Novel roles of prolactin and estrogens in breast cancer: resistance to chemotherapy

Elizabeth W LaPensee and Nira Ben-Jonathan

Department of Cancer and Cell Biology, University of Cincinnati, 3125 Eden Avenue, Cincinnati, Ohio 45267-0521, USA
(Correspondence should be addressed to N Ben-Jonathan; Email: nira.ben-jonathan@uc.edu)

Abstract

Resistance to chemotherapy is a major complication in the treatment of advanced breast cancer. Estrogens and prolactin (PRL) are implicated in the pathogenesis of breast cancer but their roles in chemoresistance have been overlooked. A common feature to the two hormones is activation of their receptors by diverse compounds, which mimic or antagonize their actions. The PRL receptor is activated by lactogens (PRL, GH, or placental lactogen) originating from the pituitary, breast, adipose tissue, or the placenta. Estrogen receptors exist in multiple membrane-associated and cytoplasmic forms that can be activated by endogenous estrogens, man-made chemicals, and phytoestrogens. Here, we review evidence that low doses of PRL, estradiol (E2), and bisphenol A (BPA) antagonize multiple anticancer drugs that induce cell death by different mechanisms. Focusing on cisplatin, a DNA-damaging drug which is effective in the treatment of many cancer types but not breast cancer, we compare the abilities of PRL, E2, and BPA to antagonize its cytotoxicity. Whereas PRL acts by activating the glutathione-S-transferase detoxification enzyme, E2 and BPA act by inducing the antiapoptotic protein Bcl-2. The implications of these findings to patients undergoing chemotherapy are discussed.

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Introduction

Each year, over a million women worldwide are diagnosed with breast cancer, accounting for 25% of all female cancers. Treatments include surgery, radiation therapy, chemotherapy, or their combinations. Neoadjuvant chemotherapy is used to reduce tumor size before surgery, while adjuvant chemotherapy is used after tumor excision. Chemotherapy is the mainstay treatment for patients with triple negative tumors (estrogen receptor (ER), progesterone receptor (PR), and human epidermal growth factor receptor 2 (Her-2)) who are resistant to hormone or targeted therapy, and for those with advanced metastatic disease (Coley 2008). Dozens of anticancer drugs have been developed, with treatment options taking into account tumor grade and histology and whether the desired outcome is curative or palliative. Most regimens combine drugs that act by different mechanisms aimed at improving the odds of suppressing tumor growth (Ocana & Pandiella 2008).

While both the selection and success of chemotherapeutic agents have increased, tumor resistance remains a major obstacle, which results in treatment failure. Some tumors are intrinsically resistant to certain drugs, while others acquire resistance following treatment. Resistance can result from drug efflux by transporters, inactivation by detoxification enzymes, altered expression of pro/antiapoptotic proteins, changes in tumor suppressor genes, and increased DNA repair mechanisms (Coley 2008). Whereas hormones such as prolactin (PRL) and estradiol (E2) have long been implicated in the pathogenesis of breast cancer, their involvement in chemoresistance has been overlooked. The objective of this review is to evaluate emerging evidence that these hormones confer resistance against a variety of chemotherapeutic agents that kill breast cancer cells by different mechanisms and discuss the clinical implications.

PRL and estrogens are dissimilar in chemical structure, receptor characteristics, and signaling mechanisms. Whereas estrogens can bind to several classical (ERα and ERβ) and nonclassical (G protein-coupled receptor 30, GPR30) receptors (Manavathi & Kumar 2006), there is only one receptor (PRLR) for PRL, albeit it exists in several isoforms which couple to different signaling pathways (Swaminathan et al. 2008). Yet, there is crosstalk between the two hormones, with PRL...
increasing the expression and phosphorylation of ERα (Carver et al. 2009), and E₂ inducing the transcription of both PRL (Duan et al. 2008) and the PRLR (Swaminathan et al. 2008). Such interactions can result in augmentation, or synergism, between the two hormones.

Several features that are common to PRL and E₂ confound the understanding of their roles in breast cancer. One is the multiple sites of origin, with both hormones reaching the breast from the systemic circulation as well as from local sources (Ben-Jonathan et al. 2002, Foster 2008). Thus, blood levels of PRL or E₂ do not reveal the full extent of breast exposure to these hormones. Another is a variable expression of their receptors in tumors, which often depends upon the luminal or basal origin of the tumor. Thus, neither hormone affects tumors that do not express its receptor. Importantly, 80–90% of breast carcinomas express the PRLR (Touraine et al. 1998), while ~75% contain ERα (Karayiannakis et al. 1996). This indicates that most breast tumors express both receptors, reinforcing their importance as therapeutic targets. Finally is the issue of receptor promiscuity, with ERs capable of binding steroidal and nonsteroidal compounds (Bai & Gust 2009), and the PRLR capable of binding other lactogens (Goffin et al. 2005). Thus, xenoestrogens can mimic or antagonize endogenous estrogens, while GH and placental lactogen (PL) can augment or interfere with PRL actions. Figure 1 illustrates the various compounds that affect breast cancer via their interactions with either the PRLR or ERs.

**Properties of selected chemotherapeutic drugs**

Over the past 20–30 years, treatment of metastatic breast cancer has evolved from the anthracyclines to taxanes to hormonal and targeted therapy and their combinations (Coley 2008). Here, we focus on those drugs that are affected by PRL and/or estrogens.

*Figure 1* Diagram of the different compounds and their sites of origin which affect breast cancer by activating either the prolactin (PRL) receptor (PRLR) or estrogen receptors (ERs). The right side of the illustration depicts the three structurally related lactogens, prolactin (PRL), GH, and placental lactogen (PL), which bind to the PRLR. The left side shows the variety of compounds which activate either classical or nonclassical ERs. These include natural estrogens: estradiol (E₂) and estriol (E₃); man-made chemicals, diethylstilbestrol (DES), ethinylestradiol (EE₂), and bisphenol A (BPA); and phytoestrogens. Adipose tissue represents the stromal compartment within the breast as well as abdominal and subcutaneous depots. Both PRL and estrogens (likely via aromatization) are also produced within tumor cells themselves, where they act as autocrine/paracrine agents.
Cisplatin is a platinum-based drug that is highly effective against testicular, ovarian, and lung cancers but has limited efficacy as monotherapy in breast cancer patients (Decatris et al. 2004). Following uptake into the nucleus, cisplatin interacts with DNA and forms adducts via intrastrand cross-links that induce cell cycle arrest. The DNA can either be repaired by the nucleotide excision pathway, or the cell is destined to die (Kelland 2007). The caspase 3-deficient MCF7 cells are not killed by cisplatin (Blanc et al. 2000), although cisplatin can induce apoptosis via a caspase 3-independent mechanism in ovarian cancer cells (Henkels & Turchi 1999).

Doxorubicin (adriamycin) is an anthracycline antibiotic used in multiple cancers, and is considered the standard treatment in breast cancer. Upon entering the nucleus, doxorubicin inhibits topoisomerase II and helicase activities, and interferes with DNA double helix religation. This stops DNA replication and induces apoptosis (Rabbani et al. 2005). Apoptosis may occur via activation of pro-apoptotic proteins, since antisense against Bcl-2 and Bcl-xL sensitizes breast cancer cells to this drug (Simoes-Wust et al. 2002). Doxorubicin can also cause replicative senescence, as evident by micronuclei formation and senescence-associated β-galactosidase staining (Chang et al. 2002).

Taxol (paclitaxel) has been highly successful in treating breast and ovarian cancer, especially in combination with anthracyclines. Taxol targets the microtubules, which mediate alignment of the chromosomes along the equatorial plane prior to segregation to daughter cells. It binds to polymerized tubulin and inhibits microtubule disassembly, thereby suppressing both microtubule treadmilling and dynamic instability (Zhou & Giannakakou 2005). Taxol-induced apoptosis often correlates with phosphorylation of Bcl-2 (Ferlini et al. 2003). Apoptosis can occur via caspase 3-dependent or -independent mechanisms (Friedrich et al. 2001).

Vinblastine, a vinca alkaloid, is another microtubule-altering drug. Unlike taxol, it binds to monomeric tubulin and prevents its polymerization. Mitosis is blocked at the metaphase/anaphase transition, and the prolonged arrest leads to cell death (Zhou & Giannakakou 2005). Vinblastine also interferes with amino acid, cAMP, and glutathione metabolism, and can induce apoptosis through the nuclear factor κB/inhibitor of κB (NF-κB/IκB) pathway (Huang et al. 2004). Apparently, c-Jun protects T47D cells from vinblastine-induced cell death, although it does not prevent the mitotic block (Duan et al. 2007). At nontoxic doses, vinblastine inhibits chemotaxis and endothelial cell proliferation, highlighting its antiangiogenic properties (Vacca et al. 1999).

Apoptotic signals are also mediated via the tumor necrosis factor (TNF) family of death receptors. The TNF-related apoptosis-inducing ligand (TRAIL) induces oligomerization of the intracellular domains (ICDs) of the death receptors and causes apoptosis in many cancer cell types without killing normal cells (Wang & El Deiry 2003). In recent clinical trials, TRAIL agonists showed no major toxicity, but therapy is limited to patient with TRAIL-sensitive tumors (Bellail et al. 2009).

The dependence of tumor expansion and metastasis on angiogenesis has lead to the development of angiogenesis blockers, which inhibit the release of pro-angiogenic proteins such as VEGF, block mitogenic/survival pathways of endothelial cells, or prevent extracellular matrix breakdown (Sessa et al. 2008). Over 300 angiogenic inhibitors have been developed, and dozens are in various phases of clinical trials. Avastin, an anti-VEGF monoclonal antibody, was the first antiangiogenic drug shown to prolong patient survival.

Mechanisms of chemoresistance

Resistance to chemotherapy results from many causes, including drug extrusion by transporters, drug metabolism, increased antiapoptotic proteins, decreased pro-apoptotic proteins, and enhanced DNA damage repair. A major problem is that tumors often exhibit resistance to a diversity of chemotherapeutic agents, which act by different mechanisms.

Multidrug resistance transporters, which target structurally diverse drugs, are major contributors to drug resistance. The best characterized are members of the ATP-binding cassette transporters, which include P-glycoprotein, multidrug resistance protein 1 (MRP1), and breast cancer resistance protein (BCRP; Higgins 2007). P-glycoprotein confers resistance against taxol, vinblastine, doxorubicin, and etoposide, with over 40% of breast tumors expressing this transporter (Trock et al. 1997). MRP1 confers resistance against anthracyclines, antifolates, and vinca alkaloids, but not against taxanes or cisplatin (Trock et al. 1997). Although originally isolated from a drug-resistant MCF7 subline, the BCRP protein is rarely found in E2-responsive cells, because of its downregulation by estrogens (Imai et al. 2005).

The glutathione metabolic pathway confers resistance against environmental insults and drugs. Glutathione-S-transferases (GSTs) are phase II detoxification enzymes that catalyze the conjugation of
glutathione to electrophilic compounds, resulting in easily extruded products (Townsend & Tew 2003, McIlwain et al. 2006). They inactivate platinum drugs, doxorubicin, cyclophosphamide, and etoposide, but not antimicrotubule drugs. Some GST isoforms inhibit JNK1 via protein:protein interactions and inactivate drugs that act via the mitogen activated protein (MAP) kinase pathway even when they are not subject to conjugation with glutathione. GSTs are inducible enzymes classified by substrate specificity and intracellular distribution into several families, e.g. α, μ, π and θ subtypes. Overexpression of GST π is associated with drug resistance and poor patient survival, while mutations in GST μ and GST π predispose the affected individuals to environmental carcinogens (Shiga et al. 1999).

Tumors can acquire drug resistance by overexpressing antiapoptotic proteins (e.g. Bcl-2 and Bcl-xL) or downregulating pro-apoptotic proteins (e.g. Bax). MCF7 cells, which express high levels of Bcl-2, are less responsive to cisplatin, but become sensitized to the drug upon Bcl-2 downregulation by RNA interference (Yde & Issinger 2006). Breast cancer cells that overexpress Bcl-xL are less sensitive to paclitaxel, which correlates with failure of the drug to activate caspase 9 (Wang et al. 2005). In addition, Bax overexpression in MCF7 cells restores their sensitivity to various apoptotic agents. Higher Bax expression levels are detected in normal breast epithelium than in adjacent tumors (Bargou et al. 1996).

Mutations in tumor suppressors strongly influence cancer cells sensitivity to anticancer drugs. Alterations in p53 are the most common genetic changes in breast cancer, with specific mutations associated with resistance to doxorubicin (Aas et al. 1996). The tumor suppressor gene BRCA1 is also frequently mutated in breast cancer. It responds to DNA damage by affecting DNA damage repair. Loss of BRCA1 confers sensitivity to many DNA-damaging agents (Kennedy et al. 2004), and its knockdown results in a twofold increase in cell sensitivity to irofulven (Wiltshire et al. 2007).

Characteristics of PRL and PRLR

PRL is a 23-kDa hormone of pituitary origin whose main target is the breast, where it stimulates proliferation, differentiation, survival, and secretory activity (Ben-Jonathan et al. 2008). Depending upon the cell context and physiological conditions, PRL can exert opposite actions such as proliferation versus differentiation in both malignant and nonmalignant cells. PRL belongs to a family of proteins, named lactogens, which share structural homology and some overlapping functions. The most prominent members are PRL, GH, and PL, which are made of a single polypeptide chain with 2–3 intramolecular disulfide bridges. Lactogens have a high homology in their primary amino acids and a similar tertiary structure, composed of four antiparallel, up–up, down–down helical bundle (Teilum et al. 2005).

Unique to humans, PRL is also produced in multiple nonpituitary sites, including the decidua, myometrium, breast, and prostate (Ben-Jonathan et al. 1996). Whereas pituitary PRL is controlled by a proximal promoter which requires the pituitary-specific Pit-1 transcription factor for transactivation, expression of extrapituitary PRL is driven by a superdistal promoter (Gerlo et al. 2006). The insensitivity of the superdistal promoter to dopamine explains the failure of dopamine agonists, such as bromocriptine, to suppress breast PRL and affect PRL-dependent tumors in patients (Ben-Jonathan et al. 2008). Within the normal breast, PRL is produced at much larger quantities by stromal adipocytes than by the epithelium (Zinger et al. 2003) and is up-regulated in carcinomas as compared with benign breast epithelium (McHale et al. 2008).

The PRLR is a member of the cytokine receptor superfamily, which is nontyrosine kinase, single-pass membrane receptor. It has a three-domain organization: an extracellular ligand-binding domain, which confers specificity, a short transmembrane domain, and an ICD (Swaminathan et al. 2008, Clevenger et al. 2009). In addition to the most abundant 80 kDa long isoform, shorter variants that couple to different signaling pathways are detectable in breast cancer. Among cell lines, T47D cells express the highest PRLR levels, followed by MCF7, BT483, MDA-MB-468, and BT474 (Peirce et al. 2001). The human PRLR is indiscriminate in its binding preferences, with GH binding not only to its receptor (GHR) but also to the PRLR. In contrast, nonprimate GH binds only to the GHR, while PRL binds only to the PRLR but not to GHR in any species (Ben-Jonathan et al. 2008). PL does not have a receptor of its own and binds only to the PRLR (see Fig. 1).

Two binding sites on the ligand are required for PRLR activation. One receptor binds to a high affinity site 1, while a second receptor binds to a lower affinity site. This forms an active ternary complex composed of one hormone molecule and receptor homodimer (Teilum et al. 2005). The existence of preformed, inactive dimers without a ligand suggests that receptor dimerization is necessary but insufficient for its activation (Clevenger et al. 2009). Ligand binding induces relative rotations of the two units, resulting in allosteric reorganization of the ICD. This brings the
ICD and Jak2 kinase into close proximity, enabling their phosphorylation. The lactogens, which differ in critical interacting residues, do not induce identical conformational changes in the receptor (Gertler et al. 1996). Instead, each imposes a different stability on the active complex, thereby affecting its dynamics and binding parameters of the associated partners.

Several PRLR antagonists, made by modifications of the PRL molecule, have been generated, which block PRL actions in vitro and in experimental animals (Goffin et al. 2005). However, their use as an effective treatment in breast cancer patients is uncertain because of their short half-life and the necessity for their administration by injection. Efforts are underway to find small molecules that selectively block the PRLR and can be delivered orally.

Binding of PRL to its receptor activates several signaling pathways, of which the Jak2–Stat5 pathway is the best understood. Jak2 is rapidly activated by PRL and phosphorylates Stat proteins. These dimerize and translocate to the nucleus, where they bind to GAS elements within the promoters of target genes. Stat5a/b mediate many of the PRL actions in normal and malignant breast cells (Clevenger et al. 2009). PRL-responsive genes that are involved, directly or indirectly, in cell cycle regulation include cyclin D1, AP-1, c-Myc, and heat shock protein α (Brockman et al. 2002, Acosta et al. 2003, Gutzman et al. 2005, Perotti et al. 2008).

Although activation of the Jak2–Stat pathway is critical for lobuloalveolar development and lactation in the normal breast, other PRL-induced pathways are important in breast cancer. One is the Ras–Raf–MAPK pathway, with ERK1/2 and c-jun N-terminal kinase being its primary mediators. PRL induces phosphorylation of ERK1/2 in both T47D and MCF7 cells, and can synergize with epidermal growth factor (EGF) to induce ERK (Acosta et al. 2003). Activation of the phosphoinositide-3-kinase (PI3K)–Akt survival pathway by PRL has been implicated in cell migration (Maus et al. 1999). Crosstalk between PRLR and ERα occurs at several levels. For example, PRL and E2 cooperatively enhance AP-1 activity (Gutzman et al. 2005), and E2 rapidly phosphorylates Stat5 (Fox et al. 2009), while PRL activates the unliganded ER (Gonzalez et al. 2009).

Role of PRL in carcinogenesis

The role of PRL in mammary tumorigenesis in rodents has long been recognized, while its involvement in breast cancer only recently became accepted. Prospective studies found a modest association between higher serum PRL levels and cancer risk in both premenopausal and postmenopausal women, primarily those with ER+ tumors (Ttworoger & Hankinson 2008). However, shortcomings of epidemiological studies include single blood sample determination and assay standardization. Most importantly, they do not take into account the local production of PRL by the breast or the status of PRLR expression in the tumors.

PRL exerts multiple actions in breast cancer cells, including increased proliferation, enhanced motility, and prolonged survival. Suppression of T47D cell proliferation by PRL antisense oligos, anti-PRL antibodies, and PRLR antagonists served as the evidence for the mitogenic activity of autocrine PRL (Chen et al. 1999, Vonderhaar 1999, Llovera et al. 2000). The role of autocrine/paracrine PRL is supported by studies with nude mice, where growth of tumors derived from T47D cells is inhibited by treatment with the hPRL antagonist G129R (Chen et al. 2002), while PRL overexpressing MDA-MB-435 cells form faster growing tumors (Liby et al. 2003).

PRL also affects cytoskeleton modulation, as reveals by its enhancement of breast cancer cell migration and induction of PI3K-dependent membrane ruffling and stress fibers (Maus et al. 1999). PRL and its cleaved fragment 16K PRL can stimulate and inhibit angiogenesis respectively, suggesting an indirect role for PRL in carcinogenesis via alterations in tumor blood supply (Clapp et al. 2008). Of great importance is a recent report that mouse PRL does not activate the human PRLR (Utama et al. 2006), raising issues of interpretation of drug responsiveness of human xenografts in mice, which are unaffected by circulating PRL.

Unlike estrogen, PRL is only a modest mitogen in breast cancer. In fact, Stat5 activation by PRL may be linked to induction of differentiation and suppression of invasion rather than to proliferation (Sultan et al. 2005). This is supported by a lower expression of activated Stat5 in node-positive breast cancer than in normal breast or less advanced tumors (Nevalainen et al. 2004). Yet, the argument that PRL acts solely as an antimetastatic factor is overreaching, since signaling pathways other than Stat5 are activated by PRL. PRL could serve as a suppressor of metastasis in advanced tumors but as a promoter of cell growth in early tumors. A switch between tumor promotion to suppression is exemplified by transforming growth factor-β (TGFβ), which inhibits the growth of normal epithelial cells but accelerates the malignant process of late-stage tumors (Bachman & Park 2005). Estrogen represents another case of contrasting actions, since in addition to its mitogenic actions it can induce apoptosis under some conditions (Lewis-Wambi & Jordan 2009).
PRL and chemoresistance

Accumulating evidence suggests that PRL opposes cytotoxicity by a wide variety of anticancer drugs. In PC3 prostate cancer cells, TRAIL-induced apoptosis is partially inhibited by PRL, which by itself has no effect on cell proliferation (Ruffion et al. 2003). Another group reported that pretreatment of ovarian carcinoma cells with PRL inhibits cisplatin-induced cell death (Asai-Sato et al. 2005). PRL also antagonizes apoptosis caused by methotrexate, an antifolate agent, in human promyelocytic leukemia HL-60 cells (Hsu et al. 2006).

Epidemiological data suggest that women with elevated blood PRL levels have increased treatment failure and worse survival (Tworoger & Hankinson 2008). Indeed, hyperprolactinemic patients with metastatic breast cancer are less responsive to taxol than those with normal serum PRL levels (Lissoni et al. 2001). A small clinical trial revealed better responsiveness in patients treated with a combination of taxol and bromocriptine, compared to those receiving only taxol (Lissoni et al. 2002). These data should be replicated in larger trials with PRL inhibitors (i.e. bromocriptine and cabergoline) together with various anticancer drugs. However, an effective blockade of the PRLR would likely be more effective in sensitizing tumors to anticancer drugs than the suppression of pituitary PRL release.

Several studies have focused on PRL as an anticytotoxic factor in breast cancer cells. Ramamoorthy et al. (2001) found that induction of apoptosis by cisplatin in T47D cells is enhanced by co-treatment with the hPRL antagonist G129R, suggesting that endogenous PRL is protective. Another antagonist, Δ1-9-G129R-hPRL, potentiates the effects of pacli-taxel and doxorubicin in breast cancer cells (Howell et al. 2008). In addition, cells that produce PRL, e.g. T47D and MCF7, are more resistant to ceramide-induced apoptosis than those with low or no PRL (Perks et al. 2004). PRL can also overcome growth arrest caused by γ-irradiation (Chakravarti et al. 2005). None of the above studies, however, have resolved the mechanisms underlying the protective effects of PRL.

Our exploration of the mechanism by which PRL antagonizes anticancer drugs was inspired by the finding that PRL overexpression in MDA-MB-435 cells enhanced tumor growth and up-regulated Bcl-2 (Liby et al. 2003). Pretreatment of breast cancer cells with low doses of PRL antagonizes cytotoxicity by taxol, vinblastine, doxorubicin, and cisplatin, albeit at different efficacies (LaPensee et al. 2009b). We were especially interested in the mechanism by which PRL opposed cisplatin, which has shown only little effectiveness in breast cancer patients. Unlike its strong apoptotic effects in MDA-MB-468 cells, cisplatin is only moderately effective in T47D cells. Reasoning that the resistance of T47D cells may be due to their high endogenous PRL levels, the mechanistic studies were conducted with MDA-MB-468 cells.

Measurement of platinum in nuclear extract by mass spectroscopy reveals that PRL reduces the amount of cisplatin bound to DNA. Lower entry of cisplatin into the nucleus could be due to transporters such as MRP that extrude the drug, or to detoxification enzymes such as GST that inactivate cisplatin (Siddik 2003). Previous work showed that PRL increases hepatic GST activity (Luquita et al. 1999). Using inhibitors of the two potential targets, we discovered that GST, but not MRP, accounts for the suppression of cisplatin entry to the nucleus by PRL. This action is mediated by the Jak–Stat and MAPK pathways, but not by PI3K pathway. Subsequent studies show that PRL induces the expression of the GST μ isoform and increases GST enzyme activity in MDA-MB-468 cells (LaPensee et al. 2009b). The GST μ- and θ-null genotypes are associated with increased survival in women with advanced breast cancer that were treated with chemotherapy (Ambrosone et al. 2001). Future studies should determine whether knockdown of specific GST isozymes abrogates the protective effects of PRL.

A model which conceptualizes the mechanism by which PRL confers resistance against cisplatin is presented in Fig. 2. After diffusing into the cell, cisplatin enters the nucleus and binds to DNA, with the ensuing cell cycle arrests leading to apoptosis. Binding of PRL to its receptor induces the activation of Jak–Stat and MAPK pathways, which separately or in concert increase the expression and activity of GST. GST conjugates cisplatin to glutathione, leading to its extrusion from the cell. Consequently, less cisplatin is available for entering the nucleus and inflicting DNA damage. The overall effect of PRL is a marked reduction in cisplatin-induced cell death. In addition to cisplatin, GST confers resistance to doxorubicin but not to the microtubule-altering drugs (L’Ecuyer et al. 2004). Thus, the mechanism by which PRL antagonizes drugs which are not substrates for GST may involve alterations in Bcl-2 family proteins.

Estrogens: multiple ligands and diverse receptors

E2, estriol, and estrone are naturally occurring estrogens, which differ in affinity for the various ERs. They have dissimilar bioactivities, with E2 being the most potent. From menarche to menopause, the ovaries
are the primary source of estrogens. After menopause, estrogens can be generated through the conversion of androgens secreted by the adrenals and the ovaries. This process is carried out in sites such as the skin and adipose tissue by the aromatase enzyme complex (Jongen et al. 2006; see Fig. 1).

Breast cancer expresses several sex steroid-producing enzymes, including aromatase, 17β-hydroxysteroid dehydrogenase, which catalyzes interconversion among estrogens, and steroid sulfatase, which hydrolyzes sulfated steroids to their bioactive forms (Suzuki et al. 2005). Although serum E2 levels in postmenopausal women are only 5–10% of those before menopause, their tumors are exposed to comparable levels of active estrogens. Indeed, the tumor/plasma ratio of E2 is >20 in breast carcinomas from postmenopausal women but only 5 in those from premenopausal women (Pasqualini et al. 1996). Aromatase inhibitors are effective in blocking the growth of early ER+ tumors (Nabholtz et al. 2009). Similar to the higher production of PRL by breast stroma (Zinger et al. 2003), estrogen synthesis is higher in the stroma than in epithelial cells due to higher expression of aromatase (Santen et al. 1997).

As schematically illustrated in Fig. 1, endocrine disruptors that mimic or antagonize endogenous estrogens are relevant to breast cancer. Estrogen-like compounds include pesticides, industrial chemicals, pharmaceuticals, and plant-derived compounds, all of which can expose humans through food or water supply (Gray et al. 2009). Many are lipophilic and can be stored in adipose tissue. The most widely studied are components of plastics, e.g. bisphenol A (BPA; discussed in the next chapter), and detergents such as octyl and nonyl phenols. Chlorinated insecticides, e.g. kepone, dichloro diphenyl trichloroethane (DDT), dieldrin, and methoxychlor, also possess estrogen-like properties. Two unresolved issues are whether early exposure to endocrine disruptors increases the risk of developing breast cancer, and what is the effect of interactions between chemicals in mixtures (Birnbaum & Fenton 2003, Gray et al. 2009).
Diethylstilbestrol (DES) and ethinylestradiol are potent pharmaceuticals used to treat symptoms of menopause, as contraceptives and as palliative therapy in advanced prostatic cancer. Given the millions of users, home toilets are the major source of these compounds in wastewater (Falconer 2006). Although excreted into urine as inactive glucuronides or sulfates, some can be degraded in sewage treatment plants and release the active compounds.

Resveratrol, daidzein, quercetin, and genistein represent the most commonly ingested and intensely studied plant-derived phytoestrogens (Martin et al. 2007, Mense et al. 2008). They show differential binding to ERα and ERβ, exert nongenomic actions, and also affect estrogen biosynthesis and metabolism. Although the general belief is that long-term consumption of phytoestrogens (i.e. soy products) helps in reducing a woman’s risk of breast cancer, this notion is controversial (Martin et al. 2007, Gray et al. 2009).

Estrogens bind to multiple receptors of diverse structure that can be localized in the membrane, cytoplasm, and nucleus. ERα and ERβ differ in their ligand-binding domain, underlying the dissimilar binding affinities of the various estrogenic ligands to the two receptors. ERα is expressed at low levels in the normal breast epithelium (Ricketts et al. 1991), but increases in in situ carcinomas (Karayiannakis et al. 1996). The expression pattern of ERβ is opposite that of ERα, suggesting that loss of ERβ expression indicates breast cancer development and/or progression (Shaaban et al. 2003). Following ligand binding, classical ERs dimerize and bind to estrogen response elements in the promoters of target genes. Recruitment of co-regulators results in the formation of complexes that mediate transcription (Nilsson et al. 2001). The plethora of cell-specific co-activators and co-repressors account, in part, for the partial agonist versus antagonist activities of tamoxifen in the uterus, breast, bone, and cardiovascular system.

Similar to the differential binding dynamics of the three lactogens to the PRLR (Gertler et al. 1996), the various estrogenic ligands can induce distinct changes in ER conformation, thereby altering co-factor recruitment and receptor stability (Bai & Gust 2009). This is exemplified by an induction of rapid ERα degradation by the pure ER antagonist ICI 182 780, but not by E2 or tamoxifen (Van Den Bemd et al. 1999). The ERs also regulate transcription via protein–protein interactions with transcription factors such as the Fos–Jun complex (Normanno et al. 2005).

Estrogens can rapidly activate the MAPK and PI3K/Akt signaling pathways, traditionally associated with membrane receptors (Bjornstrom & Sjoberg 2005), but the nature of the receptor(s) involved is controversial. In neurons, pituitary and endothelial cells, G-proteins, ion channels, cytoplasmic protein kinases, and adaptor proteins have been implicated (Manavathi & Kumar 2006, Fox et al. 2009). In breast cancer cells, one model stipulates that a subpopulation of ERs is localized to the cell membrane. Steroid receptors do not have transmembrane or kinase domains and thus are unlikely to be incorporated to the cell membrane as integral proteins. Instead, they may interact via palmitoylation of membrane-associated proteins such as caveolin, striatin, and Sch (Song et al. 2006). Both IGF1 and EGF receptors are involved in tethering ERα to the membrane and in initiating MAPK and PI3K activation. Although the above model provides an plausible explanation for nongenomic actions of E2, it does not explain the rapid actions of some xenoestrogens, which have much lower affinities to ERα and ERβ, and yet are active at subnanomolar doses (Watson et al. 2007).

GPR30, a 7-transmembrane domain receptor that signals through trimeric G-proteins, represents a different model by virtue of its direct binding to estrogens (Filardo & Thomas 2005, Prossnitz et al. 2008). Its actions have mostly been studied in SKBr3 breast cancer cells, which express GPR30 but not classical ERs (Filardo et al. 2000). Estrogen signaling can be restored in the ER-negative MDA-MB-231 cells by transfection with GPR30. Binding of E2 to GPR30 stimulates the cAMP pathways through Gzx, and Src through Gβγ. Subsequently, heparan-bound EGF is released, activates the EGF receptor and its downstream signaling that include MAPK, PI3K, and phospholipase C (PLC) (Filardo & Thomas 2005). Both tamoxifen and ICI act as agonists, rather than antagonists, of GPR30. Expression of GPR30 is higher in invasive carcinoma and is associated with larger tumor size, suggesting that it may be a predictor of aggressive disease (Filardo et al. 2006). The relatively high binding affinity of GPR30 to E2 (Kd of 3 nM) makes this receptor a likely mediator of estrogen actions in ER-negative breast cancer cells (Thomas et al. 2005), but its relative role in cells that also express ERα and ERβ is unclear.

Chemoresistance by estrogens

In spite of the abundance of man-made or plant-derived estrogen mimetics which can impact on breast cancer, little is known about their potential interactions with anticancer drugs. In addition, only few studies have examined the role of endogenous estrogens in chemoresistance. This oversight is enigmatic because
stimulation of tumor growth by estrogens involves not only increased cell proliferation but also reduced cell death. This is exemplified by the activation of both the PI3K/Akt survival pathway and Bcl-2 antiapoptotic proteins in breast cancer by estrogens (Huang et al. 1997, Rodrik et al. 2005). Perhaps research on anticytotoxic effects of estrogens has been hampered by an adherence to the classification of breast cancer cells into those that express classical ERs (estrogen-responsive) and those that do not (estrogen-unresponsive), leading many researchers to ignore cells that do not express ERα or ERβ.

As a follow-up in our studies on antagonism of cisplatin by PRL (LaPensee et al. 2009b), we ask whether E2 acts similarly and if so, by what mechanism. Low doses of E2 (0.01–10 nM) abrogate cisplatin toxicity in T47D and MDA-MBA-468 cells by increasing cell proliferation and decreasing apoptosis (LaPensee et al. 2009a). Protection by estrogen occurs in the presence of ERα and ERβ antagonists, in ERα-negative MDA-MB-468 cells, and in T47D cells with ERβ knockdown, indicating independence of classical ERs. Since both cell types express GPR30 (LaPensee et al. 2009c), this receptor is a plausible candidate for transducing survival signals by E2. Future studies should determine whether GPR30 knockdown abrogates the protective effect of E2.

Unlike PRL, E2 does not alter entry of cisplatin into the nucleus, suggesting that its protective effects occur downstream of DNA damage (LaPensee et al. 2009a). Because previous reports implicated Bcl-2 in estrogen-induced chemoresistance (Teixeira et al. 1995, Huang et al. 1997), we focused on this antiapoptotic protein. Indeed, E2 increases Bcl-2 expression in T47D cells, both in the presence and absence of cisplatin, but does not alter Bcl-xL or Bax. A Bcl-2 inhibitor partially abrogates the protection by E2, indicating that alterations in Bcl-2 may be only part of its mechanism of actions (LaPensee et al. 2009a).

Other data support the concept that estrogens confer chemoresistance. For example, MCF7 cells depleted of estrogen are twice as sensitive to doxorubicin than estrogen-treated cells (Teixeira et al. 1995). Estrogen depletion is accompanied by decreased Bcl-2 expression, and Bcl-2 reconstitution restores resistance to doxorubicin. Others reported that modulation of Bcl-2 levels affects cell sensitivity to taxol (Huang et al. 1997). Also, E2 reduced taxol cytotoxicity in cells overexpressing ERα, with the cells sensitized to taxol by treatment with the ERα antagonist ICI (Sui et al. 2007). Estrogen also antagonizes taxol- and radiation-induced apoptosis by altering JNK activity (Razandi et al. 2000). A combination of tamoxifen and TRAIL is more effective than each alone in inducing apoptosis in the ERα-negative MDA-MB-231 cells, and in arresting tumor growth in xenografts (Lagadec et al. 2008). This sensitization was associated with decreased Bcl-2 and increased Bax levels. Another mechanism by which estrogens can increase chemoresistance is by affecting drug transporters. This was revealed by estrogen-induced increase in cytoplasmic p-glycoprotein in MCF7 cells, which are resistant to doxorubicin cytotoxicity, but not in T47D cells, which are sensitive to the drug (Zampieri et al. 2002).

**BPA, breast cancer, and chemoresistance**

BPA is used in the manufacture of polycarbonate plastics and is the constituent of a wide array of consumer products, including plastic food containers, baby bottles, and the lining of metal food cans (Welshons et al. 2006). Migration of BPA into food or water from plastic containers is influenced by the manufacturing process, storage conditions, and heating by users (Kang et al. 2006, Le et al. 2008). Human exposure to BPA is well documented, with BPA detectable at 0.2–10 ng/ml in serum from most individuals tested (Welshons et al. 2006). Being lipophilic, BPA can accumulate in breast adipose tissue (Fernandez et al. 2007).

The mechanism by which BPA exerts its actions is enigmatic, since its binding affinity for ERα or ERβ is 10 000- and 1000-fold lower than that of E2 respectively (Kuiper et al. 1998). Yet, BPA at low nanomolar or subnanomolar doses often elicits activities that are similar to those of E2 (Watson et al. 2005, Hugo et al. 2008). It has been suggested that BPA binds differentially within the ligand-binding domain of the ERs or recruits a different set of co-activators (Safe et al. 2002). In addition, estrogen-related receptors (ERRs) may serve as alternative receptors for transmitting BPA signals (Ariazi & Jordan 2006). Although ERRs do not bind estrogen, ERRγ binds BPA with high affinity ($K_d$ of 5.5 nM; Okada et al. 2008). ERRγ is overexpressed in 75% of breast tumors compared to the normal epithelium (Ariazi et al. 2002). Phytoestrogens have also been identified as ERR ligands (Ariazi & Jordan 2006).

BPA rapidly activates nongenomic signaling in many cell types. In MCF7 cells, MAPK and Akt are phosphorylated within 10 min of BPA exposure, similar to that seen with E2 and other xenoestrogens (Li et al. 2006). BPA at low doses induces rapid influx of calcium in breast cancer cells (Walsh et al. 2005) and rat hippocampal neurons (Tanabe et al. 2006). In cerebellar neurons, Belcher et al. (2005) observed a
rapid BPA-induced activation of ERK1/2, PKA, and Src family kinases but not PI3K/Akt pathways. BPA at very low doses (0.01–1 nM) rapidly activates cAMP- and cGMP-dependent protein kinase and triggers rapid phosphorylation of CREB in human testicular seminoma cells (Bouskine et al. 2009). These BPA actions are neither reversed by ICI 182 780 nor reproduced by E2 or DES, leading the authors to conclude that classical ERs are not involved.

The estrogenic activity of BPA was discovered upon noticing that BPA leaching from autoclaved plastic containers increases growth of MCF7 cells (Krishnan et al. 1993). In spite of its striking structural resemblance to DES, BPA exhibits a much lower binding affinity to either ERα or ERβ (Ben-Jonathan & Steinmetz 1998). The low binding affinity of BPA to classical ERs explains its inability to exert a strong mitogenic activity in MCF7 cells. One study found increased cell proliferation in response to BPA only at 60 000 times higher concentrations than E2 (Olsen et al. 2003). Another group confirmed that BPA at a relatively high dose (1 μM) showed a modest stimulation of proliferation of MCF7 cells cultured in estrogen-depleted medium, while E2 was effective at subnanomolar concentrations (Hess-Wilson et al. 2006).

Differential gene profiling in response to BPA has also been reported. In one study, BPA induces a different set of genes than E2 in MCF7 cells, and about 15 genes in ER-null MCF7 cells, leading the authors to conclude that at least some of its actions are independent of ERα (Singleton et al. 2004). Another group added BPA to cultures of breast tissue aspirates (Dairkee et al. 2008). Expression profiling revealed that BPA is associated with high grade tumors and decreased patient survival. These data suggest that exposure to BPA may contribute to the establishment and/or maintenance of breast tumors. In both studies, however, the BPA doses were at the upper nanomolar to micromolar levels. A major criticism of studies using BPA at very high doses is that they do not reflect human exposure levels to this compound. Since BPA exhibits a ‘U’-shaped dose-dependent curve in MCF7 cells (Samuelsen et al. 2001), extrapolation from its action, or lack of action, at high doses to its presumed activity at low doses can be misleading.

Our study was the first to report that BPA at environmentally relevant concentrations confers chemoresistance (LaPensee et al. 2009c). Similar to the actions of PRL and E2, BPA antagonizes multiple anticancer drugs, showing equimolar potency with E2 in opposing cisplatin toxicity. These BPA actions do not appear to be mediated via ERα and ERβ, but the receptor involved was not identified (LaPensee et al. 2009c). In addition to GPR30, we found that both MDA-MB-468 and T47D cells express ERRγ. Given its high binding affinity for ERRγ, BPA may exert its chemoprotective effects via this receptor. ERRγ has been implicated in tamoxifen resistance in a cell line derived from invasive breast carcinoma (Riggins et al. 2008). Studies are underway with siRNA directed against ERRγ to examine its involvement in BPA-induced chemoresistance. However, we cannot rule out involvement of as yet unidentified receptor. We are also examining if BPA actions are mediated via genomic versus nongenomic mechanisms.

BPA alone, or in combination with doxorubicin (LaPensee et al. 2009c) or cisplatin (LaPensee et al. 2009a) increases Bcl-2 expression. Treatment with a Bcl-2 inhibitor completely blocks the BPA-induced antagonism of cisplatin, whereas it only partially abrogates protection by E2. This suggests that BPA and estrogen may exert protection against cytotoxicity by somewhat different mechanisms, i.e. antiapoptosis versus mitogenesis. This notion is supported by flow cytometry and BrdU incorporation showing that BPA alone increases cell survival, while estrogen alone increased cell proliferation. Figure 3 schematically illustrates the role of Bcl-2 antiapoptotic protein in mediating chemoresistance by BPA. Note that the mechanism by which BPA exerts chemoresistance against cisplatin differs from that caused by PRL (see Fig. 2).

Summary and perspectives

Hormones have long been implicated in the pathogenesis of breast cancer, but only a few studies have addressed their role in chemoresistance. Mounting evidence indicates that low doses of PRL, E2, and BPA antagonize multiple anticancer drugs that induce cell death by different mechanisms. PRL opposes cisplatin by increasing GST activity, while E2 and BPA act by increasing Bcl-2 expression. This serves as an excellent example of why targeting one mechanism of resistance may not be sufficient for slowing down tumor growth or eliminating metastases. Future studies should examine in more detail the potential crosstalk between PRL and E2 in conferring resistance, and expand in vitro studies to pre-clinical models. FDA-approved inhibitors of PRL or E2, e.g. bromocriptine and tamoxifen, should provide for an easy transition from animal models to clinical trials. As for PRL, blockade of the receptor should be more effective than attempting to reduce the hormone itself.
A reduction in the ability of PRL and estrogens to confer chemoresistance should have several benefits to breast cancer patients, including an increase in the number as well as efficacy of valuable drugs. For example, drugs such as cisplatin, which has shown success in treating many other types of cancers, could be introduced into breast cancer regimens, while the efficacy of already successful anticancer drugs such as taxol could increase. Many treatment regimens use drugs that act by different mechanisms to improve the chances of suppressing tumor growth. Hence, having more options for combination therapy should especially benefit those patients who undergo second- or third-line anticancer treatment. Furthermore, increased efficacy should enable the use of lower drug doses, thereby reducing the toxicity and side effects associated with high dose therapy and improving the quality of life. Finally, because the actions of E₂, BPA, and possibly other endocrine disruptors may be independent of ERα and ERβ, patients with ER-negative tumors could benefit from the blockade of E₂ and estrogen-like compounds.

Declaration of interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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References


Bai Z & Gurt R 2009 Breast cancer, estrogen receptor and ligands. Archiv der Pharmazie 342 133–149.


Ben-Jonathan N, LaPensee CR & LaPensee EW 2008 What can we learn from rodents about prolactin in humans? Endocrine Reviews 29 1–41.


Kang JH, Kondo F & Katayama Y 2006 Human exposure to bisphenol A. Toxicology 226 79–89.


Le HH, Carlson EM, Chua JP & Belcher SM 2008 Bisphenol A is released from polycarbonate drinking bottles and mimics the neurotoxic actions of estrogen in developing cerebellar neurons. Toxicology Letters 176 149–156.


Luquita MG, Catania VA, Sanchez-Pozzi EJ, Vore M & Mottino AD 1999 Prolactin increases the hepatic content of mu-class subunits of glutathione-S-transferase in the rat. Drug Metabolism and Disposition 27 122–124.


Peirce SK, Chen WY & Chen WY 2001 Quantification of prolactin receptor mRNA in multiple human tissues and cancer cell lines by real time RT-PCR. *Journal of Endocrinology* 171 R1–R4.


Van Den Bemd GJ, Kuiper GG, Pols HA & Van Leeuwen JP 1999 Distinct effects on the conformation of estrogen receptor alpha and beta by both the antiestrogens ICI 164,384 and ICI 182,780 leading to opposite effects on receptor stability. Biochemical and Biophysical Research Communications 261 1–5.


Welshons WV, Nagel SC & vom Saal FS 2006 Large effects from small exposures. III. Endocrine mechanisms mediating effects of bisphenol A at levels of human exposure. Endocrinology 147 856–869.


