Isothiocyanates repress estrogen receptor α expression in breast cancer cells

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Abstract. The isothiocyanates (ITCs) have long been known to possess chemopreventive activities for a variety of neoplasms including breast cancer, but the molecular mechanism by which ITCs prevent breast cancer development has not been established. In this study, we investigated the effects of benzyl and phenethyl isothiocyanate (BITC and PEITC) on the estrogen-stimulated growth of estrogen receptor α (ERα)-positive breast cancer MCF7 and T-47D cells. BITC and PEITC inhibited estrogen-stimulated cell growth and reduced the expression levels of ERα in MCF7 and T-47D cells in a dose- and time-dependent and reversible manner. In addition, BITC and PEITC also abrogated the transcriptional activity of ERα and hence inhibited estrogen-stimulated expression of the estrogen responsive gene, p52. These results demonstrated that BITC and PEITC function as potent ERα disruptors to abrogate mitogenic estrogen signaling in ER-positive breast cancer cells, which provides a molecular explanation for the growth inhibitory function of ITCs in breast cancer development, and a rational for further exploration of ITCs as chemopreventive agents for human mammary carcinogenesis.

Introduction

Breast cancer is a leading cause of cancer-related deaths among women in the United States. Despite the fact that significant advances have occurred in the understanding of the biology and etiology of breast cancer development, there is still no effective treatment and prevention for this deadly disease. Experimental evidence for the role of endogenous estrogens in breast cancer etiology has been well documented. It is believed that estrogen signaling is involved in mammary epithelial cell proliferation and differentiation. Dysregulated estrogen signaling increases the rate of cell proliferation and thus the risk of breast cancer.

The growth-promoting function of estrogen is mediated by specific receptors designated as estrogen receptors (ERs). ERα belongs to the nuclear receptor superfamily and have two isoforms (ERα and ERβ) encoded by independent genes (1). Both ERs are composed of three independent but interacting functional domains: the A/B or N-terminal domain, the C or DNA-binding domain, and the D/E/F or ligand-binding domain. In cell lines and some tissues, 17ß-estrodial (E2ß) elicits proliferation in the presence of ERα but inhibits proliferation in the presence of ERß (1). Recently, loss of tumorigenesis was observed in ERβ transfected ERα-positive breast cancer MCF7 cells (2). Therefore, ERα is considered to be responsible for the estrogen-stimulated cell proliferation while ERß has protective activity. The binding of estrogen to ERs leads to receptor phosphorylation, dimerization and recruitment of co-activators to the estrogen-bound receptor complex, which in turn binds the promoter regions of target genes via direct interaction with the DNA binding site known as estrogen response element (ERE) and activates transcription of target genes. Activated ERs can also transactivate additional target genes through protein-protein interaction with other transcription factors such as the Jun/Fos activator protein 1 (AP-1) and Sp1 (3,4). Stimulation of target gene expression by ERs in response to estrogen is prevalently thought to be responsible for estrogen-stimulated cell proliferation. Thus, targeting ERs itself and ERα-mediated mitogenic estrogen signaling provides an effective approach to treat or prevent ER-positive breast cancer.

Epidemiological and pharmacological evidence indicates that isothiocyanates (ITCs) have substantial chemopreventive activities against various types of cancer including breast, lung, bladder, pancreatic and prostate cancer (5-10). ITCs exist as conjugates in the genus Brassica of cruciferous vegetables (e.g., cabbage, cauliflower, brussels sprouts, watercress, broccoli, mustard) and the genus Raphanus (radishes and daikons) (11,12). More than 25 natural and synthetic ITCs have been demonstrated to block chemically-induced carcinogenesis effectively by blocking carcinogen metabolic activation and enhancing carcinogen detoxification (13-16). In addition to their roles in cancer prevention, isothiocyanates also potentely inhibit the malignant growth in...
cancer cells by inducing cell cycle arrest and apoptosis with little or no toxicity toward normal cells (17-19). Benzyl isothiocyanate (BITC) and phenethyl isothiocyanate (PEITC) (Fig. 1) are two well studied ITCs for their inhibitory functions in different cancer cells. BITC and PEITC were potent in inducing apoptosis and activating caspases in bladder cancer cells (20). It was also reported that BITC effectively suppressed growth of human breast cancer cells by causing G2-M phase cell cycle arrest and apoptosis induction (7). Hence, Tseng et al also examined the potency of BITC and PEITC as chemotherapy reagents for human breast cancer cells (21).

Recently, epidemiologic evidence indicated that dietary intake of dietary ITC-containing cruciferous vegetables may have preventive function against breast cancer development (9,10). However, the molecular mechanisms by which dietary ITCs prevent human mammary carcinogenesis are not well established.

In the present study, we have demonstrated that two well studied ITCs, PEITC and BITC, significantly down-regulate ERα expression, reduce ERα transcriptional activity and inhibit growth of ER-positive breast cancer MCF7 and T-47D cells.

Materials and methods
Reagents. PEITC and BITC were purchased from Sigma-Aldrich (St. Louis, MO, USA). ICI 182,780 was purchased from Tocris (Ellisville, MO, USA). The Luciferase Assay System was purchased from Promega Corp. (Madison, WI, USA). The ERα polyclonal antibody was obtained from Lab Vision Corp. (Fremont, CA, USA). The ERα antibody, the actin antibody, the goat anti-rabbit IgG-HRP and the donkey anti-goat IgG-HRP were purchased from Santa Cruz Biotechnology (Santa Cruz, CA, USA). MG-132 was purchased from CalBiochem (San Diego, CA, USA). The ECL Western Blotting Detection Reagents were purchased from GEHealthcare (Little Chalfont, Buckinghamshire, UK). The ‘Concert’ cytoplasmic RNA purification reagent was from Invitrogen (Carlsbad, CA, USA), and the ProtoScript II RT-PCR kit was purchased from New England BioLabs (Ipswich, MA, USA).

Cell culture. ER-positive breast cancer cell line, MCF7 and T-47D from ATCC (Manassas, VA, USA) were maintained in Improved Minimal Essential Medium (IMEM) from Invitrogen supplemented with 10% heat-inactivated fetal bovine serum (FBS), 1% non-essential amino-acids, 1% HEPES buffer, 1% antibiotic-antimycotic from Invitrogen, and 2 μg/ml bovine insulin (Sigma, St. Louis, MO, USA) at 37°C under 5% CO2 in a humidified incubator.

Cell growth inhibition assays. MCF7 and T-47D cells were changed to medium containing 5% charcoal-dextran stripped FBS for two days, and then seeded in 96-mm dishes at a density of 5x10^4 cells/dish in IMEM supplemented with 2.5% charcoal-dextran stripped FBS. After 24 h, cells were treated with vehicle (DMSO) and different concentrations of PEITC, BITC or ICI 182,780 for 3 days. Cells were then trypsinized and counted with a hemocytometer. Three dishes were used for each concentration point and the experiments were repeated three times.

To test the effects of the ITCs on estrogen-stimulated growth, MCF7 and T-47D cells were changed to medium containing 5% charcoal-dextran stripped FBS for two days, and then seeded in 35-mm dishes at a density of 5x10^4 cells/dish in IMEM containing 2.5% charcoal-dextran stripped FBS for another 24 h. Cells were treated with 1 nM of 17β-estradiol (E2) alone or together with different concentrations of PEITC, BITC or ICI 182,780 for 3 days. The cells were then trypsinized and counted with a hemocytometer.

DNA transfection and luciferase assay. MCF7 and T-47D cells maintained in IMEM medium containing 10% FBS were changed to medium containing 5% charcoal-dextran stripped FBS for two days, and then were seeded in 35-mm dishes at a density of 2x10^5 cells/dish for another day. Cells were transfected with the p2xERE-Luc reporter plasmid (a kind gift from Dr Katarine Pettersson at Karolinska Institute, Sweden) and a β-galactosidase expression plasmid, pCMV-β (Clontech Laboratories, Inc., Palo Alto, CA), to establish transfection efficiency. Twelve hours after transfection, cells were treated with 1 nM of E2 alone or together with different concentrations of PEITC, BITC or ICI 182,780. Twenty-four hours after transfection, cell extracts were prepared and aliquots were normalized for transfection efficiency by assay of β-galactosidase activity. Luciferase assays were performed using the luciferase reporter system in a TD 20/20 luminometer as instructed by the manufacturer.

RNA purification and RT-PCR. To examine the down-regulation of ERα mRNA by ITCs, MCF7 and T-47D cells cultured in IMEM containing 2.5% charcoal-dextran stripped FBS for two days were seeded in 6-well plates and treated with vehicle or different concentrations of PEITC, BITC or ICI 182,780 for 3 days. Cells were then harvested and washed with PBS, then trypsinized and counted with a hemocytometer. Three dishes were used for each concentration point and the experiments were repeated three times.

Figure 1. The chemical structures of phenethyl isothiocyanate (PEITC), benzyl isothiocyanate (BITC) and ICI 182,780.
FBS were treated with different concentrations of PEITC, BITC or ICI 182,780 for 12 h. To assess the effects of ITCs on estrogen-stimulated gene expression, MCF7 and T-47D cells maintained in medium containing 2.5% charcoal-dextran stripped FBS were treated with 1 nM of E2ß alone or together with different concentrations of PEITC, BITC or ICI 182,780 for 12 h. Total RNA was prepared with the ‘Concert’ cytoplasmic RNA purification reagent. One microgram of total RNA was reverse transcribed using ProtoScript II RT-PCR kit with random primers. The reverse transcription reaction was performed at 42°C for 1 h. Semi-quantitative RT-PCR of ERs, β-actin and pS2 were done using gene specific primers synthesized by Integrated DNA Technologies, Inc. (Coralville, IA, USA). The following are the primer sequences for ERs, β-actin and pS2.

ERs: forward primer, 5'-CAC TCA ACA GCG TGT CTC CGA-3'; reverse primer, 5'-CCA ATC TTT CTC TGC CAC CCT G-3'. β-actin: forward primer, 5'-TGA CGG GGT CCA CAC TGT GCC CAT GTA-3'; reverse primer, 5'-CTA GAA GCA TTT GCG GTG GAC GAT GGA GGG-3'. pS2: forward primer, 5'-TGG AGA ACA AGG TGA TCT GC-3'; reverse primer, 5'-ATC TGT GTT GTG AGC CGA CGA GG-3'.

The procedure of PCR for ERs and β-actin was carried out as following: first a denaturing at 95°C for 1 min, then the remaining PCR was performed at 94°C for 30 sec, 58°C for 30 sec and 68°C for 1 min (35 cycles for ERs and 25 cycles for β-actin). PCR for pS2 was started with a denaturing at 94°C for 3 min, then 94°C for 45 sec, 55°C for 45 sec and 72°C for 45 sec (30 cycles). At the end, there was a final elongation at 72°C for 7 min. PCR products were analyzed by electrophoresis on a 1.5% agarose gel and visualized by ethidium bromide staining under UV illumination.

Statistical analysis. Data were summarized as the mean ± standard error (SE) using GraphPad InStat software program. Tukey-Kramer Multiple Comparisons Test was used, and the significance was accepted for P-values of <0.05.
Results

PEITC and BITC repress ERα expression in MCF7 and T-47D cells. MCF7 and T-47D cells express high levels of ERα and strongly respond to mitogenic estrogen stimulation. Previously, it was reported that BITC and PEITC are potent growth inhibitors in breast cancer MCF7 cells (21), and PEITC repressed the expression of androgen receptor and inhibited growth of prostate cancer cells (22). Hence, we decided to examine the ERα expression in PEITC- or BITC-treated MCF7 and T-47D cells. Cells were incubated with different concentrations of PEITC or BITC for 12 h. Western blot analysis was performed to assess ERα expression. We found that the expression levels of ERα were dramatically reduced in PEITC- or BITC-treated MCF7 and T-47D cells in a dose-dependent manner (Fig. 2A and B). The well-known estrogen receptor disruptor, ICI 182,780 (Fig. 1) was also able to reduce levels of ERα expression but with much less efficiency compared to both BITC and PEITC at 12 h under higher concentrations (Fig. 2A and B). Furthermore, the expression levels of ERα in MCF7 and T-47D cells treated with 10 μM of PEITC or BITC for different time-points were also examined (Fig. 2C and D). ERα expression levels were started to reduce after treatment of PEITC and BITC for 6 h, and continued to decrease to a very low level at 48 h (Fig. 2C and D). As a positive control, ICI 182,780 treatment for 48 h, exhibited a strong reduction of ERα expression to a level comparable to the levels in cells treated with PEITC or BITC (Fig. 2C and D). However, both PEITC and BITC had no effect on ERβ expression (Fig. 2E and F).

PEITC and BITC repress ERα expression at the transcription level. It is well established that ICI 182,780 triggers the degradation of ERα protein through proteasome-dependent proteolysis (23). We decided to test whether the down-regulation of ERα protein by BITC and PEITC was via the same mechanism. MCF7 and T-47D cells were treated with 10 μM of BITC or PEITC alone or together with proteasome inhibitor MG-132 10 μM respectively for 12 h. Western blot analysis revealed that proteasome inhibitor MG-132 was unable to reverse the expression levels of ERα protein down-regulated by PEITC and BITC (Fig. 3). On the contrary, a further reduction of ERα protein expression was observed in the cells treated with ITCs and MG-132 (Fig. 3). However, the proteasome inhibitor MG132 efficiently blocked ICI 182,780 induced down-regulation of ERα protein (Fig. 3), consistent with the previous reports that ICI 182,780 induces degradation of ERα protein through the proteasome system (23,24). Our results thus suggested that PEITC and BITC functions through a different mechanism to repress ERα expression.

We then examined the mRNA levels of ERα in MCF7 and T-47D cells treated with different concentrations of PEITC or BITC for 12 h by RT-PCR analysis. We found that mRNA levels of ERα were dramatically reduced after the treatment of PEITC or BITC starting at 5 μM (Fig. 4), indicating that the suppression of ERα expression by PEITC and BITC occurs at the transcription level. While in ICI 182,780 treated cells, no change of ERα mRNA level was observed (Fig. 4), consistent with the previous report that ICI 182,780 has no effect on ERα transcription (23).

Down-regulation of ERα expression by PEITC and BITC is reversible. To further determine if the down-regulation of ERα by PEITC and BITC is a reversible process, the MCF7 and T-47D cells were treated with 10 μM of PEITC or BITC for 12 h, then washed with PBS twice and changed to normal medium without PEITC and BITC. The cells were harvested at different time-points after PEITC and BITC withdrawal and examined for ERα expression with Western blot analysis. The levels of ERα expression were almost fully recovered after 24 h (Fig. 5), indicating the suppression activities of PEITC and BITC is reversible. However, ERα down-regulation mediated by ICI 182,780 was not fully recovered by 24 h (Fig. 5).

PEITC and BITC inhibit ERα transcriptional activity. To further determine if PEITC and BITC would inhibit transcriptional signaling mediated by ERα. Transient transfection assays were conducted in MCF7 and T-47D cells using a luciferase reporter plasmid containing two copies of ERE binding sites. We found that E2β induced the luciferase...
reporter activity about 3-fold, which was then attenuated by PEITC or BITC in a dose-dependent manner (Fig. 6). As a positive control, the pure antagonist ICI 182,780 repressed the luciferase activity induced by estrogen treatment (Fig. 6).

We then examined the effects of PEITC and BITC on the estrogen-induced expression of pS2, an ERα targeting gene, in MCF7 and T-47D cells using RT-PCR analysis. We found that E2β at 1 nM induced pS2 expression in MCF7 and T-47D cells, which was strongly inhibited by both PEITC and BITC (Fig. 7). ICI 182,780 also antagonized the stimulatory effect of E2 in MCF7 and T-47D cells (Fig. 7). These results strongly indicated that PEITC and BITC are able to function as potent estrogen antagonists as the pure antiestrogen ICI 182,780.

Discussion

A number of studies have shown that ERα expression is elevated from very early stages of mammary carcinogenesis and thus is a risk factor for progression to invasive breast cancer (25-27). The ERα expression level in ER-positive tumors is greatly increased as compared to the neighboring normal tissues (28). This strong correlation between ERα expression and breast cancer development had made ERα an important target for drug development.

Antiestrogens designed to target ERα can be classified into two major groups: analogs of tamoxifen and its metabolites such as 4-hydroxytamoxifen that have mixed estrogenic/antiestrogenic actions, and pure antiestrogens such as ICI 182,780. Tamoxifen is commonly used for adjuvant therapy of breast cancer and is a key drug for breast cancer chemoprevention in high-risk women. ICI 182,780 impairs ERα dimerization and inhibits nuclear localization of ER (29,30). In addition, ICI 182,780 also accelerates degradation of the ERα protein without a reduction of ERα mRNA level (24).

In this report, we have demonstrated that PEITC and BITC, two well studied ITCs, strongly suppress ERα expression. The exposure of ER-positive breast cancer MCF7 and T-47D cells to PEITC or BITC resulted in a reduced level of ERα expression as demonstrated by Western blot analysis. The ERα expression was down-regulated by PEITC or BITC at a level comparable to the levels in cells treated with the pure estrogen antagonist ICI 182,780. We also found that proteasome inhibitor MG132 failed to reverse the down-regulation of ERα expression mediated by PEITC and BITC while efficiently restored the levels of ERα protein expression down-regulated by ICI 182,780. Thus, ICI 182,780 functions as an estrogen receptor disruptor to enhance degradation of ERα protein, resulting in an inhibition of mitogenic estrogen signaling.

In this report, we have demonstrated that PEITC and BITC, two well studied ITCs, strongly suppress ERα expression. The exposure of ER-positive breast cancer MCF7 and T-47D cells to PEITC or BITC resulted in a reduced level of ERα expression as demonstrated by Western blot analysis. The ERα expression was down-regulated by PEITC or BITC at a level comparable to the levels in cells treated with the pure estrogen antagonist ICI 182,780. We also found that proteasome inhibitor MG132 failed to reverse the down-regulation of ERα expression mediated by PEITC and BITC while efficiently restored the levels of ERα protein expression down-regulated by ICI 182,780. Thus, our results demonstrated that PEITC and BITC down-regulate ERα expression through a mechanism other than enhanced protein degradation through the proteasome system. A similar phenomenon was reported in the down-regulation of androgen receptor (AR) expression mediated by PEITC in prostate cancer cells; MG132 could not reverse the AR down-regulation after a 24-h incubation with PEITC (22). This result together with ours suggested that PEITC and BITC may function at the transcriptional level to negatively regulate gene expression.

We then used semi-quantitative RT-PCR analysis to demonstrate that PEITC and BITC could reduce the ERα transcripts in ER-positive breast cancer cells while ICI 182,780 had no effect on ERα mRNA as reported before (23,24). Thus, PEITC and BITC function as a negative regulator of ERα transcription. However, the molecular mechanism by which PEITC and BITC inhibit ERα transcription was not clear right now. Recently, it was reported that PEITC repress AR expression in prostate cancer cells at the transcriptional level through inhibition of the transcription...
factor Sp1 expression (22). There are several Sp1 binding sites in the proximal promoter region of ER that are essential for maximum ER transcription (31). It is thus possible that PEITC or BITC also inhibits Sp1 expression in ER-positive breast cancer MCF7 and T-47D cells, which then in turn attenuates ERα transcription. In addition, it was reported that ERα can activate transcription via formation of an ER-Sp1 complex on the GC-rich Sp1 binding sites in the promoter region of target genes and ERα enhances Sp1 DNA binding in a hormone-independent manner (32). In ERα promoter region, the formation of a multi-protein complex composed of Sp1, ERα and upstream stimulating factor 1 (USF-1) is essential for optimum ERα transcription (31). ERα might autoregulate the expression of itself through interaction with Sp1 bound to its promoter. Down-regulation of both ERα and Sp1 by PEITC and BITC may abrogate this positive feedback of ERα transcription regulation and further down-regulate ERα promoter activity.

As a result of ERα down-regulation, the transcriptional activities of ERα were reduced in ER-positive breast cancer MCF7 and T-47D cells treated with PEITC or BITC. Estrogen stimulated promoter activity of the ERE containing reporter plasmid and expression of the endogenous ERα targeting gene pS2 were dramatically reduced in the presence of PEITC or BITC. These results further confirm that PEITC and BITC repress ERα expression and its transcriptional activities. These data also indicate that PEITC and BITC may function as an inhibitor of the mitogenic estrogen signaling.

In humans, the maximal plasma concentration of PEITC after ingestion of 100 g watercress can reach as high as 1155 nM (ranges between 673 and 1155 nM, mean 928.5±250.7 nM) within 1.5 h (ranges between 1.5 and 4 h, mean 2.6±1.1 h) (33), and 1.04±0.22 μM concentration can be reached after a single 40-mg dose of PEITC (34). In animal experiments, the maximal plasma concentration of PEITC can reach 9.2±0.6 or 42.1±11.4 μM after doses of 10 and 100 μmol/kg in rats (35). Therefore, the PEITC and BITC concentrations required to produce statistically significant inhibition of ERα expression in human breast cancer cells may be achievable in vivo.

It was reported that BITC induces the G2-M phase cell cycle arrest and cell apoptosis in ER-negative breast cancer MDA-MB-231 cells and ER-positive breast cancer MCF7 cells (7). The cell cycle arrest was associated with a decrease in expression levels of proteins involved in regulation of G2-M
transition, including cyclin B1, cyclin-dependent kinase 1 and cell division cycle 25C (7). The apoptosis correlated with induction of proapoptotic proteins Bax and Bak, and down-regulation of anti-apoptotic proteins Bcl-2 and Bcl-xL (7). It was also reported that ITC treatment causes mitochondrial damage and caspase-9 activation (8). PEITC could also down-regulate JNK-specific phosphatase and function to activate JNK through suppression of JNK dephosphorylation (36). Thus, ITCs such as PEITC and BITC may regulate many cellular processes that acts together to result in growth inhibition and apoptosis induction. However, the cytotoxic effects of PEITC and BITC could not account for the down-regulated levels of ERα expression observed, since the doses of PEITC and BITC that effectively suppress ERα expression did not promote significant cell death in 12 h. Moreover, because ERα expression was totally restored after the withdrawal of PEITC and BITC for 24 h, the possibility that the apoptotic cell death induced by PEITC and BITC contributed to the down-regulation of ERα expression could be excluded.

Our findings, that the reversible down-regulation of ERα expression and mitogenic estrogen signaling by PEITC and BITC revealed that another important signaling pathway that is influenced by ITCs. Our experimental results thus strongly support the idea that the ITCs from cruciferous vegetables are important dietary factors for breast cancer chemoprevention.

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