients and, more importantly, prevent the emergence of resistance and treat patients with different phenotypes.

One such example is the aromatase inhibitors. In postmenopausal women, aromatase can inhibit the production of estrogen from different sources, without the stimulatory effect from ligand, and aromatase inhibitors can prevent the emergence of resistance more effectively than TAM, as shown in several clinical trials including primary tumors, metastatic tumors, and chemoprevention trials (Fricker 2004). Following aromatase inhibitors, the pure anti-estrogen agent, fulvestrant, was shown to be more effective than aromatase inhibitors in postmenopausal women (Coleman 2003).

Cancer cells are heterogenous. There are differences not only between different individuals but also between different cells in the same individual. Currently there are emerging new tests to examine the phenotypes of cancers before we start to treat them or before we change the treatment protocols. Additionally, the therapeutic methods can be single or combination methodologies. In treating hormone-dependent cancers, there are also several preclinical and clinical trials combining antihormone agents with anti-growth factor agents to block crosstalk, therefore preventing and overcoming antihormone resistance. It is optimistic that combination therapies may soon provide effective strategies for the treatment of breast cancers and prostate cancers, and prevent the emergence of resistance.

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References


Brady ME, Ozaone DM, Gaughan L, Waite I, Cook S, Neal DE & Robson CN 1999 Tip60 is a nuclear hormone receptor coactivator. *Journal of Biological Chemistry* **274** 17599–17604.


Dotlaw H, Leygue E, Watson PH & Murphy LC 1999 Estrogen receptor-beta messenger RNA expression in human breast tumor biopsies: relationship to steroid...


Hamann LG, Mani NS, Davis RL, Wang XN, Marschke KB & Jones TK 1999 Discovery of a potent, orally active, nonsteroidal androgen receptor agonist: 4-ethyl-1,2,3,4-tetrahydro-6-trifluoromethyl-8-pyridonol[5,6-g]-quinoline LG121071. *Journal of Medicinal Chemistry* 42 210–212.


Hong H, Kohli K, Garabedian MJ & Stallcup MR 1997 GRIP1, a transcriptional coactivator for the AF-2 transactivation domain of steroid, thyroid, retinoid & vitamin D receptors. *Molecular and Cellular Biology* 17 2735–2744.


Howell A 2001 Preliminary experience with pure antiestrogens. *Clinical Cancer Research* 7 4369s–4375s; discussion 4411s–4412s.


Ikonen T, Palvimo JJ & Janne OA 1997 Interaction between the amino-and carboxyl-terminal regions of the rat androgen receptor modulates transcriptional activity and is influenced by nuclear receptor coactivators. *Journal of Biological Chemistry* 272 29821–29828.


Jackson TA, Richer JK, Bain DL, Takimoto GS, Tung L & Horwitz K B 1997 The partial agonist activity of antagonist-occupied steroid receptors is controlled by a novel hinge domain-binding coactivator L7/SPA and the corepressors N-CoR or SMRT. *Molecular Endocrinology* 11 693–705.


K-M Rau, H-Y Kang et al.: Hormone-therapy resistance in breast and prostate cancers


Segnitz B & Gehring U 1997 The function of steroid hormone receptors is inhibited by the hsp90-specific compound geldanamycin. *Journal of Biological Chemistry* **272** 18694–18701.


Yeh S & Chang C 1996 Cloning and characterization of a specific coactivator, ARA70, for the androgen receptor in human prostate cells. *PNAS* 93 5517–5521.


Yu D, Suen TC, Yan DH, Chang LS & Hung MC 1999 Transcriptional repression of the neu protooncogene by
the adenovirus 5 E1A gene products. PNAS 87 4499–4503.