

**Advances in Brief**

**Induction of Topoisomerase II Activity after ErbB2 Activation Is Associated with a Differential Response to Breast Cancer Chemotherapy**

L. N. Harris,¹ ² Li Yang, Vlayka Liotcheva, Samuel Pauli, James Dirk Iglehart, O. Michael Colvin, and Tao Shih Hsieh

Adult Oncology, Dana-Farber Cancer Institute, Boston, Massachusetts 02115 [L. N. H.]; Department of Medicine [L. Y., V. L., S. P.], Comprehensive Cancer Center [O. M. C.], and Department of Biochemistry [T. S. H.], Duke University Medical Center, Durham, North Carolina 27710; and Department of Surgery, Brigham & Women’s Hospital, Boston, Massachusetts 02115 [J. D. I.]

**Abstract**

**ErbB2 (HER-2)** gene amplification and overexpression have been shown to predict a better outcome with doxorubicin-based chemotherapy as opposed to alkylator-based chemotherapy in early stage breast cancer. To understand the mechanism of differential response to these two regimens, we have evaluated the effect of signaling through the ErbB2 receptor on downstream enzymes that may affect drug response, using two different models. The first system employs breast cancer cells that have high levels of endogenous ErbB2 by gene amplification (BT-474 and SKBR3 cells). The second system allows us to isolate the effect of ErbB2 receptor-mediated intracellular signaling using an epidermal growth factor receptor-ErbB2 chimeric receptor activated by epidermal growth factor. Our experiments show that the cytotoxicity of doxorubicin is inhibited in ErbB2+ breast cancer cells by the anti-ErbB2 antibody, Herceptin. This is accompanied by a decrease in topoisomerase (topo) IIα protein and activity, suggesting that this is the mechanism of change in doxorubicin response. In addition, a 10–100-fold (1–2 log) decrease in the LD₅₀ of doxorubicin is seen after ErbB2 activation using the chimeric receptor model. Furthermore, we see a 100-fold decrease in the LD₅₀ of etoposide, another topo II inhibitor. This increase in doxorubicin sensitivity is associated with a 4.5-fold increase in the amount of topo IIα protein and an increase in topo II activity as measured by DNA decatenating and unknotting activities, as well as cleavable complex formation. In contrast to doxorubicin, we have observed an increased resistance to cyclophosphamide chemotherapy after chimeric receptor activation. We propose that the differential benefit seen with doxorubicin- versus alkylator-based chemotherapy in ErbB2+ breast cancer is due, in some cases, to ErbB2-mediated topo IIα activation. These data also suggest hypotheses for the optimal sequencing of Herceptin and chemotherapy agents in ErbB2+ breast cancer.

**Introduction**

The use of chemotherapy to treat early stage breast cancer has been proven to extend survival (1). Whereas doxorubicin-containing regimens show a small additional benefit over CMF³-based regimens, they are associated with rare but serious side effects [congestive heart failure and acute leukemia (1, 2)]. The choice of regimen often depends on the overall risk of recurrence and comorbidities of the patient but is generally not tumor specific. Better understanding of the predictive value of certain biological markers in the primary tumor should allow us to identify chemotherapy regimens that are most likely to be effective while minimizing toxicity. In addition, appropriate combinations of chemotherapy and new biological agents, such as the anti-ErbB2 antibody Herceptin, are best determined by understanding biological interactions between signaling pathways and treatment effects.

The ErbB2 or HER-2 oncogene is overexpressed in approximately 30% of human breast cancer specimens and is associated with a poor outcome in many studies (3–5). Recent data suggest that ErbB2 amplification and overexpression are associated with improved outcome after doxorubicin-based therapy as compared with alkylator-based therapy [CMF and PF (6, 7)]. This has led to the speculation that ErbB2 confers sensitivity to doxorubicin and resistance to alkylating agents.

In an attempt to understand the mechanism of the differential response to these regimens, we have studied the effect of activating the ErbB2 receptor on downstream enzymes that may affect drug response. Our previously published *in vitro* data have shown that activation of the ErbB2, ErbB3, and ErbB4 receptors using heregulin β-2 is associated with an increase in the DNA-modifying enzyme, topo IIα, which is accompanied by increased sensitivity to doxorubicin but resistance to an alkylator, cisplatin (8). In the current study, we have attempted to dissect the role of ErbB2 in modulating drug response using two ErbB2-dependent *in vitro* models. Data presented here demonstrate that an increase in topo II activity and greater

Received 4/12/00; revised 3/12/01; accepted 3/15/01.

The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked advertisement in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

1 L. N. H. was supported by United States Army Medical Research & Material Command Breast Cancer Research Program Grant DAMD-17-96-1-6133.

2 To whom requests for reprints should be addressed, at Dana-Farber Cancer Institute, Room 1210, 44 Binney Street, Boston, MA 02115. Phone: (617) 632-4132; Fax: (617) 632-3709.

3 The abbreviations used are: CMF, cyclophosphamide; methotrexate, and 5-fluorouracil; EGF, epidermal growth factor; EGFR, EGF receptor; topo, topoisomerase; ECL, enhanced chemiluminescence; FACS, fluorescence-activated cell-sorting; BCS, bovine calf serum; VP-16, etoposide; 4-HC, 4-hydroperoxy-cyclophosphamide.
sensitivity to doxorubicin follow ErbB2 receptor signaling. We have also observed an increased resistance to cyclophosphamide after ErbB2 receptor activation and propose that these two observations are linked by changes in topo II activity. Finally, we find that sensitivity to doxorubicin is reversed by Herceptin in ErbB2+ breast cancer cells. Whereas the role of Herceptin in early stage breast cancer has yet to be determined, our study suggests that combining this drug with doxorubicin is unlikely to be the optimal strategy against ErbB2+ tumors.

Materials and Methods

Cell Lines. NIH-3T3 cells transfected with an EGFR-ErbB2 chimeric receptor were kindly provided by C. Richter King (Lombardi Cancer Center, Washington, D.C.). The chimeric receptor was constructed by joining the extracellular domain of the EGFR with the transmembrane and intracellular portion of the ErbB2 receptor (Fig. 1; Ref. 9). The receptor is activated by EGF, with subsequent tyrosine phosphorylation of the ErbB2 receptor intracellular tyrosine kinase. Host cells (NIH-3T3 cells) do not express the ErbB2, ErbB3, or ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown). BT-474 and SKBR3 cells are breast cancer cell lines that overexpress the ErbB2 receptor by amplification and have coexpression of ErbB3 and ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown). BT-474 and SKBR3 cells are breast cancer cell lines that overexpress the ErbB2 receptor by amplification and have coexpression of ErbB3 and ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown). BT-474 and SKBR3 cells are breast cancer cell lines that overexpress the ErbB2 receptor by amplification and have coexpression of ErbB3 and ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown). BT-474 and SKBR3 cells are breast cancer cell lines that overexpress the ErbB2 receptor by amplification and have coexpression of ErbB3 and ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown). BT-474 and SKBR3 cells are breast cancer cell lines that overexpress the ErbB2 receptor by amplification and have coexpression of ErbB3 and ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown). BT-474 and SKBR3 cells are breast cancer cell lines that overexpress the ErbB2 receptor by amplification and have coexpression of ErbB3 and ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown). BT-474 and SKBR3 cells are breast cancer cell lines that overexpress the ErbB2 receptor by amplification and have coexpression of ErbB3 and ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown). BT-474 and SKBR3 cells are breast cancer cell lines that overexpress the ErbB2 receptor by amplification and have coexpression of ErbB3 and ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown). BT-474 and SKBR3 cells are breast cancer cell lines that overexpress the ErbB2 receptor by amplification and have coexpression of ErbB3 and ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown). BT-474 and SKBR3 cells are breast cancer cell lines that overexpress the ErbB2 receptor by amplification and have coexpression of ErbB3 and ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown). BT-474 and SKBR3 cells are breast cancer cell lines that overexpress the ErbB2 receptor by amplification and have coexpression of ErbB3 and ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown). BT-474 and SKBR3 cells are breast cancer cell lines that overexpress the ErbB2 receptor by amplification and have coexpression of ErbB3 and ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown). BT-474 and SKBR3 cells are breast cancer cell lines that overexpress the ErbB2 receptor by amplification and have coexpression of ErbB3 and ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown). BT-474 and SKBR3 cells are breast cancer cell lines that overexpress the ErbB2 receptor by amplification and have coexpression of ErbB3 and ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown). BT-474 and SKBR3 cells are breast cancer cell lines that overexpress the ErbB2 receptor by amplification and have coexpression of ErbB3 and ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown). BT-474 and SKBR3 cells are breast cancer cell lines that overexpress the ErbB2 receptor by amplification and have coexpression of ErbB3 and ErbB4 receptors. Two clones were available for these experiments, NIH77 and NIH82. Both clones show response to EGF with ErbB2 tyrosine phosphorylation and evidence of tritiated thymidine incorporation after receptor signaling, as confirmed by experiments in this laboratory (data not shown).
**Results**

We used two in vitro models to evaluate the role of the ErbB2 receptor in response to chemotherapy. The first involved breast cancer cells that overexpress ErbB2 and are well characterized for content of ErbB3, ErbB4, and EGFR receptors that are often coexpressed in ErbB2+ cells (16). This allowed us to evaluate the effects on signaling through ErbB2 in the context of other members of the EGFR superfamily, more closely approaching the in vivo situation. ErbB2 is constitutively active in these cells, but it can be inhibited with the anti-ErbB2 antibody, 4D5, the murine form of Herceptin.

Our second model allowed us to isolate the effect of ErbB2-mediated signaling without the presence of heterodimerizing coreceptors. Because ErbB2 has no known ligand, the receptor alone cannot be activated exogenously. Therefore we used an EGFR-ErbB2 chimeric receptor construct transfected into NIH-3T3 cells, which do not express significant levels of the EGFR superfamily members (Fig. 1; Ref. 9). Within 1 h of exposure to EGF (10 ng/ml), the ErbB2 receptor kinase is activated as demonstrated by phosphorylation of intracellular domain tyrosine residues and tritiated thymidine incorporation (data not shown).

**Inhibition of ErbB2 Signaling Leads to Increased Resistance to Doxorubicin and Decreased topo II Activity in ErbB2+ Breast Cancer Cells.** We evaluated the effect of modulating ErbB2 signaling on doxorubicin response using 4D5 antibody (Herceptin). We assessed whether inhibition of the ErbB2 kinase was associated with a change in sensitivity to doxorubicin using a tetrazolium-based cytotoxicity assay. In these experiments, we found a reproducible inhibition of doxorubicin cytotoxicity after treatment with 4D5 (10 μg/ml), for 24 h. After [3H]thymidine incorporation for 12 h, cells were treated with increasing concentrations of doxorubicin (0.001–10 μM) for another 12 h. Cells were washed and lysed, and DNA-topo II protein complexes were precipitated by KCl. The pellet was washed and resuspended in scintillation fluid, and the radioactivity of each sample was determined. Topo II cleavage activity is expressed as cpm versus micromolar doxorubicin.

**Topo II Cleavage Assay.** Topo II cleavage assays were performed using the K-SDS assay to measure the formation of protein/DNA covalent complexes after exposure to topo II inhibitor (15). Briefly, cells were serum starved for 24 h, followed by treatment with or without EGF (10 ng/ml) for 24 h. After [3H]thymidine incorporation for 12 h, cells were treated with increasing concentrations of doxorubicin (0.1–10 μM) for a period of 12 h. Cells were washed and lysed with SDS and DNA-topo II protein complexes precipitated by the addition of KCl. The pellet was washed and resuspended in scintillation fluid, and the radioactivity of each sample was determined. Topo II cleavage activity was expressed by plotting the amount of protein-linked DNA versus drug concentration (μM doxorubicin). All experiments were performed in triplicate.
crease in the LD50 of doxorubicin after EGF treatment of cells expressing significant amounts of any of the EGFR superfamily of receptors. We found a reproducible 10–100-fold (1–2 log) decrease in the LD50 of doxorubicin after EGF treatment of cells containing the EGFR/ErbB2 chimeric receptor compared with untransfected NIH-3T3 cells treated in a similar fashion. Fig. 5A demonstrates this effect. To address possible differences in cell growth rate, chimeric cells growing in serum-containing media were treated with and without EGF and then exposed to increasing doses of doxorubicin. A similar increase in sensitivity to doxorubicin was seen in this experiment (data not shown).

To determine whether these cells were sensitive to other topo II inhibitors that are not DNA intercalators, we tested the cytotoxicity of VP-16 in this system. Chimeric cells were 100-fold more sensitive to VP-16 as compared with control NIH-3T3 cells that do not express the chimeric receptor (Fig. 5B). The similarity of the effect of ErbB2 activation on doxorubicin and VP-16 dose-response curves suggests that the doxorubicin sensitivity noted in our system is mediated by topo II.

**Topo II Activity and Protein Levels Are Increased in Chimeric Cells after ErbB2 Receptor Activation.** We again used the K-SDS assay to evaluate the intracellular topo activity in chimeric cells after activation of ErbB2. We observed a marked increase in DNA cleavage complexes in the chimeric cells after treatment with EGF as compared with the same cells without EGF treatment (Fig. 6B). At a concentration of 1 μM doxorubicin, approximately six times more protein-linked DNA cleavage can be detected in the EGF-treated cells. At an even higher concentration, there is a decrease in the cleavage complex, a phenomenon common to the intercalative topo II inhibitors (17).

To further explore the functional consequence of ErbB2 receptor signaling on topo II activity, we performed two different assays: (a) unknotting of knotted P4 DNA; and (b) decatenating of catenated kinetoplast DNA rings. Both assays measure the ability of topo II to catalyze strand passage between two double-stranded DNA segments; however, the decatenation assay evaluates intramolecular strand passage activity, whereas the unknotting assay evaluates intermolecular activity. On activation with EGF, we found an increase in topo II enzymatic activity in chimeric cells by both measures. Data shown are for the decatenation assay, although similar results were seen in the unknotting assay (Fig. 6A). After ErbB2 activation, there is an enhancement of 2–4-fold strand passage activity in these assays. Taken together, these data suggest that the increase in topo II enzymatic activity on ErbB2 receptor signaling leads directly to an increase in sensitivity of these cells to topo II poisons like doxorubicin and VP-16.

Using our EGFR-ErbB2 chimeric receptor model in a time course experiment, we observed that activation of ErbB2 is associated with an increase in topo II protein from 48 to 72 h after receptor activation for both clones. This corresponds to a 4.5-fold increase in topo II protein, based on band densitometry (Fig. 7A). Equal loading is seen for actin (Fig. 7B).

**Increased Activity of Topo IIα Is Seen throughout the Cell Cycle in ErbB2-overexpressing Cells but not in ER+ Cells that Do Not Overexpress ErbB2.** The effect of ErbB2 signaling on topo IIα may be specific to the effects of this oncogene on downstream targets or may be a nonspecific effect of mitogenesis. To address this question, we performed cell cycle experiments on ErbB2-overexpressing (SKBR3) and non-ErbB2-overexpressing (MCF-7) breast cancer cells. MCF-7 cells are known to be dependent on estrogen receptor signaling for their growth. Both cell lines were blocked in early S-phase using hydroxyurea treatment and released into serum-containing media. A time course was performed to demonstrate topo IIα activity at different phases of the cell cycle. The results show that ErbB2-overexpressing cells have higher levels of topo IIα protein throughout different phases of the cell cycle compared with non-ErbB2-overexpressing MCF-7 cells (Fig. 8), although the pattern of expression is similar for both cell lines. The two cell lines had a similar...
rate of progression through the cell cycle after release into serum-containing media, as measured by FACS analysis (data not shown).

**Signaling through ErbB2 Is Associated with Resistance to 4-HC.** Cyclophosphamide is the main component of the regimen CMF that has been used to treat breast cancer. Several studies have suggested a correlation of resistance to CMF-based regimens in patients whose tumors overexpress ErbB2 (19, 20). Using the active metabolite, 4-HC, we assessed the effect of ErbB2 receptor signaling on the cytotoxicity of cyclophosphamide in our *in vitro* system. Cells containing the chimeric receptor were stimulated by ligand and then treated with or without 4-HC. In contrast to the increased sensitivity seen with doxorubicin, we saw a 10–100-fold (1–2 log) increase in the LD₅₀ of 4-HC in cells with activated ErbB2 receptor, demonstrating increased resistance to the alkylator. Fig. 9 demonstrates this effect from one of three such experiments. Therefore, the activity of the ErbB2 receptor may influence resistance to cytotoxic agents other than those that specifically target topo II.

---

**Fig. 5** Cytotoxicity assays with topo II inhibitors doxorubicin and VP-16 in NIH-EGFR/ErbB2 cells. A, NIH-EGFR/ErbB2 chimeric-transfected cells and NIH-3T3 wild-type cells were starved in serum-free media for 24 h and then incubated in media supplemented with 2% BCS and 10 ng/ml EGF. Cells were then plated at 1000 cells/well in a 96-well microtiter dish on day 0 and treated with increasing concentrations of doxorubicin (0.001–10 μM). Viability was assessed using a tetrazolium-based assay on day 7 (at confluence of control sample) with absorbance read at 490 nm. B, cells were treated as described above, except that the topo II inhibitor used for this experiment was VP-16 (0.001–100 μM).

**Fig. 6** Topo II cleavage activity in response to doxorubicin after ErbB2 receptor signaling in NIH-EGFR/ErbB2 cells. A, decatenation assay. Chimeric cells were starved in serum-free media for 24 h and then treated with or without EGF (10 ng/ml) for 48 h. After gel electrophoresis in 1% agarose, the decatenated products containing nicked circular and relaxed circular DNA were determined by densitometry and expressed as a function of the amount of nuclear protein loaded. B, cleavage assay. Chimeric cells were serum starved for 24 h, followed by treatment with or without EGF (10 ng/ml) for 24 h. After [³H]thymidine incorporation for 12 h, cells were treated with increasing concentrations of doxorubicin (0.1–10 μM) for an additional 12-h period. Cells were washed and lysed, and DNA-topo II protein complexes were precipitated by KCl. The pellet was washed and resuspended in scintillation fluid, and the radioactivity of each sample was determined. topo II cleavage activity was expressed as cpm versus micromolar doxorubicin.
Discussion

Our previous work has shown that the ErbB family of receptors can be activated in MCF-7 breast cancer cells transfected with the ligand heregulin. This is associated with up-regulation of the nuclear enzyme topo IIα and a change in sensitivity to chemotherapy agents used in breast cancer (8). In the current study, we have pursued the relationship between chemotherapy, ErbB2, and topo II. We have examined the effect of ErbB2 activation in cells that highly overexpress the receptor by activation of a chimeric receptor in heterologous cells and by inhibition of receptor signaling by the 4D5 monoclonal antibody. In each of these model systems, we were able to modulate the dose-response relationship to doxorubicin and observed consistent and concomitant changes in topo IIα levels. Furthermore, the topo II enzyme activity is also affected by changes in ErbB2 receptor activity.

Our data suggest a direct relationship between ErbB2 receptor signaling and topo II modulation. We have observed increases in both topo IIα protein and enzymatic activity after receptor activation. These changes are accompanied by increase in sensitivity to the enzyme-specific inhibitors doxorubicin (Adriamycin) and VP-16. In addition, the anti-ErbB2 antibody, Herceptin, can reverse this effect. Furthermore, we see the opposite effect on response to cyclophosphamide, with increased resistance to the latter. We hypothesize that the increase in topo II activity observed after ErbB2 receptor signaling is responsible for the differential sensitivity of these cells to doxorubicin- versus alkylator-based therapy seen in the in vivo setting.

Topo IIα is a DNA-modifying enzyme that can pass a segment of DNA duplex through a reversible, enzyme-mediated double-strand break (21). Drugs that target topo II include the anthracyclines (doxorubicin and daunorubicin), VP-16, teniposide, and amascarine (17). These agents appear to act by binding to the enzyme-DNA complex and inducing lethal cellular damage by the inhibition of the religation step during the transient DNA cleavage reaction. Increase in topo IIα expression is associated with sensitivity to these agents in both cell lines and tumors, presumably due to increased target on which the drug may act (22, 23).

A study evaluating 230 breast cancer tumor specimens demonstrated that increased expression of topo IIα is associated with ErbB2 overexpression, even when adjusted for proliferative index (24). In a subset of 49 of these tumors, coamplification of topo IIα and ErbB2 genes occurred as these genes colocalize to chromosome 17 (25). This study shows that topo IIα may also increase by nongenetic mechanisms through temporary increases in ErbB2 receptor activation. We see increased topo II levels and activity in cell lines where ErbB2 is not amplified but is activated by a ligand. In addition, NIH-3T3 cells that contain a normal gene dosage of topo IIα up-regulate this protein after activation of a chimeric receptor that has been transfected into these cells. Therefore, we conclude that increased levels of topo IIα may be due either to gene amplification or to increased activity of the ErbB2 receptor. In addition, we have shown that topo IIα levels appear to be higher in some ErbB2-amplified breast cancer cells, compared with transformed breast cancer cells that are not dependent on ErbB2 for growth. In this setting, both ErbB2 and topo IIα activity can be down-regulated using the anti-ErbB2 antibody, Herceptin.

Large clinical trials suggest a benefit from doxorubicin in ErbB2+ breast cancer that is not as great as that with alkylator-based therapy. In the cooperative group study performed by the National Surgical Adjuvant Breast and Bowel Project (NSABP-B11), an improved outcome with a doxorubicin-containing regimen was seen only in patients whose tumors overexpressed ErbB2 (7). In another large study, Cancer and Leukemia Group B (CALGB) 8869, patients whose tumors overexpressed ErbB2 had a better survival if they were treated with higher doses of doxorubicin-containing chemotherapy, in contrast to their ErbB2- counterparts (26). Furthermore, we have also
shown that stage IV breast cancer patients who exhibit higher levels of circulating ErbB2-extracellular domain, are 6 times more likely to respond to doxorubicin-containing therapy than to CMF regimens (27). These clinical studies suggest that response to doxorubicin is influenced by ErbB2. In vitro studies presented in the current report corroborate clinical studies and suggest that topo IIα is involved in the mechanism behind response to chemotherapy in ErbB2+ cells.

The relationship between ErbB2 overexpression in human breast cancer and poor outcome after CMF treatment suggests resistance to alkylating agents (20, 21). Although other agents (methotrexate and 5-fluorouracil) are part of this regimen, it is generally accepted that cyclophosphamide is the most effective agent in this combination. In two separate studies, patients whose breast tumors overexpressed ErbB2 did not appear to achieve as much benefit from postoperative CMF chemotherapy as did their non-ErbB2-overexpressing counterparts. Thus, our observations are consistent with the clinical picture, where overexpression of ErbB2 is associated with relative resistance to cyclophosphamide.

Previous studies have demonstrated that resistance to alkylators such as cyclophosphamide is multifactorial (28, 29). The most commonly described mechanisms are alterations in drug transport, modulation of glutathione levels, and enhanced repair of DNA adducts. It has been observed that some cell lines selected for resistance to alkylators have elevated levels of topo IIα, and it has been suggested that topo II is involved in DNA repair through its modulation of chromatin structure (30, 31). Although cause and effect have not been proven, similar resistance to 4-HC was associated with increased topo II activity in the in vitro system used for our studies. It has been shown that inhibition of ErbB2 can reduce the rate of unscheduled DNA repair, increase intranstrand adduct formation, and delay the rate of adduct decay in ErbB2+ cells (32, 33). We speculate that topo II activity may be, in part, responsible for this modulation of repair activity. It is possible that other replication and repair-associated proteins are involved in a response to ErbB2 signaling and that components of this response confer sensitivity to topo II inhibitors, whereas other components confer resistance to alkylators. Topo II may be a member of this multifactorial response, perhaps as part of a multienzyme complex important in repair of DNA damage.

Our experiments demonstrate that ErbB2 signaling leads to alterations in both the level and enzymatic activity of topo II. This, in turn, is associated with increased sensitivity to doxorubicin and resistance to cyclophosphamide. Although a direct connection has not been proven, we suggest that alteration in topo II activity, brought on by ErbB2 receptor signaling, may be one mechanism by which differential sensitivity of ErbB2+ tumors to doxorubicin-versus cyclophosphamide-based regimens occurs in the clinical setting.

Recent development of the humanized monoclonal antibody, Herceptin, has provided useful therapy for HER-2+ patients, particularly in combination with chemotherapy. However, many questions remain about the ideal way to give Herceptin, its duration of use, and how best to monitor patients on therapy. Our study further suggests that the ideal way to combine Herceptin with chemotherapy involves combinations with cyclophosphamide where inhibition of topo II may lead to reversal of drug resistance. This hypothesis is supported by observational data from other in vitro work (34). Moreover, our experiments suggest that combinations of Herceptin with doxorubicin are not ideal because this does not allow us to take advantage of increased topo II activity in ErbB2+ cells. Further understanding of the relationship between a given molecular lesion and response to chemotherapy will help us recommend our treatments in a more patient-specific manner.

Acknowledgments

We thank Dr. Jeffrey Marks for advice and support.

References


Induction of Topoisomerase II Activity after ErbB2 Activation Is Associated with a Differential Response to Breast Cancer Chemotherapy

L. N. Harris, Li Yang, Vlayka Liotcheva, et al.

*Clin Cancer Res* 2001;7:1497-1504.

Updated version  Access the most recent version of this article at: [http://clincancerres.aacrjournals.org/content/7/6/1497](http://clincancerres.aacrjournals.org/content/7/6/1497)

Cited articles  This article cites 32 articles, 14 of which you can access for free at: [http://clincancerres.aacrjournals.org/content/7/6/1497.full.html#ref-list-1](http://clincancerres.aacrjournals.org/content/7/6/1497.full.html#ref-list-1)

Citing articles  This article has been cited by 18 HighWire-hosted articles. Access the articles at: [content/7/6/1497.full.html#related-urls](content/7/6/1497.full.html#related-urls)

E-mail alerts  Sign up to receive free email-alerts related to this article or journal.

Reprints and Subscriptions  To order reprints of this article or to subscribe to the journal, contact the AACR Publications Department at pubs@aacr.org.

Permissions  To request permission to re-use all or part of this article, contact the AACR Publications Department at permissions@aacr.org.