Introduction

Breast cancer is the second leading cause of cancer-related deaths in North American women. Basal-like breast cancer (BLBC), one of four subtypes of breast cancer, accounts for 13% of all breast carcinomas. Although not as common as the other subtypes, BLBC is characterized by a unique mRNA profile with CK5/6 expression. BLBCs are the most deadly and aggressive type (1, 2). This aggressiveness is due to the fact that it is also the most chemoresistant of the breast cancer subtypes (3). Biologically, it is characterized by a unique mRNA profile with CK5/6 expression and inactivation of BRCA1. In addition, 70% to 90% of BLBC tumors are characterized as triple-negative breast cancer (TNBC) because they lack progesterone and estrogen receptor expression and HER-2 amplification (1, 4, 5). The poor prognosis is linked to its enrichment for tumor-initiating cells known as cancer stem cells (CSCs; refs. 6–8). CSCs engage in self-renewal, induce tumors at low-cell density, and produce tumors with differentiated and heterogeneous cell profiles. Moreover, they exhibit gene expression profiles that diverge from their more differentiated cancer cell counterparts. Breast CSCs form tumorspheres in vitro, they are more tumorigenic in mice, and more resistant to standard chemotherapy and radiation than differentiated cells (9, 10). In BLBC, CSCs are identified by their extracellular expression of CD44+/CD24− and elevated enzymatic activity of aldehyde dehydrogenase (ALDH; refs. 11, 12). These CSCs are also identified based on the aberrant regulation of their self-renewing pathways, including Wnt, Hedgehog, and Notch signaling (11, 13).

One promising approach to prevent BLBC recurrence and metastasis is to target pathways that regulate CSCs such as the Wnt/β-catenin pathway (3, 14). The cell surface receptor LRP6, essential for Wnt/β-catenin signaling, is a potential target as its expression is upregulated in 20% to 36% of human breast cancers and most significantly in the BLBC subtype. Suppression of LRP6 has been proved to be sufficient in inhibiting the Wnt/β-catenin signaling pathway in breast cancer; therefore, ...
it is an excellent potential target for the treatment of BLBC (14–17).

Wnt proteins activate the Wnt/β-catenin pathway by binding to its surface receptors LRPs5/6. This binding induces the receptors to interact with the transmembrane receptor, frizzled, which leads to the subsequent phosphorylation of LRPs5/6 (18). This leads to a build-up of β-catenin, an intracellular signal transducer, in the cytoplasm. β-Catenin can then translocate to the nucleus, in which it interacts with T-cell factor (TCF). This interaction triggers the transcription of the Wnt pathway target genes, which include survivin, Axin2, and cyclin D1. The expression of these genes leads the cell to undergo proliferation, self-renewal, and survival. In the absence of a Wnt ligand, β-catenin is tagged for degradation by the “destruction complex” comprised of adenomatous polyposis coli, Axin, and GSK3β, thereby rendering the β-catenin target genes transcriptionally inactive.

The Wnt/β-catenin pathway can be inhibited at the extracellular level by secreted inhibitors such as Dkkopf proteins or secreted frizzled-related proteins (19, 20). Chemically, this inhibition can be achieved by salinomycin or niclosamide, which both are able to inhibit the binding of a Wnt ligand to LRPs5/6 receptors (21, 22). Inhibitors of Wnt/β-catenin signaling, such as niclosamide, are reported to stimulate frizzled internalization and promote LRPs6 degradation, thus preventing proliferation and causing apoptosis (22–24). Niclosamide (trade name Niclocide) is a teniacide in the antihelminth family. ALDEFLUOR Kit including diethylamino benzaldehyde was obtained from StemCell Technologies. Chemically, this inhibition can be achieved by salinomycin or niclosamide alone and in combination with TRA-8.

Materials and Methods

Drugs and antibodies

Niclosamide was purchased from Sigma-Aldrich. Niclosamide for in vitro use was dissolved in dimethyl sulfoxide (DMSO) at a 4.8-mmol/L concentration and stored at 4°C until further use. For animal studies, niclosamide was dissolved in DMSO until a homogeneous suspension was observed at which time Cremophor was added to make a final solution of 25% DMSO and 75% Cremophor. The liquid was slowly inverted to obtain a clear orange solution, which was stored at 4°C. Purified TRA-8 (immunoglobulin G1, IgG1) mAb was prepared at the University of Alabama at Birmingham (Birmingham, AL), as described previously, and was provided by Dr. Tong Zhou (32). IgG1 and isotype-specific IgG1 control antibody were obtained from Southern Biotechnology Associates. ALDEFLUOR Kit including diethylamino benzaldehyde was obtained from StemCell Technologies. Monoclonal anti–phosphorylated-LRP6, Axin2, cyclin D1, p(Tyr705)-STAT3, and STAT3 were purchased from Cell Signaling Technology, Inc.. Monoclonal anti–β-catenin was purchased from BD Biosciences. Survivin antibody for Western blots was purchased from Santa Cruz Biotechnology.

Cells, cell culture, and patient pleural effusion samples

The 2LMP subclone of the human breast cancer cell line MDA-MB-231 was obtained from Dr. Marc Lippman (University of Miami, Miami, FL) and maintained in improved minimum essential medium (MEM) supplemented with 10% FBS (HyClone). BLBC cell lines, HCC1187 and HCC1143, were obtained from American Type Culture Collection (ATCC) and cultured according to supplier’s directions. SUM159 was obtained from Asterand and grown according to supplier’s recommendation. MCF10A immortalized, nontransformed epithelial cells were obtained from ATCC. Cell lines were obtained 3 years ago, frozen in aliquots, which were passaged no more than 15 times, and then a new aliquot was used. They were not authenticated. All cell lines were maintained in antibiotic-free medium at 37°C in a 5% CO₂ atmosphere and routinely screened for mycoplasma contamination.

Generation and characterization of tumorspheres and NAAE cells

BLBC cells were seeded in 96-well ultralow attachment plates (Corning) at 40,000 cells/mL in mammary epithelial
basal medium (MEBM) supplemented with bullet kit (bovine pituitary extract, insulin, human recombinant epidermal growth factor, and hydrocortisone); complete media is called MEGM (Lonza). These nonadherent cells then formed tumorspheres. Cells were tested for ALDH activity at 6, 12, 24, 48, and 72 hours after plating by flow cytometry as previously described (34). In addition, cells were sorted for the ALDH+ population and retention of ALDH was analyzed at the same time points. Both sorted and nonsorted cells were found to be maximally enriched for ALDH at 12 hours, but then decreased at later time points. The NAAE cells obtained at the 12-hour time point (20,000 cells) were injected into the mammary fat pad (MFP) of nonobese diabetic/severe combined immunodeficient (NOD/SCID) mice. The nonadherent cells at 72 hours after plating (20,000 cells) were also injected into the MFP of mice. To evaluate the difference between the tumorigenicity of the NAAE cells (12 hours after plating) and the nonadherent cells (72 hours after plating), the tumors were measured twice weekly until mice were euthanized in accordance to Institutional Animal Care and Use Committee (IACUC) regulations.

Generation of LRP6 knockdown cell line

LRP6 protein expression was knocked down in the adherent 2LMP cell line using Mission Lentiviral transduction particles SHC1LV, MOI of 1 of the TRCN0000034405 (Lot 01091309MN, 1.5 × 10⁷ TU/mL). We used Mission transduction particles for nonmammalian short hairpin RNA (shRNA) as a control, SHC1002V, MOI 3 (Lot 04301208MN, 2.6 × 10⁷ TU/mL; Sigma-Aldrich). Cells were selected using ready-made solution puromycin dihydrochloride (Sigma-Aldrich). LRP6 knockdown was confirmed using Western blot analysis of LRP6.

Western blotting

To evaluate in Wnt/β-catenin pathway signaling in NAAE cells and adherent cells, adherent and NAAE 2LMP cells were seeded (1 × 10⁶ cells/well) in 6-well plates. Cells were lysed in 0.5 mL of lysis buffer (PBS containing 1% Triton X-100 and 1 mmol/L phenylmethylsulfonylfluoride) at 4°C for 15 minutes. Equal quantities of protein were subjected to SDS-PAGE under reducing conditions. Following transfer to immobilon-P membrane, successive incubations with anti-LRP6, anti-β-catenin, anti-free β-catenin, anti-total β-catenin or anti-actin, and horseradish peroxidase–conjugated secondary antibody were carried out for 60 to 120 minutes at room temperature. The immunoreactive proteins were then detected using the ECL system (PerkinElmer). Films showing immunoreactive bands were scanned by Kodak Digital Science DC120 Zoom Digital Camera (Kodak). Cytosolic free β-catenin analysis was done with GST–E-cadherin binding assay (22). Uncomplexed cytosolic free β-catenin in 100 mg of total cell lysate was subjected to SDS-PAGE and detected using the mAb to β-catenin.

For treatment studies, 2LMP adherent and NAAE cells, and patient samples were seeded (1 × 10⁶ cells/well) in 6-well plates and treated for 24 hours with niclosamide (0, 0.5, 0.25, 0.125 μmol/L). Additional proteins detected were Axin 2, survivin, cyclin D1, p(Tyr705)-STAT3, and STAT3. 2LMP and HCC1187 adherent and NAAE cells were seeded in the same manner and treated with TRA-8 alone (25 and 125 ng/mL) for 2 hours. Anti–total β-catenin and anti-actin antibodies were used.

TOPflash luciferase reporter assay

NAAE cells from all four BLBC cell lines were plated at 40,000 cells per well. The next day, the cells were transfected with 0.05 mg of TCF/lymphoid enhancer factor (LEF) activity reporter (TOPflash; plasmid from Dr. Randall Moon’s laboratory, Upstate Biotechnology). Cells were transfected using Lipofectamine 2000 (Invitrogen) in Opti-MEM (Gibco/Invitrogen) as per the manufacturer’s instructions. Six hours after transfection, cells were treated with 0.25 μmol/L niclosamide for 24 hours. Adherent BLBC cells were plated and transfected in the same manner. In one experiment, adherent cells were treated with 0.25 μmol/L niclosamide for 48 hours and 0.25 ng/mL TRA-8 for 24 hours. In another experiment, adherent SUM159, HCC1143, and HCC1187 cells were treated with 1 μmol/L niclosamide and 2LMP cells with 0.25 μmol/L niclosamide for 24 hours. Each cell line was also concurrently transfected with Wnt3A (5 ng/mL; R&D Systems) alone and in combination with niclosamide.

Patient samples were plated in the same manner and transfection was attempted with the plasmid, but obtaining a consistently high transfection efficiency for the analysis proved challenging. Therefore, the method was revised to use lentivirus pCignal Lenti TCF/LEF Reporter at multiplicity of infection (MOI) of 25 (Qiagen) to transfect the cells. Twenty-four hours after transfection with the lentivirus, cells were treated with 4 μmol/L of niclosamide for 24 hours. Total protein was harvested 24 hours after treatment and luciferase activity was measured using a Turner 20/20 luminometer (Promega). The luciferase reading was normalized to the total protein concentration as reported previously (39). The luciferase activity was normalized to untreated control and represented as a mean ± SE for a minimum of three replicates.

Tumorsphere inhibition assay

NAAE cells for all four BLBC cell lines were plated at 2,000 cells/well in 50 μL media, then treated with niclosamide (0.25–1.0 μmol/L) for 24 hours, followed by treatment with TRA-8 (1 ng/mL 2LMP, 0.5 ng/mL SUM159, 25 ng/mL HCC1143, and 5 ng/mL HCC1187) for an additional 24 hours. Two independent investigators used a reticle eyepiece to visually count tumorspheres. Mean tumorsphere inhibition was calculated relative to no treatment. Samples were run in quadruplicate in three independent experiments and error bars represent ± SE.

In vitro cytotoxicity studies

2LMP, SUM159, HCC1143, HCC1187, NAAE and attached cells, MCF10A, LRP6 knockdown, or shRNA-
Niclosamide Is Cytotoxic to CSCs

NAAE cells were seeded at 2,000 cells/50 μL of media. Adherent cells were plated in optically clear tissue culture–treated black plates (Costar). NAAE cells and patient samples were plated in low-attachment plates in MEGM media. To assess the viability of cells exposed to niclosamide or TRA-8, all cells were treated with niclosamide (0.125–8 μmol/L) or TRA-8 (0.1–500 ng/mL) for 24 or 48 hours. In combination treatment studies, after 24 hours exposure to niclosamide, TRA-8 (0.25–500 ng/mL) was added for an additional 24 hours before the cells were lysed and analyzed for viability using the ATPlite luminescence-based assay (PerkinElmer) as previously described (40). Alternatively, cells were treated concurrently with niclosamide and TRA-8 for 48 hours. TRA-8 and niclosamide were diluted in culture medium immediately before use, and the final concentration of DMSO was always ≤0.001%. All samples were assayed in triplicate or quadruplicate and are reported as the mean ± SE.

In vivo therapy and toxicity studies

Female athymic nude mice at 4 weeks of age were purchased from Harlan. In vivo generation of tumors was accomplished by resuspending 2 × 10^6 2LMP cells in 100 μL (1:1 Matrigel and PBS) and injecting cells into the MFP of athymic nude mice (n = 5). Mice were randomly assigned into four groups and treated when the tumors reached approximately 16 mm² (7 days after implantation). Mice were intraperitoneally injected twice weekly with TRA-8 (200 μg), niclosamide (30 mg/kg; 50% cremophore EL:50% DMSO) 5 days a week, the combination, or with vehicle control (50% cremophore EL:50% DMSO) 5 days a week for 3 weeks. Tumor size (surface area) was calculated by a × b, in which a is the largest diameter and b is the diameter perpendicular to a. Tumors were measured with a Vernier caliper 2 times a week until mice were euthanized in accordance with the IACUC regulations.

To assess tumor and normal tissue toxicity, a separate animal study was conducted with three mice per group and treated with vehicle control 5 days a week, niclosamide (20 mg/kg) 5 days a week, TRA-8 (200 μg) twice weekly, and the combination for a total of 2 weeks. All animals were monitored daily and weighed twice a week. After 2 weeks of treatment, animals were euthanized and harvested into formalin at room temperature and then processed to paraffin blocks. The tissues from each of the four groups were coded and hematoxylin and eosin stains were performed on 4-μm tissue sections. The board-certified diagnostic pathologist who evaluated the tissues for toxicity was blinded about the treatment group. In addition, portions of the tumors were evaluated for changes in protein expression by Western blot analysis.

Immunohistochemistry

Patient pleural effusion samples were stained by immunohistochemistry for LRPI, Moc31, and calretinin (Cell Signaling Technology, Inc.). Mouse tumor tissue was also analyzed for p-STAT3 and β-catenin expression. Cells were harvested into histogel and embedded into a paraffin block. For each sample, the staining intensity (0, 1+, 2+, and 3+) and the percentage of cells staining positive (0%–100%) was determined by a blinded board-certified pathologist. An H-score was calculated as the product of the intensity and the percentage of cells with positive staining.

Statistical analysis

T tests were used to compare means when appropriate. General linear models were used to make comparisons over time. Enhanced combination effect was further confirmed by a concentration–effect curve using the nonlinear regression method and isobologram methods (data not shown; ref. 41). Experimental animal treatment groups were composed of 5 animals each to provide evidence of substantial tumor sensitivity to TRA-8 therapy with or without niclosamide. For xenograft models, tumor-doubling time (TDT) was estimated for each animal using empirical distribution, and median TDT between treatment groups was compared using the Kruskal–Wallis nonparametric statistical test.

Results

Analysis of cells

In this study, we investigated four BLBC cell lines: 2LMP, SUM159, HCC1143, and HCC1187. All cell lines were analyzed as adherent cells in normal tissue culture plates with media that contained serum. In addition, cells were plated in ultralow attachment plates with MEGM media and were noted to form tumorspheres, which are composed of nonadherent cells. Nonadherent cells were further analyzed for the stem cell marker, ALDH, at various time points and compared with cells that were sorted for ALDH. Both types of cells were noted to have elevated levels of ALDH 12 hours after being plated, which then decreased with time. The nonsorted and nonadherent aldehyde-enriched cells at the 12-hour time point were termed NAAE.

Characterization of NAAE cells

Cells were tested for ALDH activity at 6, 12, 24, 48, and 72 hours for the 2LMP and SUM159 cell lines and at 6, 12, and 24 hours for the HCC1143 cells. These cells were compared with cells that were sorted for the ALDH population and subsequently analyzed for ALDH expression at the same time points. Both sorted and nonsorted cells were found to be enriched for ALDH at the 12-hour time point, but subsequently both populations returned to the presorted expression level; therefore, the NAAE cells represent a CSC-enriched population at the 12-hour time point (Fig. 1A). To verify enhanced tumorigenicity of the NAAE cells (12 hours after plating), they were injected into mice and compared with cells that were cultured for 72 hours before injection, which had reduced ALDH activity. The NAAE cells formed aggressive large tumors,
indicating their enrichment for CSCs compared with tumors formed by cells from the 72-hour time point (P = 0.01). NAAE xenografts developed earlier and formed larger tumors over time, indicating enrichment for tumor-initiating CSCs (Fig. 1B).

2LMP NAAE cells were also analyzed by Western blot for p-LRP6, LRP6, free and total β-catenin (Fig. 1C) and compared with adherent 2LMP cells. The NAAE cells demonstrated higher free β-catenin and lower LRP6 and p-LRP6 expression. Similar levels of total β-catenin were observed in both NAAE and adherent populations.

Niclosamide inhibits Wnt/β-catenin and STAT3 signaling in BLBC cell lines

To characterize the effect of niclosamide on the Wnt/β-catenin pathway, we performed the signaling TOPflash luciferase reporter assay, which measures the level of nuclear β-catenin, on NAAE cells and adherent cells. Wnt3A ligand was added to the four adherent BLBC cell lines to upregulate the Wnt/β-catenin pathway. Nuclear β-catenin was decreased by niclosamide treatment in all four adherent cell lines (0.25 μmol/L in the more sensitive cell line, 2LMP, and 1 μmol/L in the other three cell lines) after upregulation by Wnt3A ligand (P < 0.05). Three of the four cell lines had niclosamide-mediated Wnt/β-catenin inhibition in the absence of the Wnt3A ligand (P < 0.05; Supplementary Fig. S2). NAAE cells from all four BLBC cell lines showed significant inhibition of Wnt/β-catenin signaling following 24 hours of treatment with 0.25 μmol/L niclosamide without the addition of the Wnt3A ligand (P < 0.01; Fig. 2A).

Western blot analysis of Wnt/β-catenin signaling proteins (LRP6, pLRP6, free and total β-catenin), three target genes (Axin2, survivin, and cyclin D1), and two STAT3 pathway proteins [phosphorylated (tyr705) and total STAT3] after 24 hours treatment with niclosamide (0.125–0.5 μmol/L) showed a dose–response inhibition of the Wnt/β-catenin and STAT3 pathways in both the adherent and NAAE 2LMP cells (Fig. 2B). Cell death was also calculated for these doses to assure that Western results were not a consequence of cell death. The highest
dose of 0.5 µmol/L did not induce more than 60% kill of the adherent or the NAAE cells when cells were plated according to the Western blotting protocol (Supplementary Fig. S3). The 0.125-µmol/L dose caused almost no cell kill, yet did produce decreases in the Wnt/β-catenin target genes, suggesting that the Wnt/β-catenin pathway is downregulated at noncytotoxic doses of niclosamide.

**Effect of niclosamide and TRA-8 treatment in vitro**

Our laboratory has previously published on TRA-8 cytotoxicity to BLBC cells (35) and their CD44+ /CD24− /ALDH+ cell-sorted populations (34); therefore, we hypothesized that the combination of two CSC-targeting agents, TRA-8 and niclosamide, would produce increased cytotoxicity of NAAE cells. NAAE cells were pretreated with niclosamide for 24 hours followed by 24 hours treatment with TRA-8, and the number of tumorspheres was compared with single agents or no treatment. Tumorsphere formation was inhibited in all four cell lines with niclosamide and TRA-8 alone, but the combination of the two agents produced a significant increase in tumorsphere inhibition compared with either agent alone (P = 0.03; Fig. 3A). Cytotoxicity of niclosamide and TRA-8 was also tested against NAAE cells (Fig. 3B). The cytotoxicity results correlated with the tumorsphere inhibition results in all four cell lines.

**Effect of niclosamide and TRA-8 on Wnt/β-catenin signaling**

The TCF/LEF plasmid reporter TOPflash assay was used to evaluate the combination of niclosamide and TRA-8 on the Wnt/β-catenin signaling pathway in BLBC adherent cells. The TOPflash assay was also attempted for the combination treatment on NAAE cells, but sufficient transfection was never achieved. All four BLBC cell lines were treated for 48 hours with 0.25 µmol/L of niclosamide. After the first 24 hours, TRA-8 at 0.25 ng/mL was added. Wnt/β-catenin pathway inhibition occurred after treatment with niclosamide or TRA-8 alone as compared with no treatment (Fig. 4A).
Combination treatment produced significantly greater inhibition of the Wnt/β-catennin reporter than single agents in three of the cell lines.

TRA-8, unlike niclosamide, was previously not known to influence Wnt/β-catennin signaling. Western blots were used to examine the effect of TRA-8 on β-catennin. Total β-catennin levels decreased (low exposure) with evidence of fragmentation (high exposure) of the protein after a 2-hour TRA-8 treatment of 2LMP adherent and NAAE cells. However, with HCC1143, TRA-8 treatment only produced a decrease in total β-catennin in NAAE cells (Fig. 4B).

Given our observation that niclosamide’s inhibition of the Wnt/β-catennin pathway resulted in reduced expression of survivin, we hypothesized that decreasing LRP6 would enhance the cytotoxicity of the apoptotic agent TRA-8. Knockdown of LRP6 using Mission Lentiviral transduction particles shRNA on adherent 2LMP cells produced enhanced TRA-8-mediated cytotoxicity (Fig. 4C). LRP6 knockdown was confirmed by Western blot, which also showed reduced survivin expression compared with a vector control (Supplementary Fig. S4).

Effect of niclosamide and TRA-8 on established 2LMP tumors

Given the impressive in vitro observations of niclosamide and TRA-8 cytotoxicity with BLBC cell lines, we carried out a combination therapy study in an orthotopic BLBC animal model. Animals received niclosamide (30 mg/kg 5 days a week), or TRA-8 (200 μg twice weekly), or both treatments for a total of 3 weeks and were compared with mice that received a vehicle control. The mice that received TRA-8 alone had a significant inhibition of tumor growth (P < 0.05), similar to what had been previously reported by our laboratory (35). Animals treated with niclosamide had similar tumor growth inhibition compared with those treated with TRA-8, whereas animals treated with the combination of agents had significant tumor growth inhibition compared with untreated controls (P < 0.01) and to either single agent alone (P < 0.05; Fig. 5).

To further investigate the potential toxicity of niclosamide and TRA-8 in the mice, we performed a 2-week in vivo treatment of both single agents and the combination. Although this treatment regimen of niclosamide was 20 mg/kg, there was still a significant decrease in tumor
growth in both the single-agent treatment and further inhibition with the combination treatment. The weight of the treated mice, both with a single agent and the combination did not decrease over time (Supplementary Fig. S5). In addition, the tissue architecture for the kidney, spleen, liver, small and large intestines was analyzed and found to be normal. Furthermore, the tumors in the mice were analyzed by immunohistochemistry, which showed that treated mice had reduced expression of p-STAT3, cytosolic, and nuclear β-catenin, and increased expression of cleaved caspase-3 with niclosamide, TRA-8, and the combination treatment (Supplementary Table S2). This shows that niclosamide, TRA-8, and the combination repress tumor growth by inhibiting the Wnt/β-catenin pathway, the STAT3 pathway, and by causing apoptosis. Western blot analysis of tumor tissue resulted in reduced expression of survivin in niclosamide-treated mice and further reduction with combination treatment (results not shown). These results further demonstrate the combination effect of TRA-8 and niclosamide.

**Primary BLBC patient samples response to niclosamide and TRA-8**

The combination of niclosamide and TRA-8 was further investigated on patient BLBC tumor cells collected from pleural effusions from triple-negative treatment-resistant patients. All four samples (UAB01, UAB03, UAB04, and UAB05) stained positive for LRP6 by immunohistochemistry (data not shown). All four patient samples showed significant cytotoxicity when treated with niclosamide for 48 hours (1–8 μmol/L; Fig. 6A). TOPflash assay using lentiviral reporter was performed on UAB03 and UAB05 because these two samples had adequate number of cells available, whereas UAB01 and UAB04 had too few cells. The decrease in percentage luciferase activity in the TCF/LEF viral reporter after 24 hours of treatment with 4 μmol/L niclosamide showed Wnt/β-catenin pathway inhibition in these two samples (Fig. 6B). Patient sample UAB03 also had enough cells for Western blot assay to be performed. Niclosamide demonstrated dramatic inhibition of Wnt/β-catenin pathway proteins (LRP6 and β-catenin) and cyclin D1, as well as reduced p-STAT3 and total STAT3 expression in this patient sample when treated for 24 hours with 4 μmol/L niclosamide (Fig. 6C). When niclosamide and TRA-8 treatment was combined in two patient samples, UAB05 and UAB03, tumor cell cytotoxicity was enhanced compared with TRA-8 alone for patient sample UAB05, and a modest combination effect was seen in patient sample UAB03 (Fig. 6D). The higher concentrations of niclosamide that were needed for cytotoxic, Western, and TOPflash effects in the patient samples compared with the cell lines may reflect the drug-resistance history and metastatic nature of the patient samples. Cells collected from two BLBC patient pleural effusion samples
calipers twice a week. Each point in the curve represents the mean pleural mesothelial cells (data not shown).

were metastatic breast cancer epithelial cells rather than marker for mesothelial cells, confirming that the cells metastatic breast cancer, and negative for calretinin, a marker for cells in the sample were positive for Moc31, a marker for immunochemistry staining, which indicated that more than 50% trajectories and mesenchymal–epithelial transition markers that could potentially influence observed dynamic CSC marker expression (42).

Figure 5. Effect of niclosamide and TRA-8 in vivo on 2LMP orthotopic tumor growth. Tumors were established in athymic nude mice by MFP implantation of 2 × 10^6 2LMP cells. The therapy started when tumors reached a size of 16 mm^2. Niclosamide (30 mg/kg) was given intraperitoneally 5 days a week, TRA-8 (200 μg) was given intraperitoneally 2 × weekly for 3 weeks. Tumor size was measured with calipers twice a week. Each point in the curve represents the mean ± SE (n = 5). Single-agent niclosamide or TRA-8 versus control (†, P < 0.05), combination treatment versus control (‡, P < 0.01), combination treatment versus TRA-8 or niclosamide (#, P < 0.05).

(UAB03 and UAB05) were characterized by immunohistochemistry staining, which indicated that more than 50% of cells in the sample were positive for Moc31, a marker for metastatic breast cancer, and negative for calretinin, a marker for mesothelial cells, confirming that the cells were metastatic breast cancer epithelial cells rather than pleural mesothelial cells (data not shown).

Discussion

Most cancer treatment regimens assume that all cancer cells have equal malignant potential and respond similarly to therapy. More recently, therapies are being designed to target both bulk tumor cells and CSCs with the goal to prevent recurrence and metastasis. Therefore, therapies that target both the CSC maintenance pathways and induce apoptosis in the bulk tumor cell population could potentially result in increased chances for survival. We previously described that TRA-8 kills BLBC cell lines both in vitro and in xenograft mouse models and preferentially kills their CSC population. In an effort to improve on this strategy, this study demonstrated that niclosamide, a potent inhibitor of Wnt/β-catenin signaling, produced similar cytotoxicity with bulk tumor cells (attached cells), CSC-enriched cell populations (NAAE cells), and primary tumor cells from patients with BLBC both alone and in combination with TRA-8.

Because CSCs represent a small fraction of the total tumor cell population, it is difficult to run mechanistic studies with these cells especially by techniques such as Western blot and the TOPflash reporter assay that require a large number of cells. NAAE cells were discovered as a tool to analyze the effect of drugs on CSC-enriched popu-
decrease in p-STAT3, which shows that it affects other pathways, in addition to the Wnt/β-catenin pathway involved in tumor initiation and progression. The ability of niclosamide to deplete survivin expression could be the mechanism by which there is an increase in apoptosis when BLBC cells are treated with TRA-8. Survivin normally inhibits caspase-9 activation within the apoptosome, a key step in the apoptotic cascade (49). The 2LMP LRP6 knockdown cells had enhanced sensitivity to TRA-8, and reduced survivin activity, further validating our hypothesis that inhibition of canonical Wnt/β-catenin signaling can sensitize cells to death receptor–mediated apoptosis.

The extrinsic apoptotic pathway has been shown to regulate β-catenin activity by TRAIL’s ability to decrease full-length β-catenin expression (30, 50). Although TRAIL can induce apoptosis in tumor cells, many cancer cells develop resistance, which could be overcome by combination treatment. β-Catenin can be targeted to sensitize apoptosis-resistant cancer cells. TRA-8 and niclosamide led to reduction of β-catenin expression, coinciding with maximal apoptosis. The ability of TRA-8 to reduce β-catenin was confirmed by TOPflash reporter assay and Western blot analysis of cleaved β-catenin. Future studies will focus on characterizing the mechanism by which TRA-8 can inhibit β-catenin activity and the results could help further elucidate how TRA-8 preferentially induces apoptosis in CSCs.

Overall, this study provides new insights into the treatment of CSCs from BLBC. It further supports existing literature that niclosamide’s inhibition of Wnt/β-catenin signaling and reduction in p-STAT3 produces enhanced cytotoxicity against CSCs. In addition, the results demonstrate that the combination of niclosamide and TRA-8 targets the CSC subpopulation and potentially prevents recurrence and metastasis in patients with BLBC. The combination of these two agents or similar compounds can potentially be translated into clinical trials, helping patients with BLBC who have very few treatment options available to them.

Figure 6. Metastatic pleural effusion patient sample sensitivity to niclosamide alone and in combination with TRA-8. A, sensitivity of patient samples to 48-hour niclosamide-mediated cytotoxicity (1, 2, 4, and 8 μmol/L) compared with untreated controls. Individual experiments were assayed in quadruplicate and bars represent mean ± SE (P < 0.01). B, activity of TCF/LEF viral reporter in the TOPFlash assay was evaluated for patient samples UAB03 and UAB05. Both samples were treated with 4 μmol/L niclosamide for 24 hours in triplicate. Bars, mean ± SE. Niclosamide compared with control (*, P < 0.05). C, Western blot analysis of patient sample UAB03 after 24-hour treatment with niclosamide (4 μmol/L). D, cytotoxicity of patient samples UAB03 and UAB05 pretreated with niclosamide (0.5, 1, 2, 4, and 8 μmol/L) for 24 hours followed by 24 hours with TRA-8 (50 or 500 ng/mL). Cell viability was analyzed using ATPlite assay.
Disclosure of Potential Conflicts of Interest

A.F. LoBuglio has ownership interest in anti-DR5. D.J. Buchsbaum has ownership interest in U.S. Patent Nos. 7,279,160, 7,476,383, and 7,704,502. No potential conflicts of interest were disclosed by the other authors.

Authors’ Contributions

Conception and design: A.I. Londoño-Joshi, R.C. Arend, R.S. Samant, A. Forero-Torres, A.F. LoBuglio, Y. Li, D.J. Buchsbaum


Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): A.I. Londoño-Joshi, R.C. Arend, W. Lu, B.J. Metge, W.E. Grizzle, M. Conner, Y. Li, D.J. Buchsbaum

Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): A.I. Londoño-Joshi, B. Hidalgo, W.E. Grizzle, M. Conner, A. Forero-Torres, Y. Li, D.J. Buchsbaum

Writing, review, and/or revision of the manuscript: A.I. Londoño-Joshi, R.C. Arend, A.I. Londoño-Joshi, M. Conner

Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): A.I. Londoño-Joshi, M. Conner

Study supervision: A.I. Londoño-Joshi, R.S. Samant, A.F. LoBuglio, D.J. Buchsbaum

No potential conflicts of interest were disclosed by the other authors.

Acknowledgments

The authors thank Dr. Andrea Frost, Dr. Charles N. Landen, Ashwini A. Katre, Chandrika Kurpad, and Denise K. Oelschlager for histologic preparation and analysis of mouse normal tissues and patient pleural preparations, and Andres Aristizabal for his technical assistance.

Grant Support

This study was supported in part by NIH SPORE in Breast Cancer P50 CA899039 (D.J. Buchsbaum), NIH Grant R01 CA124531 (R.S. Samant), Komen for the Cure Promise Grant KG090969 (A. Forero-Torres), Breast Cancer Research Foundation of Alabama (A. Forero-Torres), and DOD Training grant W81XWH-11-1-0151 (A.I. Londoño-Joshi). Flow cytometry support was provided by David Keyser (supported by NIH grant P50 AR43611). B. Hidalgo is supported by a T32 NHLBI Training Grant, 5T32HL072757. The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked advertisement in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

Received July 19, 2013; revised December 20, 2013; accepted January 21, 2014; published OnlineFirst February 19, 2014.

References
