Genistein Prevents BRCA1 CpG Methylation and Proliferation in Human Breast Cancer Cells with Activated Aromatic Hydrocarbon Receptor

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Abstract

Background: Previous studies have suggested a causative role for agonists of the aromatic hydrocarbon receptor (AhR) in the etiology of breast cancer 1, early-onset (BRCA-1)–silenced breast tumors, for which prospects for treatment remain poor.

Objectives: We investigated the regulation of BRCA1 by the soy isoflavone genistein (GEN) in human estrogen receptor α (ERα)–positive Michigan Cancer Foundation-7 (MCF-7) and ERα-negative sporadic University of Arizona Cell Culture-3199 (UACC-3199) breast cancer cells, respectively, with inducible and constitutively active AhR.

Methods: In MCF-7 cells, we analyzed the dose- and time-dependent effects of GEN and (-)-epigallocatechin-3-gallate (EGCG) control, selected as prototype dietary DNA methyltransferase (DNMT) inhibitors, on BRCA1 expression after AhR activation with 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) and in TCDD-washout experiments. We compared the effects of GEN and EGCG on BRCA1 cytosine-phosphate-guanine (CpG) methylation and cell proliferation. Controls for DNA methylation and proliferation were changes in expression of BRCA1 and estrogen receptor-1 (ESR1) CpG methylation, cyclin D1, and cell growth. Finally, we examined the effects of GEN and αNF on BRCA1, AhR-inducible cytochrome P450 (CYP)-1A1 (CYP1A1) and CYP1B1, and AhR mRNA expression.

Results: In MCF-7 cells, GEN exerted dose- and time-dependent preventative effects against TCDD-dependent downregulation of BRCA1. After TCDD washout, GEN rescued BRCA1 protein expression while reducing DNMT-1 and cyclin D1. GEN and EGCG reduced BRCA1 CpG methylation and cell proliferation associated with increased p53. In UACC-3199 cells, GEN reduced BRCA1 and estrogen receptor-1 (ESR1) CpG methylation, cyclin D1, and cell growth while inducing BRCA1 and CYP1A1.

Conclusions: Results suggest preventative effects for GEN and EGCG against BRCA1 CpG methylation and downregulation in ERα-positive breast cancer cells with activated AhR. GEN and flavone antagonists of AhR may be useful for reactivation of BRCA1 and ERα via CpG demethylation in ERα-negative breast cancer cells harboring constitutively active AhR. Curr Dev Nutr 2017;1:e000562.

Introduction

The breast cancer 1, early-onset (BRCA1) gene encodes a tumor suppressor protein involved in DNA repair and cell cycle control (1). In women who carry a mutated BRCA1 copy (BRCA1<sup>−/−</sup>), the silencing of the wild-type allele creates a BRCA1-deficient phenotype, which is associated with a high probability (~60–80%) of developing breast cancer (2, 3). On the other hand, sporadic breast cancers, which represent the majority (~90%) of breast...
tumor cases, do not have mutations in BRCA1 (BRCA1<sup>+/−</sup>) but display a “BRCAness” phenotype commonly observed in hereditary BRCA1 tumors. This phenotype includes absent or markedly reduced concentrations of BRCA-1 (4, 5), loss of estrogen receptor α (ERα), and basal-like pathology subtype (6). Therefore, elucidating the nonmutational mechanisms that contribute to silencing of BRCA1 has important implications for the prevention of both hereditary and sporadic breast cancers.

Epigenetics refers to modifications in chromatin structure [i.e., histone posttranslational modifications and DNA cytosine-phosphate-guanine (CpG) methylation] and noncoding RNAs (7). Sporadic breast cancers that have hypermethylated BRCA1 share features with hereditary BRCA1 mutation tumors [i.e., they tend to be triple-negative with reduced or absent expression of ERα, progesterone receptor (PR), and human epidermal growth factor receptor 2] (8). CpG methylation of BRCA1 is associated with reduced BRCA-1 expression in 50–60% of higher-histologic-grade sporadic tumors (9, 10). A high degree of correlation (~75%) is generally observed between hypermethylation of the BRCA1 and estrogen receptor-1 [ESR1 (ERα)] promoters and reduced expression of BRCA-1 and ERα protein (11, 12), which are invariably associated with resistance to endocrine therapies based on antagonists of the ERα (i.e., tamoxifen) (13). Therefore, main objectives in breast cancer research are to identify the mechanisms linking silencing of BRCA1 to the development of ERα-negative breast cancers, and clarify whether or not opportunities exist for the prevention of these tumors with dietary components.

Agonists of the aromatic hydrocarbon receptor (AhR) are ubiquitous in the environment and include dietary compounds, metabolites of FAs, industrial xenobiotics, and photoproducts generated in the skin from UV radiation (14). Results from our laboratory document that the BRCA1 gene is a target for epigenetic regulation by AhR. In the absence of exogenous ligands, AhR forms a transcription complex with ERα and various cofactors (p300, steroid receptor coactivator-1) (15) contributing to the transcriptional activation of BRCA1 by 17β-estradiol (E2) (16). Conversely, in the presence of agonists, AhR binds to xenobiotic response elements (XRE) with consensus 5'-GCGTG-3' sequence and harbored in the BRCA1 gene (17), and disrupts transcriptional activation by E2 (18). This repressive effect is coupled to the recruitment of DNA methyltransferase (DNMT) 1 and methyl binding protein (MBD) 2, loss of acetylated histone (AcH) 4 and AcH3K9 (19), and gain of trimethylated H3K9 (H3K9me3) and DNA CpG methylation (20). Recently, we reported that in rodent mammary tissue (21) and human breast tumors (22) with activated AhR, hypermethylation of BRCA1 was associated with reduced BRCA-1 and ERα expression. These cumulative data raised the question of whether or not dietary compounds that possess DNMT and AhR inhibitory properties may protect against CpG hypermethylation of BRCA1 and, ultimately, prevent breast tumorigenesis.

Genistein (GEN), a common dietary isoflavone, exerts antagonistic properties toward DNMT enzymes (23, 24). Evidence that it induces BRCA1 expression in ERα-positive breast cancer cells suggests potential relevance for this isoflavone in cancer prevention (25). Rodent offspring exposed to GEN in utero, through weaning (26), and prepuberty (27, 28) showed reduced mammary tumorigenesis in adult life. Through the inhibition of DNMT activity, GEN was shown to reactivate the expression of various tumor suppressor genes (i.e., ataxia telangiectasia mutated, adenomatous polyposis coli, phosphatase and tensin homolog) in ERα-positive Michigan Cancer Foundation-7 (MCF-7) and ERα-negative M.D. Anderson Cancer Center-metastatic breast cancer-231 (MDA-MB-231) breast cancer cells (29). Here, we investigated the impact of GEN and (−)-epigallocatechin-3-gallate (EGCG) control on BRCA1 methylation and expression in a human ERα-positive breast cancer cell line (MCF-7) with inducible AhR and hypomethylated BRCA1. We extended the BRCA1 expression and DNA methylation studies with GEN and α-naphthoflavone (αNF; 7,8-benzoflavone), a synthetic flavone and AhR antagonist, to a human ERα-negative cell line model University of Arizona Cell Culture-3199 (UACC-3199) of sporadic breast cancer harboring constitutively activated AhR and hypermethylated BRCA1 (4).

Methods

Cell culture

Human MCF-7 and UACC-3199 breast cancer cells were obtained from the American Type Culture Collection and maintained, respectively, in DMEM or Roswell Park Memorial Institute (RPMI) 1640 media (Mediatech) supplemented with 10% fetal calf serum (Hyclone Laboratories). The 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) concentration so far was 10 nM.

FIGURE 1 GEN prevents repression of BRCA-1 in breast cancer Michigan Cancer Foundation-7 cells with activated aromatic hydrocarbon receptor. Cells were cultured for 72 h in control medium containing E2 (10 nM) or TCDD (10 nM) (A) or E2 + TCDD and various concentrations of GEN (B) as described in Methods. Bands show immunocomplexes for BRCA-1 and the internal standard GAPDH. (C, D) Bars represent means ± SEMs of BRCA-1 expression (fold of control) from 4 (C) and 2 (D) separate experiments performed in duplicate. Labeled means without a common letter differ, P < 0.05. BRCA-1, breast cancer 1, early onset; E2, 17β-estradiol; GEN, genistein; TCDD, 2,3,7,8-tetrachlorodibenzo-p-dioxin.
(TCDD) was supplied by the National Cancer Institute, Division of Cancer Biology, Chemical and Physical Carcinogenesis Branch (NIH), and distributed by Midwest Research Institute (contracts 64 CFR 72090 and 64 CFR 28205). GEN, αNF, EGCG, and E2 were obtained from Sigma-Aldrich and solubilized in stock solutions with ethanol, which was added to DMEM or RPMI as the vehicle control. Cells (passages 3–15) were plated in 6-well plates at a density of 5 × 10⁵ cells/well in Phenol-Red free DMEM (MCF-7) or RPMI (UACC-3199) supplemented with 10% charcoal-stripped fetal calf serum (22). For Western blotting, cells were washed with ice-cold PBS and scraped with cold lysis buffer containing protease inhibitor. For proliferation measurements, cells were washed with ice-cold PBS and counted by 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) colorimetric assay (Promega), as described previously (30). This assay is based on the conversion of the yellow tetrazolium dye MTT to purple formazan crystals by metabolically active cells. Briefly, 2 × 10⁴ cells were seeded in 96-well tissue culture plates and maintained overnight. Six replicates were assigned to each experimental treatment. After treatment, 15 μL MTT dye solution was added to each well, and the plate was incubated for 4 h at 37°C. Solubilization/stop solution (100 μL) was added for 1 h at room temperature, and the absorbance at 570/650 nm was recorded by using a Synergy HT plate reader (Bio-Tek Instruments).

**Western blot analysis**

Western blot analyses were performed as previously described (22). Immunoblotting was carried out with antibodies against human BRCA-1 (catalog no. 9010), DNMT-1 (catalog no. 5119), cyclin D1 (catalog no. 92G2), phospho-p53-(Ser20) (catalog no. 9287), and GAPDH (catalog no. 2118) obtained from Cell Signaling Technology, and ERα (catalog no. sc-542) obtained from Santa Cruz Biotechnology. Immunocomplexes were detected by using enhanced chemiluminescence (GE Healthcare Life Sciences). The GAPDH protein was used as an internal control for normalization of protein expression.
Promoter CpG methylation

qPCR analysis of human BRCA1 and ESR1 promoter CpG methylation was performed as described previously (20) with bisulfonated genomic DNA with the use of the following unmethylated (U)- and methylated (M)-specific primers (Sigma-Aldrich):

**BRCA1**: U-sense: 5'-TTGGTTTTTGTGGTAATGGAAAAG-TGT-3'; and U-antisense: 5'-CAAAAAATCTCAACAAACTCACAACCA-3'; M-sense: 5'-TGTTAAACGGAAGCG-3'; and M-antisense: 5'-ATCTCAACGAACTCACGC-3'

**ESR1**: U-sense: 5'-GGATATGGTTTTGTGTAATTGGAAAAAG-TGT-3'; and U-antisense: 5'-AAAAAATCTCAACAAACTCAACCA-3'; M-sense: 5'-TGTTAAACGGAAGCG-3'; and M-antisense: 5'-ATCTCAACGAACTCACGC-3'

The qPCR was carried out in a volume of 10 μL consisting of the following master mix: 5 μL SYBER Green mix (Life Technologies), 1 μL each of forward and reverse primers, 2 μL nuclease-free water, and 1 μL bisulfonated genomic DNA. Data from qPCR of bisulfonated DNA were presented as ratios of CpG M:U.

mRNA analyses

Total RNA was purified by using an RNeasy Mini Kit as per the manufacturer's instructions (Qiagen) (22). Concentrations and quality of RNA were verified by using the Nanodrop1000 Spectrophotometer (Thermo Scientific). Equal amounts of total RNA (500 ng) were transcribed into cDNA by using the ISCRIPTr supermix kit (Bio-Rad Laboratories). Next, cDNA aliquots were analyzed by qPCR with the use of the SYBR Green PCR Reagents kit (Life Technologies). Briefly, reactions were assayed at a final volume of 25 μL consisting of the following master mix: 12.5 μL SYBR Green mix, 1 μL each of forward and reverse primers, 9.5 μL nuclease-free water, and 1 μL cDNA. Amplification of GAPDH mRNA was used for normalization of transcript levels. The primer (Sigma-Aldrich) sequences were as follows—BRCA1: sense, 5'-AGCTCGCTGAGACTTCCTGGA-3'; antisense, 5'-CAATTCAATGTAGACAGACGT-3'; CYP1A1: sense, 5'-TAACATCGTCTTGGACCTCTTTG-3'; antisense, 5'-GTCGATAGCACCATCAGGGGT-3'; CYP1B1: sense, 5'-GGTTTTTGAGTTTTTTGTTTTG-3'; antisense, 5'-AACTTACTACTATCCAAATACACCTC-3'; CYP2E1: sense, 5'-TGGTTTTTGTGGTAATGGAAAAG-TGT-3'; antisense, 5'-CAAAAAATCTCAACAAACTCAACCA-3'; CYP1B1: sense, 5'-GGTTTTTGAGTTTTTTGTTTTG-3'; antisense, 5'-AACTTACTACTATCCAAATACACCTC-3'.

**FIGURE 4** GEN and EGCG induce p53 expression in breast cancer Michigan Cancer Foundation-7 cells with activated aromatic hydrocarbon receptor. Cells were cultured for 24, 48, and 72 h in control medium containing E2 (10 nM), E2 + TCDD (10 nM), and E2 + TCDD + 1 μM GEN or EGCG. (A) Bands show immunocomplexes for p53 and the internal standard GAPDH. (B) Bars represent means ± SEMs of p53 expression (fold of E2) from 2 separate experiments performed in duplicate. Labeled means without a common letter differ, P < 0.05. EGCG, (-)-epigallocatechin-3-gallate; E2, 17β-estradiol; GEN, genistein; TCDD, 2,3,7,8-tetrachlorodibenzo-p-dioxin.

**FIGURE 5** Short-term reversal effects of GEN and EGCG on BRCA-1 expression in breast cancer Michigan Cancer Foundation-7 cells with activated aromatic hydrocarbon receptor. Cells were precultured for 48 h in control medium plus E2 (10 nM) or E2 + TCDD (10 nM). Then, media were washed out and cells were cultured for an additional 24 and 48 h in the presence of E2 alone or E2 + 1 μM GEN or EGCG. Panels A and B show, respectively, bands and quantitation (fold of E2; means ± SEMs) of immunocomplexes for BRCA-1 from 3 independent experiments performed in duplicate. (C) Bands show immunocomplexes for ERα and the internal standard GAPDH. (D) Bars represent means ± SEMs of cell proliferation determined by MTT assay (fold of control) from 2 separate experiments with 6 replicates. Labeled means without a common letter differ, P < 0.05. BRCA-1, breast cancer 1, early onset; EGCG, (-)-epigallocatechin-3-gallate; E2, 17β-estradiol; GEN, genistein; MTT, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide; TCDD, 2,3,7,8-tetrachlorodibenzo-p-dioxin.
RESULTS

Statistical analysis

Densitometry after Western blotting was performed by using Kodak ID Image Analysis Software (Eastman Kodak Company). Statistical analyses were performed by 1-factor ANOVA after assessing data normality by using a Shapiro-Wilk test and variance homogeneity by using Bartlett’s test. Post hoc multiple comparisons among all means were conducted by using Tukey’s test after main effects and interactions were found to be significant at $P \leq 0.05$. Data are presented as means ± SEMs. When ≥3 means were compared, significant differences are highlighted with different letters (a > b > c).

Results

**GEN prevents AhR-dependent downregulation of BRCA-1**

In control experiments, we first confirmed that at 24-h post-treatment, E2 (10 nM) induced an increase of ~2.0-fold in BRCA-1 protein expression compared with the vehicle control (Figure 1A, B). This dose of E2 was used throughout this study and was similar to that used previously to investigate regulation of BRCA-1 in human breast cancer cells (16) and detected in women around the human menstrual phase and in patients receiving E2 replacement therapy (31, 32). In contrast, as documented previously (19, 20), an equimolar dose (10 nM) of TCDD did not change basal BRCA-1 concentrations (Figure 1B), but it reduced (~50%) E2-induced BRCA-1 expression (Figure 1C, D). This dose of TCDD was used throughout this study and approached the concentration found in blood (33, 34) and lipid tissue (35) of women exposed to environmental AhR agonists. Compared with E2 plus TCDD, doses of 0.5 and 1.0 μM GEN counteracted the repressive effects of TCDD on BRCA-1 expression (Figure 1C, D), whereas 2.0 μM GEN had no protective effects. Conversely, GEN at 5, 10, and 20 μM synergized with TCDD to lower BRCA-1 expression to control levels.

In follow-up experiments, we examined the time-dependent effects of GEN at the 1-μM concentration, which approaches the serum concentration of GEN measured in persons with habitual soy intake and is known to induce BRCA-1 expression in breast cancer cells (25). The cotreatment with GEN protected against
TCDD-mediated repression of BRCA-1 at 24 h, an effect that persisted at 48 and 72 h (Figure 2A, C). As a positive control for GEN, we used EGCG, which in previous studies was shown to reactivate methylation-silenced genes in cancer cells (36). At equimolar concentrations (1 μM), EGCG counteracted the repressive effects of TCDD and restored BRCA-1 expression to E2 levels by 48 and 72 h (Figure 2B, C).

Growth of MCF-7 cells was induced (~2.0 fold) by E2 within 72 h. The treatment with TCDD had no effects on cell proliferation, whereas the combination of TCDD plus E2 reduced cell growth by ~30% (Figure 3A) compared with E2 alone. The co-treatment with GEN and EGCG repressed E2-induced cell growth by ~50%, irrespective of the presence or absence of TCDD. Inhibitory effects (~50%) on E2-induced cell growth were also seen for EGCG, whereas the combination of GEN plus EGCG reduced cell growth by ~80% compared with E2 treatment. As a control for cell proliferation, we examined by Western blotting changes in cyclin D1, whose expression in MCF-7 cotreated with E2 plus TCDD was reduced (~30%) by GEN (Figure 3B, C). In contrast, GEN and EGCG increased the expression of the tumor suppressor p53 (Figure 4).

GEN reverses AhR-mediated BRCA-1 downregulation

We next asked whether or not GEN could exert reversal effects on BRCA-1 after the removal of AhR agonist. MCF-7 cells were cultured in the presence of E2 or E2 plus TCDD for 24 h. Then, cells were cultured for an additional 24 and 48 h in fresh control medium containing E2 alone or E2 plus GEN or EGCG. The post-treatment with EGCG at 48 h, but not E2 alone or E2 plus EGCG at 24 h, restored BRCA-1 expression to E2 levels (Figure 5A, B). Similarly, the post-treatment with GEN for 24 and 48 h induced (~0.5–0.7 fold) BRCA-1 expression compared with the E2 control. As previously shown (19), the expression of ERα was not influenced by cotreatment with TCDD plus E2 or GEN plus E2 after washout of TCDD (Figure 5C). Compared with control, the treatment with E2 did not induce cell growth (Figure 5D). We did, however, observe a significant reduction (~60%) in cell proliferation with GEN (1 μM), irrespective of the presence or absence of E2. We extended the washout studies to longer time periods and found that the post-treatment for 7, 8, and 9 d with E2 plus GEN rescued BRCA-1 expression above E2 alone (Figure 6A, C). Reversal effects on BRCA-1 were also seen for EGCG at days 8 and 9 compared with the E2 control (Figure 6B, C). Overall, these results suggested that post-treatment with GEN and EGCG reversed AhR-dependent downregulation of BRCA-1, albeit with different efficacy (GEN > EGCG).

GEN counteracts AhR-inducible BRCA1 CpG methylation

DNMT-1 is a maintenance DNA methylation enzyme (7). Therefore, we tested whether or not the BRCA-1 responses to AhR activation and GEN were linked to changes in DNMT-1 expression. We found that after washout of TCDD, the post-treatments of MCF-7 cells with E2 for 24 and 48 h were associated with a 1.8- and 2.8-fold accumulation of DNMT-1, respectively (Figure 7A, B). In contrast, the post-treatment with E2 plus GEN reduced DNMT-1 to control levels. These DNMT-1 changes correlated with induction (1.3-fold) in methylation of a CpG island flanking the BRCA1 transcription start site of exon 1A (Figure 7C, D). Conversely, the post-treatment with GEN lowered BRCA1 CpG methylation compared with E2 control (~50%) and E2 plus TCDD (~80%). Similarly, the post-treatment with EGCG reduced BRCA1 methylation compared with the E2...
control (~70%) and E2 plus TCDD (~90%). These DNA demethylation results were consistent with earlier reports documenting reactivation of tumor suppressor genes by GEN (23, 37) and EGCG (36).

**GEN reverses BRCA1 silencing associated with constitutively active AhR**

ERα-negative UACC-3199 cells harbor constitutive hypermethylated BRCA1 (4) and active AhR (22). Compared with control, E2 (10 μM) and GEN at 1 and 5 μM did not influence BRCA1 expression, which, however, was induced ~0.4-fold by 10 and 20 μM GEN (Figure 8A, B). As a positive control for AhR inhibition, we used the synthetic flavone αNF (2 μM) (14), which in UACC-3199 cells induced BRCA1 and ERα expression irrespective of the presence or absence of E2 (Figure 8C, D). Western blots of cell lysates from MCF-7 cells (Figure 8C) provided a positive control for the detection of BRCA1 and ERα immunocomplexes.

![Graph](image_url)

**FIGURE 9** GEN and αNF inhibit cell proliferation in UACC-3199 cells with constitutively active aromatic hydrocarbon receptor. (A) UACC-3199 cells were cultured for 72 h in control medium and in the presence of E2 (10 nM), GEN (1 and 10 μM), and E2 + GEN or αNF (2 μM) and E2 + αNF. Bars represent means ± SEMs of quantitation (fold of control) of proliferation determined by MTT assay from 2 separate experiments with 5 replicates. (B) Bands show representative immunocomplexes for cyclin D1 and the internal standard GAPDH in UACC-3199 cells cultured for 72 h in control medium and after treatment with E2, αNF, E2 + αNF, or E2 + GEN. (C) Bars represent means ± SEMs of cyclin D1 quantitation (fold of control) from 2 independent experiments performed in duplicate. Labeled means without a common letter differ, P < 0.05. E2, 17β-estradiol; GEN, genistein; MTT, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide; UACC, University of Arizona Cell Culture; αNF, α-naphthoflavone.

The treatment of UACC-3199 cells for 72 h with E2 and GEN (1 and 10 μM) or αNF (2 μM) (Figure 9A) reduced cell proliferation by ~50% and 20%, respectively. The antiproliferative effects of GEN (10 μM) and αNF (2 μM) increased to ~70% and 50%, respectively, in combination with E2. The expression of cyclin D1 (Figure 9B, C) was reduced by αNF (~40%) and to a larger degree by 10 μM GEN (~70%), regardless of the absence or presence of E2. Interestingly, although E2 alone reduced growth of UACC-3199 cells (Figure 9A), it did not elicit measurable changes in cyclin D1 expression compared with the control (Figure 9C).

The upregulation of BRCA1 protein by GEN in UACC-3199 cells was paralleled by demethylation of BRCA1 and ESR1 (ERα), as determined by qPCR amplification of bisulfonated DNA (Figure 10A). The treatment with αNF reduced by ~60% BRCA1 CpG methylation, thus providing a positive control for methylation changes related to AhR. GEN and αNF stimulated BRCA1 mRNA by ~10- and 6.0-fold, respectively, compared with E2 treatment (Figure 10B).

**GEN and αNF preferentially induce CYP1A1 in breast cancer cells with constitutively active AhR**

CYP1A1 and CYP1B1 genes are transcriptional targets for AhR, which is constitutively active in subsets of preclinical and human breast tumors (38, 39). The treatment with GEN alone or in combination with E2 induced (1.2-fold) CYP1A1 mRNA (Figure 11A) but did not affect the expression of CYP1B1 (Figure 11B) or AhR (Figure 10C). As previously shown (22), we found that αNF induced a large increase (~40-fold) in CYP1A1 (Figure 10A) and a smaller accumulation (1.0- to 1.7-fold) in CYP1B1 (Figure 11B) while lowering (~50%) AhR (Figure 11C) mRNA. Overall, these cumulative data indicated that in ERα-negative breast epithelial cells with constitutively active AhR, both GEN and αNF stimulated BRCA1 via CpG demethylation, an effect that was associated with reactivation of ESR1 and preferential activation of CYP1A1 over CYP1B1.

**Discussion**

Historically, AhR has been investigated for its role in the transcriptional regulation of genes encoding phase I enzymes (e.g., CYP1A1, CYP1B1). However, studies also proposed a causative role for AhR in the etiology of breast tumorigenesis (39). Our published findings obtained from human breast cell lines (17–20) and rodent mammary tissue (21) indicated that the activation of AhR induced a pattern of BRCA1 methylation around exon 1a that overlapped with that observed in human sporadic breast tumors with reduced BRCA1 expression (10) and overexpressing AhR (22). Therefore, the first objective of this study was to examine in ERα-positive breast cancer cells with wild-type BRCA1 (4) and a functional AhR pathway (40) the regulation by GEN of BRCA1 expression and CpG methylation. To activate AhR, we used the agonist TCDD because of its long half-life (~8 y) (33). Therefore, changes in BRCA1 expression could be analyzed without the confounding effects due to reactive metabolites. We focused on GEN as a cancer preventative because it is the major isoflavone in soy, and its consumption during early life has been linked to reduced breast cancer risk in Asian (41) and North...
American (42) women. We found that GEN exerted bimodal effects on MCF-7 cells with activated AhR. Doses ranging from 5 to 20 \( \mu \text{M} \) amplified the repressive effects of TCDD on BRCA-1 expression. The latter results were supportive of the tumor-promoting effects previously observed for GEN in ER\(_\alpha\)-dependent (43) and AhR-dependent (44) mammary tumor models. In contrast, the treatment of MCF-7 cells with lower doses of GEN (0.5 and 1.0 \( \mu \text{M} \)) counteracted the effects of TCDD and restored BRCA-1 expression to E2 levels. In previous studies, similar concentrations (0.5–1.0 \( \mu \text{M} \)) of GEN were shown to stimulate BRCA-1 expression in breast cancer cells (25). We also found that 1.0 \( \mu \text{M} \) GEN antagonized cell proliferation, an effect associated with downregulation of cyclin D1 and upregulation of p53. These results were in accord with earlier reports that highlighted the requirement for cyclin D1 in cell proliferation (45) and with other studies that showed that GEN induced G1 arrest in ER\(_\alpha\)-positive breast cancer cells (46) and protected against AhR-induced mammary tumorigenesis (27, 28).

The presence of putative binding elements for AhR and ER\(_\alpha\) in the \( \text{DNMT}1 \) gene (47, 48) may explain, at least in part, the increased DNMT-1 expression observed in MCF-7 cells treated with TCDD and E2. Conversely, GEN reduced DNMT-1 expression and \( \text{BRCA1} \) CpG methylation. Repression of DNMT-1 by GEN has been described previously in human breast cancer cells (MCF-7, MDA-MB-231) (29). EGCG provided a positive control for \( \text{BRCA1} \) methylation experiments with GEN in MCF-7 cells. It has been shown to reactivate the expression of methylated-silenced tumor suppressor genes (36).

The second objective of this study was to test if GEN could reactivate \( \text{BRCA1} \) under conditions of constitutive expression and activation of AhR. For this purpose, we turned to the ER\(_\alpha\)-negative

**FIGURE 10** Reversal effects of GEN and \( \alpha\)NF on \( \text{BRCA1} \) CpG methylation in UACC-3199 cells with constitutively active aromatic hydrocarbon receptor. (A) Bars represent means ± SEMs of quantitation from 2 independent experiments performed in triplicate of \( \text{BRCA1} \) and \( \text{ESR1} \) promoter CpG methylation (fold of control) in UACC-3199 cells after treatment for 72 h with E2 (10 nM), GEN (1, 5, and 10 \( \mu \text{M} \)), or \( \alpha\)NF (2 \( \mu \text{M} \)). (B) Bars represent means ± SEMs of quantitation of \( \text{BRCA1} \) mRNA (fold of E2) by qPCR from 2 independent experiments performed in quadruplicate with GEN (1 \( \mu \text{M} \)) and \( \alpha\)NF (2 \( \mu \text{M} \)) and corrected for GAPDH mRNA as the internal standard. Labeled means without a common letter differ, \( P < 0.05 \). \( \text{BRCA1} \), breast cancer 1, early onset; \( \text{CpG} \), cytosine-phosphate-guanine; \( \text{ESR1} \), estrogen receptor-1; E2, 17β-estradiol; GEN, genistein; M:U, methylated/unmethylated; UACC, University of Arizona Cell Culture; \( \alpha\)NF, \( \alpha\)-naphthoflavone.

**FIGURE 11** GEN and \( \alpha\)NF differentially regulate expression of \( \text{CYPs} \) and AhR in UACC-3199 cells with constitutively active AhR. UACC-3199 cells were cultured for 72 h in control medium or in the presence of E2 (10 nM) + GEN or \( \alpha\)NF. Bars represent means ± SEMs of quantitation (fold of control) of \( \text{CYP}1\text{A1} \) (A), \( \text{CYP}1\text{B1} \) (B), and AhR (C) mRNA from 2 independent experiments performed in quadruplicate and corrected for GAPDH mRNA as the internal standard. Labeled means without a common letter differ, \( P < 0.05 \). AhR, aromatic hydrocarbon receptor; \( \text{CYP} \), cytochrome P450; \( \text{CYP}1\text{A1} \), cytochrome P450-1A1; \( \text{CYP}1\text{B1} \), cytochrome P450-1B1; E2, 17β-estradiol; GEN, genistein; UACC, University of Arizona Cell Culture; \( \alpha\)NF, \( \alpha\)-naphthoflavone.
UACC-3199 cell line, which was derived from a sporadic human breast tumor harboring wild-type, but hypermethylated, BRCA1 (4), and constitutively high levels of AhR (22). GEN doses of 10 and 20 μM induced BRCA1 expression, whereas lower concentrations (1 and 5 μM) had no effects. These data suggest that higher amounts of GEN may be needed to trigger a BRCA1 response in ERα-negative breast tumors overexpressing AhR. The CpG demethylation of BRCA1 and ESR1 observed in UACC-3199 cells with 10 μM GEN may be clinically relevant because comparable serum concentrations have been measured in animals (49, 50) and humans (51, 52) for GEN (~4.5 μM) and for total isoflavones (~3.0–7.0 μM). Previous studies of isoflavones and catechins showed weak affinity for AhR with half maximal inhibitory concentration (IC₅₀ > 50–200 μM) (53). Therefore, it is unlikely that GEN and EGCG induced demethylation of BRCA1 through physical interference with AhR. Possibly, the CpG demethylating effects of GEN and EGCG could be due to reduced DNM1-1 expression (29) and activity on BRCA1 (20) and ESR1, as recently reported in ERα-negative breast cancer cells (54).

Previous studies documented the antiproliferative effects of E2 and GEN in ERα-negative breast cancer cells (55). GEN was shown to have greater affinity for ERβ than for ERα, whereas the binding affinities of E2 for ERα and ERβ were equivalent (56). Therefore, E2 and GEN may inhibit the growth of ERα-negative cells by targeting ERβ (57). In support of this idea, agonism and overexpression of ERβ have been shown to attenuate the proliferation of triple-negative breast cancers through cell cycle arrest in the G1 phase (58) and to reduce tumor formation by causing G2 phase arrest (59). Furthermore, CpG demethylation of BRCA1 and ESR1 (ERα) by GEN and αNF in UACC-3199 cells suggested that regimens based on dietary flavonoids may have clinical relevance for therapy of tumors with BRCA1/BRCA2 deficiency. In support of this inference, we noted that GEN and αNF hampered the expression of cyclin D1 and the growth of UACC-3199 cells. αNF is an AhR antagonist at the BRCA1 gene (60), with IC₅₀ approaches ~0.4 μM (53), and a potent aromatase inhibitor (61). It shares structural similarity with GEN and the flavonol galangin (3,5,7-trihydroxyflavone; IC₅₀ ~0.2 μM) (53), which was found to block the proliferation of ERα-negative breast cancer cells overexpressing AhR (62).

Finally, we reported that treatment of UACC-3199 cells with GEN and αNF activated preferentially CYPIA1 with only modest (αNF) or no (GEN) effects on CYPIB1. This selective activation of CYPIA1 may have therapeutic relevance because increased CYPIA1 expression associates with reduced basal AhR activity (63) and increased apoptosis (64). In addition, a reduction in 4-hydroxylation of E2 by αNF, a reaction catalyzed by CYPIB1, was shown to reduce the production of the highly carcinogenic metabolite 4-hydroxy-E2 and mammary tumorigenesis (65). In summary, the results of this study suggest preventative effects for GEN and EGCG against proliferation and AhR-mediated BRCA1 CpG methylation in ERα-positive breast cancer cells. We also presented evidence that GEN and αNF, selected respectively, as a prototype flavone and AhR antagonist, may hold promise for reactivation of BRCA1 in ERα-negative sporadic breast tumors with constitutively activate AhR.

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