Estrogen-mediated Down-Regulation of E-cadherin in Breast Cancer Cells

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Abstract

E-cadherin is an important mediator of cell-cell interactions, and has been shown to play a crucial role in breast tumor suppression. Its inactivation occurs through instability at its chromosomal locus and mutations, but also through epigenetic mechanisms such as promoter hypermethylation and transcriptional silencing. We show here that estrogen treatment causes changes on the E-cadherin levels in both normal and tumorigenic breast epithelial cells, and that this down-regulation is reversed by selective estrogen receptor modulators (SERMs). The reduction in E-cadherin levels is via a decrease in promoter activity and subsequent mRNA levels. Chromatin immunoprecipitation assays revealed that estrogen receptor and corepressors were bound to the E-cadherin promoter, and that overexpression of corepressors such as scaffold attachment factor B resulted in enhanced repression of E-cadherin. We propose that estrogen-mediated down-regulation of E-cadherin is a novel way of reducing E-cadherin levels in breast cancer cell lines and primary ductal and lobular breast cancers.

Introduction

E-cadherin is a glycoprotein with a large extracellular domain, a transmembrane domain, and a short intracellular domain that interacts with catenins. Recent studies have shown that estrogen causes down-regulation of E-cadherin levels in both normal and tumorigenic breast epithelial cells, and that this down-regulation is reversed by selective estrogen receptor modulators (SERMs). The reduction in E-cadherin levels is via a decrease in promoter activity and subsequent mRNA levels. Chromatin immunoprecipitation assays revealed that estrogen receptor and corepressors were bound to the E-cadherin promoter, and that overexpression of corepressors such as scaffold attachment factor B resulted in enhanced repression of E-cadherin. We propose that estrogen-mediated down-regulation of E-cadherin is a novel way of reducing E-cadherin levels in breast cancer cell lines and primary ductal and lobular breast cancers.

Materials and Methods

Cells, Transfections, and CAT Assay. Human breast cancer cells (MCF-7L, MDA-MB-231, MDA-MB-435, 2T4D, ZR75) were maintained in IMEM supplemented with 10% fetal bovine serum (Hyclone, Logan, Utah), 200 μM penicillin, 200 μg/ml streptomycin, and 6 ng/ml insulin. The immortalized human breast epithelial MCF10A cells were kept in DMEM/F12 medium supplemented with 5% horse serum, 10 ng/ml insulin, 20 ng/ml epidermal growth factor, 100 ng/ml cholera toxin, 2 mM glutamine, 500 ng/ml hydrocortisone, 200 IU/ml penicillin, and 200 μg/ml streptomycin. To express ER in these cells, 5 × 10^5 cells were plated in a 6-cm dish and were transfected with 1 μg of HA-tagged ER (ER-HA-pcDNA3.1) for 5 h. After transfection, the cells were placed in phenol red-free IMEM containing 5% CSS for an additional 24 h before being lysed in 5% SDS for subsequent immunoblotting (see "Western and Northern Blot Analysis" below). The experiments were performed three independent times.

For reporter assays, cells were transiently transfected using Fugene (Roche, Indianapolis, IN) following the manufacturer’s protocol. One day before transfection, cells were plated at 2 × 10^5 in 6-well plates. For E2 induction experiments, the cells were treated either in SFM, which consisted of phenol red-free IMEM + 10 mM HEPES (pH 7.4) + 1 μg/ml fibronectin (In Vitrogen, Carlsbad, CA) + trace elements (Biosources, Worcester, MA) + 1 μg/ml transferrin (Invitrogen) or in phenol red-free IMEM containing 5% CSS (Hyclone). Most E2 induction experiments were performed at least twice; the experiments in MCF-7L cells were performed at least three times each. For the promoter analysis, 1 μg of E2-mediated promoter (-178/+92 bp) CAT construct (11) was transfected, and 24 h later, the medium was replaced with IMEM + 5% CSS containing the appropriate ligand. Forty-eight h later, cells were washed twice with PBS, and CAT activity was measured using the CAT reporter assay.

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3 The abbreviations used are: ER, estrogen receptor (α); IMEM, Iscove’s MEM; CSS, charcoal-stripped serum; SFM, serum-free medium; E2, estradiol; IRS-1, insulin-receptor substrate 1; PGR, progesterone receptor; ChIP, chromatin immunoprecipitation; TAM, 4-hydroxytamoxifen; SAFB, scaffold attachment factor B; SAGE, serial analysis of gene expression; GAPDH, glyceraldehyde-3-phosphate dehydrogenase.

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ELISA from Roche (Indianapolis, IN). Values were corrected for protein concentrations and are presented as relative CAT activity. For transient transfections, triplicate samples were measured in each experiment. The data are presented as the average ± SE and are representative of three independent experiments.

**SAFB1 Overexpression in MCF-7 Cells.** To transiently overexpress SAFB1, subconfluent MCF-7L cells plated in a 10-cm dish were transfected overnight with 2 μg of SAFB1-HA-pcDNA1 (12, 13) using Fugene (Roche, Indianapolis, IN) following the manufacturer’s protocol. The next morning, the medium was changed, and 24 h later, the cells were lysed in 5% SDS. The generation of MCF-7 cells expressing inducible HA-SAFB1 has recently been described elsewhere (13).

**Western and Northern Blot Analyses.** Proteins were resolved on 8% SDS-PAGE, and electrophoretically transferred to nitrocellulose. The membrane was blocked in PBS/0.1% Tween 20 (PBST) + 5% milk for 1 h at room temperature. Antibodies to E-cadherin (Santa Cruz Biotechnology, Santa Cruz, CA), IRS-1 (Upstate Biotechnology Inc., Waltham, MA), HA (Covance), SAFB1 (Upstate Biotechnology Inc.), PgR (Santa Cruz Biotechnology, ER) (Vector, Novacasta, Burlingame, CA), and β-actin (Sigma, St. Louis, MO) were diluted at 1:1000, 1:1000, 1:5000, and 1:5000, respectively, in PBST + 5% milk. After washing six times for 5 min each time with PBST, the membrane was incubated with horseradish peroxidase-linked antiamouse IgG (Amersham Pharmacia Biotech, Piscataway, NJ) at 1:1000 in PBST + 5% milk and washed six times for 5 min each time, and the signal was developed using enhanced chemiluminescence according to the manufacturers instructions (Pierce, Rockford, IL).

For Northern blots, 10 μg of total RNA were separated by electrophoresis in a 1.2% formaldehyde-agarose gel. RNA isolation (CsCl gradient) and Northern blotting was performed after standard procedures. The human E-cadherin probe for hybridization was purchased from Research Genetics (Clone ID 2286727), and fold changes in RNA levels were determined using software on the Molecular Imager FX (Bio-Rad). The presented Northern blot is representative of two independent experiments.

**ChIP assays.** MCF-7 cells (3 × 10⁶) were plated in 15-cm dishes in phenol red-free DMEM supplemented with 10% CSS. After 36 h, the cells were transfected with 250 ng of plasmid DNA (mouse E-cadherin promoter, pCAD-Ecad-3000; Refs. 11, 14) using Lipofectamine and following the manufacturer’s protocol. The next morning, the cells were treated with vehicle only, 10⁻⁸ M E₂, or 10⁻⁸ M TAM for 45 min. After washing the cells with PBS (three times), they were cross-linked with 1% formaldehyde for 10 min at room temperature. Cells were rinsed three times with ice-cold PBS, collected into 100 mM Tris-HCl (pH 9.4)-10 mM DTT, then incubated for 15 min at 23°C. After centrifugation for 10 min × 1500 g, the pellets were washed three times with TE buffer [200 mM NaCl, 1 mM EDTA, 5 mM EGTA, and 10 mM HEPES (pH 6.5)] and buffer II [200 mM NaCl, 1 mM EDTA, 0.5 mM EGTA, and 10 mM HEPES (pH 6.5)]. Cells were then resuspended in 0.3 mL of lysis buffer [1% SDS, 10 mM EDTA, 20 mM Tris-HCl (pH 8.1), protease inhibitors], sonicated three times for 10 s each time, followed by centrifugation for 10 min. Supernatants were diluted in 1% Triton X-100, 2 mM EDTA, 150 mM NaCl, 20 mM Tris-HCl (pH 8.1), and 250 μg were precleared with 2 μg of sheared salmon sperm DNA and protein G-Sepharose (40 μl of 50% slurry) for 2 h at 4°C. Immunoprecipitation was performed overnight at 4°C with specific antibodies (2 μg of protein each). After immunoprecipitation, 50 μl of protein G-Sepharose and 2 μg of salmon sperm DNA were added, and the incubation was continued for 1 h. Precipitates were washed sequentially, each in TSE I [0.1% SDS, 1% Triton X-100, 2 mM EDTA, 20 mM Tris-HCl (pH 8.1), and 150 mM NaCl], TSE II [0.1% SDS, 1% Triton X-100, 2 mM EDTA, 20 mM Tris-HCl (pH 8.1), and 500 mM NaCl], and buffer III [0.25% L-SDS, 1% NP40, 1% deoxycholate, 1 mM EDTA, and 10 mM Tris-HCl (pH 8.1)]. Precipitates were then washed three times with TE buffer [10 mM Tris (pH 8.1)-1 mM EDTA], extracted with 1% SDS-0.1 M NaHCO₃, and heated at 65°C for at least 6 h to reverse the formaldehyde cross-linking. After DNA purification (QIAquick Spin kit), the proximal E-cadherin promoter (−234 to +62 bp) was amplified using the following primer set: forward primer, 5'-TCTTTTTGTAATCCCATGTCTCCCGT-3'; and reverse primer, 5'-C CGGGCACGGTAGTGACCGAAG-3'. The PCR of the pS2 promoter was performed as described previously (15). The antibodies for the ChIP assays were purchased from Santa Cruz Biotechnology (ER, N-CoR, rabbit IgG) and from UBI (SAFB).

The experiments were performed three times.

**Animals, Treatments, and Tissues.** Animal care was in accordance with institutional guidelines. Female ovariectomized BALB/c athymic nude mice (4–6 weeks old; Harlan Sprague Dawley Inc., Madison, WI) supplemented with estrogen pellets (0.25 mg, Innovative Research, Rockville, MD) were inoculated s.c. with 5 × 10⁶ MCF-7 cells, as described previously (16). When tumors reached a diameter of 7–9 mm (2–4 weeks), the animals were randomly allocated to continue estrogen treatment or to discontinue estrogen treatment by removal of the estrogen pellets. In this tumor model, estrogen stimulates tumor growth and estrogen withdrawal results in tumor growth inhibition. Tumors were removed during estrogen treatment (E₂ tumor group) and at 3 weeks after estrogen withdrawal treatment (−E₂ tumor group) and kept at −70°C for later analyses. Tumor powders were manually homogenized in a 5% SDS solution. After boiling and microcentrifugation, clear supernatants were collected, protein concentration was determined by the bicinchoninic acid method (Pierce, Rockford, IL), and Western blotting was performed as described above. This in vivo experiment was performed once.

**Results**

**Estrogen Down-Regulates E-Cadherin Protein Levels in MCF-7 Cells in Vitro and In Vivo.** To analyze whether E-cadherin protein levels are regulated by E₂, we placed ER-positive MCF-7L cells in a medium containing CSS and treated them with E₂ at a concentration ranging from 10⁻¹⁰ to 10⁻⁷ M for 24 h. Immunoblot analysis was performed using E-cadherin-specific antibodies, as well as β-actin antibodies for a loading control. As shown in Fig. 1A, E₂ treatment resulted in a dose-dependent decrease of E-cadherin. Interestingly, we never observed this E₂-mediated down-regulation of E-cadherin in the absence of serum, i.e. when the cells were kept in SFM (Fig. 1B). This result suggests that the E₂-mediated down-regulation of E-cadherin depends on other factors present in the serum, possibly “cross-talking” with ER.

Next we asked whether the down-regulation could be reversed by antiestrogens. Therefore, we treated MCF-7 cells with E₂ only, with the nonsteroidal antioestrogen TAM only, or with a combinations of both (Fig. 1C). As expected, the addition of antioestrogen to E₂-treated cells blocked E-cadherin down-regulation, reflecting the inactivation of ER activity. We observed the same effect with the pure steroidal antioestrogen ICI 182,780 (data not shown). As a control we immunoblotted for the estrogen-inducible proteins IRS-1 and PGR, levels of which were both potently increased by estrogen. Additionally, confirmation of ER function was shown by the down-regulation of ER (Fig. 1C) which is known to be degraded by E₂ and stabilized by TAM (17).

Interestingly, treatment with TAM alone increased levels of E-cadherin protein over baseline, reflecting the inhibitory effects of the residual E₂ in the CSS. Indeed, CSS can contain up to 10⁻¹¹ M E₂ (data sheet from manufacturer). Further supporting this is our finding that increasing amounts of CSS resulted in a dose-dependent decrease of E-cadherin levels (Fig. 1D). We think that this is attributable to residual E₂ because (a) it can be reversed by TAM (Fig. 1C and data not shown); and (b) treatment with a range of growth factors such as epidermal growth factor, insulin-like growth factor-1 (IGF-1), or heregulin in SFM did not lower E-cadherin levels (data not shown).

Next we asked whether this estrogen-mediated down-regulation of E-cadherin in MCF-7 cells in tissue culture could also be observed when MCF-7 cells were grown as xenografts in athymic mice. Therefore, athymic ovariectomized mice were given injections of MCF-7 cells blocked E-cadherin down-regulation, reflecting the inactivation of ER activity. We observed the same effect with the pure steroidal antioestrogen ICI 182,780 (data not shown). As a control we immunoblotted for the estrogen-inducible proteins IRS-1 and PGR, levels of which were both potently increased by estrogen. Additionally, confirmation of ER function was shown by the down-regulation of ER (Fig. 1C) which is known to be degraded by E₂ and stabilized by TAM (17).
results in down-regulation of E-cadherin protein not only in MCF-7 cells grown in tissue culture but also in vivo. Although numerous (direct and indirect) factors can influence gene expression in an in vivo situation, we think that these data, together with our in vitro experiments, strongly support an estrogen-mediated down-regulation of E-cadherin.

**Estrogen Down-Regulates E-cadherin Levels in Both Normal and Transformed Breast Epithelial Cell Lines.** To exclude the possibility that the effect seen in MCF-7 was cell line-specific, we measured E-cadherin levels in two ER-negative breast cancer cell lines (MDA-MB231 and MDA-MB-435) and two other ER-positive breast cancer cell lines (T47D and ZR75). There was no expression in the ER-negative cell lines (data not shown), a finding that was recently described and analyzed by Fujita et al. (9). However, in the ER-positive cell lines, we detected estrogen-mediated down-regulation of E-cadherin, which was reversed by antiestrogen treatment (Fig. 2A).

We next asked whether this repression is specific to transformed cells, or whether it could also be found in cell lines with less severe genetic abnormalities. Because normal or immortalized breast epithelial cell lines do not express ER, we transiently transfected immortal but nontransformed MCF10A cells with ER to study E-cadherin regulation (Fig. 2B). Transient transfection of these cells with a green fluorescent protein-tagged ER construct revealed transfection of up to 10% of cells (data not shown). No ER was detected in cells transfected alone. Stimulation of ER-transfected cells with E2 resulted in an increase in expression of the estrogen-regulated gene IRS-1, and a minor decrease in ER levels. This confirmed that the ER was active in these cells. Furthermore, these cells also showed a decrease in E-cadherin levels. In other experiments, the transient expression of ER alone (i.e., not stimulated with E2) also caused a down-regulation, which is presumably caused by residual E2 action; however, decreased E-cadherin levels were always noted after E2 stimulation. Therefore, estrogen-medi-
ated repression of E-cadherin levels can be detected in both immortalized breast epithelial and cancer cell lines.

**Estrogen Treatment Results in Decreased E-Cadherin RNA Levels and Promoter Activity.** To determine whether estrogen decreased E-cadherin at the mRNA level, we treated MCF-7L cells with E2 or a combination of E2 and antiestrogen for 6 h and then isolated total RNA. Northern blot analysis was performed using an E-cadherin probe, with GAPDH as a loading control. As shown in Fig. 3A, E-cadherin RNA levels were decreased 2-fold in the presence of E2. Substantiating the estrogen regulation at the RNA level is the finding that TAM treatment blocked the E2-mediated down-regulation and, when given alone, caused an increase in the E-cadherin levels.

This finding encouraged us to analyze whether the decreased promoter activity was the direct result of recruitment of ER and corepressors, we performed ChIP assays. Therefore, we transfected MCF-7 cells with a plasmid containing the E-cadherin fragment known to be repressed on estrogen treatment. The cells were then treated with E2 for 45 min, and the recruitment of ER and corepressors (N-CoR and SAFB1) was analyzed by ChIP (Fig. 3C) as described in "Materials and Methods." We also examined the recruitment of ER and corepressors at the pS2 promoter. As described previously (15), estrogen treatment resulted in strong recruitment of ER to the pS2 promoter. We repeatedly detected a low level of ER binding in the absence of E2, possibly reflecting low levels of E2 in the stripped serum. Corepressors (N-CoR and SAFB1) showed constitutive binding to the pS2 promoter, which was released on E2 treatment. In stark contrast to results obtained with the pS2 promoter, the E-cadherin promoter showed strong constitutive binding of ER in the absence of estrogen. E2 treatment of cells with estrogen for 45 min did not result in release of corepressors, as observed for the pS2 promoter (Fig. 3B).

To directly test whether the corepressors might modulate E-cadherin levels, we transiently overexpressed the ER corepressor...
SAFB1, and also generated stable tetracycline-inducible SAFB1 over-expressing breast cancer cell lines (Fig. 3D). Transient overexpression of SAFB1 in MCF-7L cells resulted in stronger estrogen-mediated repression of E-cadherin, as shown in Fig. 3D. We confirmed this data in MCF-7 RA (‘tet on”) cells which consistently showed 3-fold overexpression of SAFB1 on doxycycline treatment (Fig. 3E). Thus, ER corepressor levels are a major determinants in the regulation of E-cadherin expression.

Discussion

In this study, we have shown that E-cadherin is an estrogen-downregulated gene in human breast cancer cells. A number of studies in various tissues and cell lines have previously described connections between steroid receptor pathways and E-cadherin. Prinsac et al. (18) and Habermann et al. (19) have shown that developmental exposure to estrogen was associated with changes in epithelial cell adhesion and decreased E-cadherin levels in the adult rat prostate. E2 treatment resulted in a decrease of N-cadherin (20) and increase of E-cadherin (21) levels in the mouse ovary. In breast cancer cells, estrogen treatment was reported to induce cytoskeletal rearrangements (22) including delocalization of E-cadherin (23). Interestingly, tamoxifen restored the function of E-cadherin in an MCF-7 subline with a functionally inactive cell surface E-cadherin (MCF-7/6); however, this was an extremely rapid event (30 min) and did not require protein synthesis (24). Thus, although a number of reports have addressed a potential effect of estrogen on E-cadherin, our study represents the first attempt to investigate estrogen-mediated down-regulation of E-cadherin as a novel mechanism of its inactivation in human breast cancer.

In contrast to the well-characterized estrogen induction of a number of genes, estrogen-mediated down-regulation of genes has only recently gained more attention. In a SAGE study using estrogen-treated MCF-7 cells, an equal number of induced and repressed genes were identified (25). A recent study has shown that transcription of the nuclear coactivator src-3/AIB1 (amplified in breast cancer) is repressed by E2 (26). We think that estrogen-mediated repression of E-cadherin is a critical regulatory pathway in ER-positive cells, and that deregulation of this repression in breast cancer may have dramatic effects such as the promotion of transformation and metastasis. The observation that a number of genes, including E-cadherin, have been described as both induced and repressed might be explained by our finding that the repression can only be seen in the presence of serum but not in SFM, suggesting that cross-talk with other pathways is necessary. For instance, kinases can regulate ER and coregulators (for a recent review, see Ref. 27), and the absence or presence of a specific kinase might determine whether the gene becomes induced or repressed on estrogen treatment. We hypothesize that there are three distinct sets of genes: one that can only be induced by estrogen, one that can only be repressed by estrogen, and one that can be induced or repressed depending on cellular context. Experiments are ongoing to test this hypothesis.

As for the mechanism of estrogen down-regulation of gene expression, our ChIP analyses suggest an involvement of ER corepressors and ER in a complex at the E-cadherin promoter. Several previous studies have suggested that a balance of coactivators and corepressors may modulate ER action, and may be deregulated in breast cancer and, in particular, in endocrine resistance. Our data support this hypothesis by showing that an excess of SAFB1 enhances the ability of ER to down-regulate E-cadherin levels. Thus, our data imply that a critical balance between ER and ER cofactors is a determinant in the regulation of E-cadherin levels in breast cancer. However, a potential caveat of our experiments is the use of a transiently transfected promoter. Studies analyzing the recruitment of both coactivators and corepressors to the endogenous E-cadherin promoter in mouse and human cell lines are ongoing.

The connection between ER and E-cadherin is obviously very complex. ER-negative cell lines are often (but not always, as shown in Fig. 2R in MCF10A cells) E-cadherin-negative, and this has recently been analyzed in more detail. The repressor MTA3 is an estrogen-regulated gene that regulates Snail expression, which in turn represses E-cadherin (9). Thus, in the absence of ER (and MTA3), aberrant expression of Snail results in a loss of expression of E-cadherin. Additionally, as shown here, in ER-positive tumors, estrogen can result in down-regulation of E-cadherin expression. How do these findings relate to known clinical data? Not surprisingly, there is little consensus between numerous studies addressing the relationship between hormone receptor status and E-cadherin expression. There have been studies showing a positive (28), a negative (29), or no correlation (30) between E-cadherin and ER levels. This might, at least in part, be explained by the analysis of “mixed samples,” i.e., ER-positive as well as ER-negative samples. As clearly shown by Fujita et al. (Fig. 7 in Ref. 9), ER-positive and ER-negative tumors display very different and even opposite correlations between ER, E-cadherin, Snail, and MTA3. We would like to propose that this, at least in part, results from the estrogen-mediated down-regulation of E-cadherin in ER-positive samples. More clinical studies analyzing either only ER-positive or only ER-negative cases are needed to support these models. Potentially, our findings could have clinical impact, because restoration of E-cadherin expression might be an important result of antiestrogen therapy, and, thus, selective estrogen receptor modulators (SERMs) should be tested regarding their effects on E-cadherin expression.

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References


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