Dietary Chemopreventative Benzyl Isothiocyanate Inhibits Breast Cancer Stem Cells *In Vitro* and *In Vivo*

Su-Hyeong Kim, Anuradha Sehrawat, and Shivendra V. Singh

Abstract

A small subset of mammary tumor-initiating cells (also known as breast cancer stem cells; bCSC), characterized by expression of different markers [CD44<sup>high</sup>/CD24<sup>low</sup>/epithelial-specific antigen (ESA)<sup>+</sup>], aldehyde dehydrogenase-1 (ALDH1) activity, and ability to form mammospheres under ultra-low attachment culture conditions, are suspected to evade conventional therapies leading to disease recurrence. Elimination of both therapy-sensitive epithelial tumor cells and therapy-resistant bCSC is therefore necessary for prevention of breast cancer. We have shown previously that a nontoxic small-molecule constituent of edible cruciferous vegetables (benzyl isothiocyanate; BITC) inhibits mammary cancer development in mouse mammary tumor virus-<i>neu</i> (MMTV-<i>neu</i>) transgenic mice by causing epithelial tumor cell apoptosis. The present study shows efficacy of BITC against bCSC *in vitro* and *in vivo*. Mammosphere formation frequency and CD44<sup>high</sup>/CD24<sup>low</sup>/ESA<sup>+</sup> and/or ALDH1<sup>+</sup> populations in cultured MCF-7 (estrogen receptor-positive) and SUM159 (triple-negative) human breast cancer cells were decreased significantly in the presence of plasma achievable concentrations of BITC. BITC administration in the diet (3 μmol BITC/g diet for 29 weeks) resulted in a marked decrease in bCSCs in the MMTV-<i>neu</i> mice tumors *in vivo*. Overexpression of full-length Ron as well as its truncated form (sfRon), but not urokinase-type plasminogen activator receptor, conferred near complete protection against BITC-mediated inhibition of bCSCs in MCF-7 cells. The BITC treatment downregulated protein levels of Ron and sfRon in cultured breast cancer cells and in tumor xenografts. Ron overexpression resulted in upregulation of bCSC-associated genes Oct-4, SOX-2, and Nanog. In conclusion, the present study indicates that BITC treatment eliminates bCSCs in *vitro* and *in vivo*. Cancer Prev Res; 6(8): 782–90. ©2013 AACR.

Introduction

Breast cancer remains a major public health concern for women worldwide accounting for more than 40,000 deaths each year in the United States alone despite tremendous advances toward targeted therapies (1, 2). Preventive strategies, as exemplified by selective estrogen receptor (ER) modulators (e.g., tamoxifen and raloxifene) and aromatase inhibitors (e.g., exemestane) for breast cancer risk reduction (3–5), are necessary to alleviate disease-related cost, morbidity, and mortality associated with this disease. Unfortunately, the currently available preventive options are ineffective against ER-negative breast cancers as well as a subset of women with ER-positive cancer (3–5). Unwanted side effects associated with the long-term use of selective ER modulators and aromatase inhibitors further underscores the need for novel cancer preventive options that are not only safe but can also target ER-positive as well as ER-negative breast cancers.

Bioactive small molecules from edible plants remain attractive for prevention of breast and other cancers due to their favorable safety profile (6, 7). Benzyl isothiocyanate (BITC) is one such naturally occurring phytochemical in cruciferous vegetables (e.g., garden cress) with *in vivo* preventive efficacy in experimental animals (8, 9). For example, BITC treatment before the carcinogen challenge inhibited polycyclic aromatic hydrocarbon–induced mammary cancer in rats (8). Previous work from our own laboratory has revealed that BITC administration in the diet confers significant protection against ER-negative breast cancer development in mouse mammary tumor virus-<i>neu</i> (MMTV-<i>neu</i>) transgenic mice without any signs of overt toxicity (9). The growth of human breast cancer cells (MDA-MB-231) implanted in athymic mice is retarded markedly after treatment with BITC (10).

BITC is structurally quite simple but elicits a complex set of signaling events leading to apoptotic as well as autophagic...
cell death in breast cancer cells (11–14). The molecular circuitry of BITC-induced cell death involves inhibition of complex III of the mitochondrial respiration and ensuing production of reactive oxygen species (11–13). Remarkably, a normal human mammary epithelial cell line (MCF-10A) is significantly more resistant to apoptotic and autophagic cell death as well as production of reactive oxygen species resulting from BITC exposure compared with cancerous mammary cells potentially contributing to its safety profile (11–13). The BITC-induced apoptosis and autophagy are not confined to cellular models as these effects are observed in epithelial mammary tumor cells in vivo (9, 13).

The current paradigm insists on elimination of both therapy-sensitive epithelial tumor cells and therapy-insensitive breast cancer stem cells (bCSC) for prevention and treatment of this disease (15, 16). The bCSCs are not only intrinsically resistant to therapies but also have the ability to self-renew and enrich after treatment leading to tumor recurrence (15–17). Evidence continues to accumulate to indicate that bCSCs share biochemical features of epithelial–mesenchymal transition (EMT), a process implicated in the induction of adherens junction protein E-cadherin and biochemical features of EMT inhibition characterized by breast cancer xenograft growth (9, 13). The BITC-induced apoptosis and autophagy are not confined to cellular models as these effects are observed in epithelial mammary tumor cells in vivo (9, 13).

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Materials and Methods

Ethical issues concerning use and care of laboratory animals

The use of mice and their care for the studies described herein were in accordance with the University of Pittsburgh Institutional Animal Care and Use Committee guidelines (protocol #12080818).

Reagents and cell lines

BITC (purity > 98%) was purchased from LKT laboratories. Reagents for cell culture including medium, FBS, and antibiotics were purchased from Invitrogen-Life Technologies. Sources of the antibodies were as follows: anti-Ron, which recognizes both full-length Ron (pro-Ron), Ronβ (active form), and short form (sRon): Santa Cruz Biotechnology, anti-N-cadherin: Cell Signaling Technology; anti-E-cadherin: BD Biosciences, and anti-vimentin and anti-actin: Sigma-Aldrich. The MCF-7 and MDA-MB-231 cells were purchased from the American Type Culture Collection and authenticated before the work. The cells were last authenticated in February 2012. The SUM159 cell line was purchased from Asterand and authenticated by the provider. The MCF-7 and MDA-MB-468 cells stably transfected with a plasmid encoding for urokinase-type plasminogen activator receptor (uPAR) were generously provided by Dr. Steven L Gonas (University of California, San Diego, CA; ref. 23).

The wild-type and Ron and sRon overexpressing MCF-7 cells were generously provided by Dr. Alana L Welm (University of Utah, Salt Lake City, UT; ref. 24). Each cell line was maintained at 37°C in an atmosphere of 95% air and 5% CO2 according the recommendations of the providers.

Mammosphere formation assay

Mammosphere formation assay was conducted as described by Li and colleagues (25). Single cells were plated in ultra-low attachment plates (Corning) at a density of 500 to 5,000 cells/well in serum-free mammary epithelium basal medium (Lonza) supplemented with 1% penicillin/streptomycin, 250 U/mL insulin, 1 μg/mL hydrocortisone (Sigma), 20 ng/mL EGF (R&D Systems), 20 ng/mL basic fibroblast growth factor (Stem Cell), and 2-mercaptoethanol. Indicated concentrations of BITC were added to the media for primary mammosphere assay. Stock solution of BITC was prepared in dimethyl sulfoxide (DMSO), and an equal volume of DMSO (final concentration <0.15%) was added to controls. After 5 days, the primary mammospheres were harvested, dissociated with trypsin, and then passed through a 40-μm strainer. Single cells were then replated in ultra-low attachment plates for second (5 days) and third-generation (7 days) mammosphere formation assays without further treatment with BITC or DMSO. The mammospheres were counted under an inverted microscope.

Flow cytometric analysis of aldehyde dehydrogenase 1-positive (ALDH1+) cells

The flow cytometric quantitation of ALDH1+ cells was carried out by following the manufacturer’s instructions (Stem Cell). Briefly, cells were suspended in assay buffer containing an ALDH1 substrate (bodipy-aminoacetaldehyde) and incubated at 37°C for 30 minutes. As a positive control, half of the sample was transferred to a tube containing the ALDH1 inhibitor diethylaminobenzaldehyde (DEAB). Before flow cytometric analysis, cells were resuspended in assay buffer and mixed with 1 μg/mL propidium iodide.

Analysis of CD44high/CD24low/epithelial-specific antigen-positive (ESA+) population

Cells were trypsinized, washed with PBS twice, and stained with 20 μL of anti-ESA [fluorescein isothiocyanate (FITC)-conjugated, BD Biosciences], anti-CD24 (PE-conjugated, BD Biosciences), and anti-CD44 (APC-conjugated, BD biosciences) antibodies. Cells were incubated in dark for 30 minutes at room temperature followed by washing with PBS. The cells were analyzed using CyAn ADP Analyzer from Beckman Coulter.

In vivo experiment

Three- to 5-week-old female MMTV-neu transgenic mice [homozygous; strain FVB/N-Tg(MMTV-neu) 202Mul/J] were purchased from Jackson Laboratories and acclimated for 1 week before start of the experiment. The mice were randomized into 2 groups with 10 mice in each group. The
control mice were placed on basal AIN-76A diet, whereas the experimental group of mice was fed AIN-76A diet supplemented with 3 μmol BITC/g diet (447.6 mg BITC/kg diet). The diet was replaced every 3 to 4 days at the time of cage change. Diet consumption and body weights were recorded once weekly. Each mouse in every group was also monitored on alternate days for any other signs of distress such as impaired movement, unusual posture, indigestion, and areas of redness or swelling. Mice with tumors were sacrificed after 29 weeks of treatment. Tumor tissue was dissected and washed with PBS and digested in Dulbecco’s modified Eagle medium (DMEM) supplemented with 300 U/ml collagenase and 100 U/ml hyaluronidase for 3 to 4 hours at 37°C. Cells were resuspended in Hank’s balanced salt solution (HBSS) supplemented with 2% FBS and ammonium chloride. The resultant suspension was resuspended in 0.25% Trypsin-EDTA and 5 mg/ml dispase, 0.1 mg/ml DNase1 in HBSS and filtered through 40 μm strainer. The cells were used for ALDH1 assay or mammosphere formation assay. Mammosphere formation from tumor samples was conducted as described by Liao and colleagues (26). Single cells were plated in ultra-low attachment plate in DMEM/F12 supplemented with 2% FBS, 10 mmol/L HEPES, 5% bovine serum albumin, 1% penicillin/streptomycin, 10 μg/ml insulin, 20 ng/ml EGF, 20 ng/ml basic fibroblast growth factor, B27, 10 μg/ml heparin, and 2-mercaptoethanol for 7 days.

Western blotting

Cell lysates and xenograft supernatants were prepared as described previously (27, 28). Western blotting was conducted as described previously (27, 28).

Real-time quantitative PCR

Total RNA from DMSO-treated control and BITC-treated cells was isolated using RNAeasy kit (Qiagen). First-strand cDNA was synthesized using Superscript Reverse Transcriptase (Invitrogen-Life Technologies) with oligo (dT)20 primer. Primers were as follows: Ron: forward 5'-AGGCCACGCT-CAGTGTCTAT-3', reverse 5'-GGGACCATAGGATCTGTCA-3'; Oct-4: forward 5'-GTGGAGGACAACTCGTGATG-3', reverse 5'-TGCCACAGCTTCCCTTTCT-3'; Nanog, forward 5'-ATTCAGCAGACCGGTACCTCC-3', reverse 5'-TTTTT-GGGACACCTTCTCTCTG-3'; and SOX-2, forward 5'-CGAG- TGAAACTTTTGTCGGA-3', reverse 5'-TGTCAGGGCCGC- GCAG-3'. The quantitative PCR (qPCR) was done using 2× SYBR Green master mix (Applied Biosystems-Life Technologies) with 95°C (60 seconds), 55°C annealing (60 seconds for Ron), 60°C annealing (60 seconds for Oct-4, Nanog, and SOX-2), and 72°C (60 seconds) for 40 cycles. Relative gene expression was calculated using the method described by Livak and Schmittgen (29).

Quantitation of macrophage-stimulating protein

A commercially available kit from R&D Systems was used for quantitative measurement of macrophage-stimulating protein (MSP) in cell lysates. Manufacturer’s instructions were followed for quantitation of the MSP levels.

Statistical analysis

Two-tailed unpaired Student t test with Welch correction or one-way ANOVA followed by Dunnett’s adjustment (for dose–response effects) or Bonferroni test (for multiple comparisons) were used to determine statistical significance of difference in measured variables. Results are expressed as mean ± SD. Difference was considered significant at P<0.05.

Results

BITC inhibited self-renewal of bCSC

Initially, we used MCF-7 (ER-positive) and SUM159 (triple-negative) human breast cancer cells to determine the effect of BITC on bCSCs. The BITC concentrations used in these experiments were (0.5–1 μmol/l) lower than pro-apoptotic doses (11, 12). Figure 1A exemplifies mammospheres resulting after 5 days of treatment of MCF-7 and SUM159 cells with DMSO (control) or the indicated concentration of BITC. First-generation mammosphere frequency was decreased significantly and dose dependently in the presence of BITC in both cell lines when compared with DMSO-treated control (Fig. 1B). The mammospheres from the first generation were disaggregated and the resulting single cells were replated without further treatment with DMSO (control) or BITC. Second- (after 5 days) and third-generation (after 7 days) mammosphere frequency was significantly lower in BITC-treated MCF-7/SUM159 cells compared with control (Fig. 1B). Inhibitory effect of BITC on bCSCs was confirmed by flow cytometric analysis of ALDH1 activity (Fig. 1C). As can be seen in Supplementary Fig. S1, the ALDH1 activity was reduced in the presence of BITC in a dose-dependent manner. For example, the BITC treatment (1 μmol/l, 72 hours) caused an approximate 46% and 42% decrease in ALDH1 activity in MCF-7 and SUM159 cells, respectively, compared with DMSO-treated control (Fig. 1C). Consistent with these observations, percentage of CD44high/CD24low/ESA+ fraction was lower in BITC-treated MCF-7 and SUM159 cell cultures compared with control (Fig. 1D). Collectively, these results indicated in vitro inhibition of bCSCs in the presence of BITC.

Dietary BITC administration decreased bCSCs in MMV neu-mice tumors in vivo

We next proceeded to determine the in vivo efficacy of BITC against bCSCs using MMTV-neu mouse model. Ratio nale for the use of this model in the present study was based on the following considerations: (i) we have shown previously that dietary administration of BITC (3 μmol/g diet) prevents mammary cancer development in MMTV-neu mouse model (9) and (ii) increased self-renewal and replicative potential of bCSCs has been reported in this model (30). We used the same protocol of BITC treatment (3 μmol BITC/g diet for 29 weeks) to determine the effect on bCSCs. After 29 weeks of BITC administration, the tumor incidence in the control and BITC treatment groups was 40% and 20%, respectively. Tumors from the control mice (n = 4) and those treated with BITC (n = 2) were disaggregated and single-cell suspensions were used for mammosphere formation assay (Fig. 2A). At each cell seeding density, the
number of mammospheres from BITC-treated tumors was markedly lower compared with those from control tumors but the difference did not reach statistical significance due to an outlier in the control group and small sample size in the BITC treatment arm (Fig. 2B). Nevertheless, consistent with these results, the ALDH1 activity was about 83% lower in the tumors from BITC-treated mice compared with control mice ($P = 0.07$ by two-tailed unpaired Student $t$ test with Welch’s correction; Fig. 2C). These results provided in vivo evidence for BITC-mediated inhibition of bCSCs.

**uPAR was dispensable for BITC-mediated inhibition of bCSCs**

Studies have shown that overexpression of uPAR alone is sufficient to drive both EMT and stemness in human breast cancer cells (23, 31). Recent work from our own laboratory has revealed transcriptional repression of uPAR in BITC-treated breast cancer cells (22). We therefore raised the question of whether inhibition of bCSCs upon treatment with BITC was due to uPAR suppression. Overexpression of uPAR (overexpression of uPAR was confirmed, results not shown) increased mammosphere formation frequency in MCF-7 cells by about 1.5-fold. Mammosphere formation frequency was decreased in a dose-dependent manner upon treatment with BITC in MCF-7 cells stably transfected with the empty vector as well as uPAR plasmid. However, when the results were normalized against corresponding DMSO-treated control, the percentage of inhibition in mammosphere formation frequency upon treatment with BITC was comparable for MCF-7 cells and MCF-7/uPAR cells (Fig. 3A). These results were confirmed by analysis of ALDH1 activity (Fig. 3B). Consistent with results in MCF-7 cells
overexpression of uPAR failed to confer any protection against BITC-mediated inhibition of mammosphere formation (Fig. 3C) or ALDH1 activity (results not shown) in MDA-MB-468 cells. Collectively, these results indicated that uPAR suppression was dispensable for BITC-mediated inhibition of bCSCs at least in breast cancer cells used in the present study.

**BITC downregulated Ron in breast cancer cells**

The Ron tyrosine receptor kinase and/or its 55 kDa N-terminally truncated form (sRon) has been implicated in EMT induction as well as metastasis of breast cancer (32–34). Initially, we designed experiments to determine whether BITC treatment affected Ron and/or sRon protein levels. Exposure of MDA-MB-231 cells, which express substantial amount of Ron and sRon proteins, to BITC resulted in a dose- and time-dependent decline in protein levels of pro-Ron and its active form (Ronβ) and truncated form (sRon; Fig. 4A). The BITC-mediated suppression of Ron protein was accompanied by downregulation of its mRNA (Fig. 4B, top). BITC treatment also caused a significant decrease in protein levels of Ron ligand MSP (Fig. 4B, bottom). Moreover, BITC-mediated inhibition of MDA-MB-231 xenograft growth in vivo (10) was associated with downregulation of Ron and sRon protein levels (Fig. 4C).
We used the MCF-7 cells for functional studies to determine the role of Ron and sfRon in BITC-mediated inhibition of EMT and bCSCs. Protein levels of exogenously expressed Ron and sfRon were decreased in the presence of BITC (Fig. 4D). Overexpression of sfRon, but not full-length Ron, triggered EMT as evidenced by suppression of E-cadherin and induction of mesenchymal markers N-cadherin and vimentin (Fig. 4D). BITC treatment caused induction of E-cadherin in control and Ron-overexpressing MCF-7 cells but not in cells with stable overexpression of sfRon (Fig. 4D). These results indicated that overexpression of sfRon attenuated BITC-mediated induction of epithelial marker E-cadherin.

**Overexpression of Ron and sfRon conferred protection against BITC-mediated inhibition of bCSCs**

The inhibition of ALDH1+ fraction resulting from BITC exposure was nearly completely abolished by overexpression of Ron as well as sfRon (Fig. 5A). The mammospheres from Ron- and sfRon-overexpressing MCF-7 cells were relatively larger in size than those observed from parental MCF-7 cells (Fig. 5B). In agreement with ALDH1 activity data, BITC-mediated inhibition of mammosphere formation (Fig. 5C) and CD44high/CD24low population (Fig. 5D) was significantly attenuated by overexpression of Ron and sfRon. Moreover, the Ron- and/or sfRon-overexpressing MCF-7 cells exhibited a significant increase in mRNA levels of bCSC-associated genes Oct-4, Sox-2, and Nanog (Fig. 6). These results indicated that BITC-mediated inhibition of bCSCs was attenuated by overexpression of Ron and sfRon at least in MCF-7 cells.

**Discussion**

We have shown previously that mammary cancer prevention by BITC in MMTV-neu mice is associated with tumor cell apoptosis. The present study building upon these observations shows, for the first time, that BITC treatment inhibits self-renewal of bCSC as evidenced by mammosphere formation, ALDH1 activity, and cell surface...
expression of cancer stem cell markers CD44 and ESA. Of note, BITC-mediated in vitro inhibition of bCSC is observed at concentrations (0.5–1 μmol/L) that are not very cytotoxic but within the plasma achievable levels (35). We also provide evidence that BITC administration eliminates bCSCs in vivo. On the basis of these observations, it is reasonable to propose that elimination of both epithelial tumor cells via apoptosis and autophagy induction and bCSCs likely contributes to breast cancer prevention by BITC.

Overexpression of uPAR alone is sufficient to drive EMT (MDA-MB-468) and/or stemness (MCF-7 and MDA-MB-468) in breast cancer cells (23, 31). The uPAR and its ligand uPA constitute an integral component of the extracellular matrix proteolysis, cell–extracellular matrix interaction, as well as cell signaling involving receptor tyrosine kinases (36, 37). High uPA/uPAR level has been shown to be an adverse prognostic indicator for different cancers including breast tumors (38). Downregulation of constitutive uPA in cultured HT29 human colon cancer cells and suppression of hepatocyte growth factor–stimulated secretion of uPA in MDA-MB-231 cells upon treatment with BITC has been reported previously (39, 40). We have also shown recently that BITC treatment causes transcriptional repression of uPAR protein in several breast cancer cells, but this system is dispensable for BITC-mediated inhibition of EMT (22). The present study reveals that overexpression of uPAR fails to confer any protection against BITC-mediated inhibition of bCSCs in MCF-7 or MDA-MB-468 cells. However, it is possible that suppression of uPA/uPAR system by BITC contributes to its inhibitory effect on breast cancer cell proliferation and possibly metastasis. Additional work is needed to experimentally test this possibility.

Ron (recepteur d’origine nantais) tyrosine kinase expression is very low in normal human breast epithelium, but its overexpression has been observed in about 50% of primary breast cancers (41). Moreover, increased expression of the Ron receptor correlates with more aggressive phenotype in node-negative breast tumors (42). Mammary-specific overexpression of wild-type Ron as well as constitutively active Ron induces highly metastatic breast tumors in mice (34). Studies have also indicated that Ron receptor tyrosine kinase
can promote cell spreading and survival in breast cancer cells independent of its only known ligand MSP (43). Activation of Ron by hepatocyte growth factor–like protein has been shown to confer resistance to tamoxifen in breast cancer cell lines (44). The present study shows, for the first time, that overexpression of full-length Ron and sfron induces stemness in MCF-7 cells that is accompanied by increased expression of stem cell–associated genes Oct-4, SOX-2, and Nanog. We also found that BITC treatment inhibits protein and/or mRNA levels of full-length Ron receptor tyrosine kinase and its 55-kDa N-terminally truncated form (sfron). Moreover, overexpression of full-length Ron and sfron confers near complete protection against BITC-mediated inhibition of bCSC in MCF-7 cells. On the other hand, overexpression of sfron, but not the full-length Ron, is sufficient to attenuate BITC-mediated induction of E-cadherin.

The novel findings of the present study are: (i) overexpression of full-length Ron as well as its truncated form (sfron) is sufficient to drive stemness in MCF-7 cells; (ii) BITC treatment inhibits bCSCs in vitro and in vivo; and (iii) BITC-mediated inhibition of bCSC is nearly fully abolished by overexpression of Ron and sfron at least in MCF-7 cells. In conclusion, the present study identified Ron receptor tyrosine kinase as a critical target of bCSC inhibition by BITC.

References


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