Targeting Tumor Hypoxia: Suppression of Breast Tumor Growth and Metastasis by Novel Carbonic Anhydrase IX Inhibitors

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Running Title: Targeted inhibition of CAIX suppresses breast cancer progression

SD and CTS are founding members of Metasignal Therapeutics Inc.
Abstract

Carbonic Anhydrase IX (CAIX) is a hypoxia and HIF-1 inducible protein that regulates intra- and extracellular pH under hypoxic conditions and promotes tumor cell survival and invasion in hypoxic microenvironments. Interrogation of 3,630 human breast cancers provided definitive evidence of CAIX as an independent poor prognostic biomarker for distant metastases and survival. shRNA-mediated depletion of CAIX expression in 4T1 mouse metastatic breast cancer cells capable of inducing CAIX in hypoxia resulted in regression of orthotopic mammary tumors and inhibition of spontaneous lung metastasis formation. Stable depletion of CAIX in MDA-MB-231 human breast cancer xenografts also resulted in attenuation of primary tumor growth. CAIX depletion in the 4T1 cells led to caspase-independent cell death and reversal of extracellular acidosis under hypoxic conditions in vitro. Treatment of mice harboring CAIX-positive 4T1 mammary tumors with novel CAIX-specific small molecule inhibitors that mimicked the effects of CAIX depletion in vitro resulted in significant inhibition of tumor growth and metastasis formation in both spontaneous and experimental models of metastasis, without inhibitory effects on CAIX-negative tumors. Similar inhibitory effects on primary tumor growth were observed in mice harboring orthotopic tumors comprised of lung metastatic MDA-MB-231 LM2-4Luc+ cells. Our findings demonstrate that CAIX is vital for growth and metastasis of hypoxic breast tumors and is a specific, targetable biomarker for breast cancer metastasis.
Introduction

Cancer metastasis is a complex process that results in establishment of secondary tumors in distant organs (1). There is increasing recognition that hypoxia plays an important role in cancer progression and metastasis (2, 3), including breast cancer metastasis (4, 5). Furthermore, there is now growing evidence that altered tumor metabolism and hypoxia inducible factor 1α (HIF-1α)-regulated enzymes such as carbonic anhydrase IX (CAIX) and CAXII may be vital to the process of tumor progression to metastasis (2, 6).

CAIX is a dimeric membrane-bound enzyme that efficiently catalyzes the reversible hydration of CO₂ (7, 8). CAIX is selectively expressed in hypoxic tumors, including breast malignancies (9, 10), and its presence is a poor prognostic marker for patients with breast cancer (11, 12). The tumor-specific expression of CAIX and its association with cancer progression and poor treatment outcome has led to interest in targeting this enzyme for cancer therapy (8). Studies have focused on the utilization of CAIX as a biomarker of hypoxic tumors, spurring the development of specific antibodies and sulfonamide-based small molecules for imaging CAIX in vivo (13-17). However, the relevance of CAIX function to the biology of tumors has only recently come into focus. Evidence suggests that, together with the activity of proteins such as the Na+/H+ exchanger NHE1, Na⁺-HCO₃⁻ co-transporters and monocarboxylate transporters MCT-1 and MCT-4 (18, 19), the activity of CAIX plays an important role in the survival of tumor cells in hypoxic regions of tumors (18, 20) through the regulation of tumor pH (18, 20). The HCO₃⁻ produced at the extracellular surface
by CAIX is transported into the cytosol to control an intracellular pH (pHi) that is challenged by the abnormally acidic extracellular pH (pHe) produced in hypoxia (18, 20-22). The protons derived from CAIX activity further contribute to the decrease in pHe, thereby potentiating extracellular matrix breakdown and cell invasion (6, 19). Therefore, CAIX may increase metastatic potential by allowing aggressive tumor cells to survive the hostile environment imposed by hypoxia, and may further function to potentiate extracellular acidosis, facilitating growth and invasion of surviving cells (18, 20-22).

Although targeting CAIX for the treatment of cancer has garnered much scientific and clinical interest, appropriate carbonic anhydrase-relevant cell and animal models of tumor hypoxia for testing novel, CAIX-active compounds have only recently become available (23). To date, studies have focused on the role of CAIX in the regulation of primary tumor growth (22, 24). Importantly, neither the functional requirement of CAIX in breast tumor growth and metastasis in vivo, nor the benefit of therapeutic targeting this enzyme in aggressive breast cancer has been addressed.

In this study, we provide definitive evidence, using a large (>3600) cohort of human breast cancer samples, that CAIX is a poor prognostic marker for distant metastasis and survival. Furthermore, using a combination of gene depletion strategies and pharmacologic inhibition with novel small molecule inhibitors, we demonstrate a functional requirement of CAIX in the growth and metastasis of mouse and human breast tumors in several pre-clinical models.
Our findings establish CAIX as a therapeutic target for the treatment of CAIX-positive breast cancer.

**Materials and Methods**

**Cell culture and hypoxic exposure**

The acquisition, generation and culture of the luciferase expressing mouse breast cancer cell lines 4T1, 66cl4 and 67NR have been described previously (25). The MDA-MB-231 human breast cancer cell line was obtained from the American Type Culture Collection (ATCC) and was maintained as described previously (26). The MDA-MB-231 LM2-4 Luc+ cell line was provided by Dr. Robert Kerbel (University of Toronto, Canada) in July, 2010 and cells were cultured as described previously (27). For in vitro studies, cell lines were passaged for a maximum of 3 months, after which fresh seed stocks were thawed for experimental use. All cells were incubated at 37°C with 5% CO2 in a humidified incubator (normoxia). For culture in hypoxia, cells were maintained in 1% O2 and 5% CO2 balanced with N2 at 37°C in a humidified incubator in a sealed anaerobic workstation. Cell lines were evaluated routinely for morphology, hypoxia-induced CAIX expression and in vivo tumor growth.

**Generation of transfected and transduced cells**

shRNAmir vectors targeting mouse CAIX and a non-silencing sequence (Open Biosystems) were transfected into 4T1 cells using LipofectAMINE-PLUS (Invitrogen Life Technologies) according to the manufacturer’s instructions. Transfected cells were selected using hygromycin. Stable shCAIX clones were derived by limited dilution cloning. For (re-)introduction of CAIX, human CAIX
(gift from Dr. Jacques Pouysségur, University of Nice) was transfected into 4T1 cells stably expressing mouse shCAIX and Zeocin was used for selection.

For stable depletion of human CAIX in the MDA-MB-231 cells, two different shRNA mir constructs (Open Biosystems) were transduced into cells using lentivirus as per the manufacturer’s instructions. Transduced cells were selected using puromycin.

All transfected and transduced cell lines were selected, propagated and frozen as seed stocks at early passage. For in vivo studies, cells were thawed from frozen stocks, passaged 1-2 times to expand the culture and implanted in mice. Cell lines were tested for mycoplasma contamination by a commercial testing facility prior to implantation in mice.

**Measurement of extracellular pH**

Changes in pH were assessed using procedures published previously (28-30). In brief, cells were plated and allowed to recover overnight. A standard volume of 3 ml of fresh media/dish was then added and cells were incubated in normoxia or hypoxia for 72 h. Care was taken to ensure that cultures grown in normoxia and hypoxia were subconfluent and contained similar cell numbers. Media was collected and pH was measured immediately using a digital pH meter.

**Pharmacological Inhibitors**

The chemical properties of the sulfonamide, CAI17, have been described previously (8, 30). For in vitro studies, CAI17 was dissolved in DMSO, stored at -80°C and diluted into culture medium prior to application. Subconfluent cells were incubated with CAI17 for 72 hours, washed 3x in PBS and imaged using a
Zeiss Axioplan epifluorescence microscope. For in vivo studies, CAI17, ureidosulfonamide U-104, and glycosylcoumarins GC-204 and GC-205 were solubilized in 37.5% PEG400/12.5% ethanol/50% saline prior to injection. Drug aliquots were made fresh daily or were prepared, frozen at -80°C in single-use aliquots and thawed prior to administration. Drugs were administered by i.p. injection, except for CAI17 where the first 2 doses were administered by i.v. injection, followed by i.p. injection of the remaining doses. Specific dosing schedules are described in the appropriate figures.

**Analysis of protein expression**

Cells or flash-frozen tumor tissues were lysed as described previously (26). Equal amounts of protein were loaded on SDS-PAGE gels. Western blots were performed as described previously (26) using mouse CAIX (1:500), human CAIX (1:1000) (R&D Systems), caspase 3 (1:1000; Cell Signaling), PARP-1 (1:1000; Cell Signaling) and β-actin (1:10,000, Sigma) antibodies.

**Mouse tumor models**

All animal studies and procedures were done in accordance with protocols approved by the Institution Animal Care Committee at the BC Cancer research Centre and the University of British Columbia (Vancouver, BC, Canada).

**Syngeneic orthotopic tumors and spontaneous metastasis**

4T1 cells (1 x 10^6) or 67NR cells (2 x 10^6) were orthotopically implanted into the fourth mammary fat pad of 7-9 week-old female BALB/c mice as described previously (25). Primary tumor growth rates were calculated from caliper measurements using the modified ellipsoid formula \((L \times W^2)/2\). Tumor formation
and metastasis progression was monitored and quantified using bioluminescent imaging as previously described (25, 27).

Experimental metastasis assays

For studies involving genetic depletion of CAIX, 4T1 or 67NR cells \((5 \times 10^5)\) were injected directly into the tail vein of 7-9 week-old female BALB/c mice. Mice were imaged once per week to follow the growth of metastases. Mice were euthanized 20 days post-injection and lungs were resected for further analysis. Tumor burden in the lung was quantified by manually counting nodules visible on the lung surface. For studies using U-104, 4T1 cells \((1 \times 10^5)\) were injected as described above, while \(2 \times 10^5\) cells were used for studies with GC-204 and GC-205.

Human xenograft tumors

For studies involving CA IX depletion, \(1 \times 10^7\) MDA-MB-231 cells suspended in a 50% Matrigel/PBS solution were implanted subcutaneously in 6-8 week-old female NOD.CB17-prkdc^scid/J mice. For primary breast tumor xenografts using the MDA-MB-231 LM2-4^Luc+ variant, cells were implanted orthotopically in mice as described above. Therapy was initiated when the tumors reached 200 mm^3. For both models, tumor growth was monitored by caliper measurement.

Immunohistochemistry

2 h before tumor excision mice were injected i.p. with a saline solution containing 1500 mg/kg BrdUrd (Sigma) and 60 mg/kg Pimonidazole (Chemicon), and i.v. 5 min before with DiOC_7(3) \((70 \mu l, 0.6 \text{ mg/ml}; \text{ Molecular Probes})\). Tumors were
then harvested and analyzed for vasculature, perfusion, hypoxia, apoptosis, proliferation and necrosis as described previously (31, 32). Paraffin embedded tumor sections were also stained for CAIX (1:50 for lung metastases, Santa Cruz Biotechnology) as previously described (25).

**Apoptosis assay**

TUNEL labeling (Roche Applied Science) was employed for analysis of apoptosis according to the manufacturer’s instructions. Briefly, subconfluent cells grown on coverslips were incubated for 48 h in normoxia or hypoxia in 1% serum, fixed and analyzed for TUNEL-positive cells. Quantification was achieved by counting the number of TUNEL-positive cells in 5 random fields/cell line at 20x magnification.

**Clinical Analysis**

The methods used to create the TMAs have been described (33). 3,630 cases had adequate tumor and staining results for assessment of all biomarkers. Immunohistochemistry for ER, PR, HER2, CK 5/6, EGFR and Ki67 was performed concurrently on serial sections and scored as described previously (33). CAIX expression was assessed using a murine monoclonal antibody (M75; 1:50) (34). Scoring of CAIX expression was either 0: no staining or 1: any staining and performed independently and blindly by 2 pathologists. This scoring system has been developed and validated for this very large TMA, and has been used previously to demonstrate prognostic significance for breast cancer biomarkers such as HER-2 and Ki67 (33, 35). The stained images of the complete tissue core set are available at the publicly accessible website.
Statistical Analysis

Results were subjected to statistical analysis using the Data Analysis ToolPack in Excel software. Two-tailed p values were calculated using Student’s t-test. Data were considered significant for p<0.05. Statistical analysis for the clinical outcomes was performed using SPSS 13.0 (Chicago, IL), S-Plus 6.2 (Seattle, WA) and R 2.1.1 (http://www.r-project.org). In univariate analysis, BCSS (date of diagnosis of primary breast cancer to date of death with breast cancer as the primary or underlying cause) and RFS (date of diagnosis of primary breast cancer to the date of a local, regional or distant recurrence) and distant RFS (date of diagnosis of primary breast cancer to the date of a distant recurrence) were estimated by Kaplan-Meier curves. Log-rank test was used to estimate the survival differences. For multivariate analysis, a Cox proportional hazards model was used to estimate the adjusted hazard ratios and significance. To assess the violations of proportional hazard models, smoothed plots of weighted Schoenfeld residuals were used.

Results and Discussion

CAIX is a poor prognostic marker in a large cohort of breast cancer patients

Although previous studies have reported that CAIX expression in several types of cancer, including breast cancer, correlates with poor patient prognosis (11, 34, 36, 37), the sample sizes have been relatively small and adjuvant
treatments not uniform. To provide definitive evidence for CAIX as an important breast cancer prognostic marker, we analyzed the expression of CAIX in a primary breast tumor tissue microarray (TMA) containing more than 3600 patient samples subjected to standardized treatment with a median follow-up of 10.5 years (Table S1). Previously, we demonstrated prognostic significance of CAIX in a cohort of 103 breast cancers in which CAIX expression was examined both as a continuous and a categorical variable (11). We found that even 1% staining was significantly prognostic. For the large cohort of patients examined here, a simplified scoring system (present vs absent) allows for less analytical variability, an issue which plagues immunohistochemical testing for hormone receptors and the HER-2 receptor in breast cancer. CAIX expression was seen in 15.6% of assessable tumors and CAIX was differentially expressed among the biological subtypes, with the highest correlation in the basal breast cancers (51%) and the lowest proportion in the luminal A subtype (8%) (Table S2).

In Kaplan-Meier analyses, CAIX expression was significantly associated with worse relapse free survival (Figure 1A), distant relapse free survival (Figure 1B) and breast cancer specific survival (Figure 1C), achieving very high levels of statistical significance. The 10 year distant relapse free survival and breast cancer specific survival rates in the CAIX positive versus CAIX negative groups were 57% compared to 73%, and 62% compared to 78%, respectively. In multivariate analyses, including all standard prognostic variables and biological subtypes, CAIX expression remained a strong independent poor prognostic factor with a hazard ratio of 1.4 (Table S3). These data confirm and extend the
results of previous studies, and demonstrate a clear link between CAIX expression and a higher rate of distant metastasis for breast cancer. Our data substantiate previous studies that have also shown CAIX as a poor prognostic marker of breast cancer (11, 12). In addition, other studies have shown a clear correlation between the expression of CAIX, hypoxia-induced HIF-1α and altered metabolic proteins such as GLUT-1 (4, 9, 38), although HIF-1α is a more labile protein, and thus more susceptible to pre-analytical variables.

**Preclinical models for interrogating the requirement of hypoxia-induced CAIX expression in breast cancer**

Tumor hypoxia is linked both to the expression of CAIX and to the selection of tumor cells that are better able to metastasize. However, while a few studies have investigated the role of CAIX in the regulation of primary tumor growth (22, 24), the relationship between CAIX expression and metastatic potential has not been investigated. Therefore, to interrogate the functional role of CAIX in metastatic breast cancer, we were interested in selecting tumor models that exhibit both hypoxic microenvironments and the ability to metastasize. We have shown previously that the highly metastatic 4T1 mouse mammary tumor (39) overexpresses CAIX (25). Further characterization of this model revealed that it is poorly vascularized and contains large regions of hypoxia and necrosis (Figure 2A). Indeed, tumors formed by 4T1 cells have significantly fewer blood vessels, and significantly higher amounts of hypoxia, necrosis and apoptosis compared with tumors formed by isogenic, non-metastatic (25) 67NR cells (Figure 2A and 2B). Furthermore, bioinformatic
analysis of differential gene expression data (25) identified several hypoxia-regulated genes, including CAIX, that are expressed at higher levels in the 4T1 tumors relative to the 67NR tumors (Figure 2C). These attributes make the 4T1 mouse mammary tumor a robust model for examining the effects of manipulating CAIX expression and activity on the progression of breast cancer.

In addition to this syngeneic mouse model, we selected the MDA-MB-231 human breast tumor cell line as previous studies have shown this model to be hypoxic and to have hypoxia-inducible levels of CAIX (40, 41). We confirmed the effect of hypoxia on CAIX expression in these cell lines to validate them as appropriate models for subsequent in vivo studies. In keeping with previously published findings (25, 41), we found that both cell lines induced CAIX expression in hypoxia (Figure 2D, Supplemental Figure 1A), in contrast to the absence of hypoxia-induced CAIX in the 67NR cells (Figure 2D, Supplemental Figure 1A). These models reflect the clinical findings shown in Figure 1 and in other studies (11, 12) of hypoxia-induced upregulation of CAIX expression.

**Depletion of CAIX in 4T1 cells inhibits cell survival and alters pHe**

Next, we silenced CAIX gene expression in the 4T1 cells (Figure 3A) and the MDA-MB-231 cells (Figure 3B) by stably expressing CAIX shRNA constructs. 4T1 cells expressing a non-silencing control shRNA (shNS) upregulated expression of CAIX in hypoxia as expected, whereas hypoxia-induced CAIX expression was markedly attenuated in 2 independent clones expressing a single, identical shRNA targeting mouse CAIX (shCAIX; Figure 3A, Supplemental Figure 1B). Similarly for the MDA-MB-231 cell line, two distinct shRNA
sequences targeting human CAIX were transduced and hypoxia-induced CAIX expression was analyzed. Only one of the transduced shRNA constructs was found to effectively deplete CAIX expression (Figure 3B, Supplemental Figure 1C). The cell line expressing the “non-silencing” CAIX shRNA sequence was used as a control in subsequent in vivo experiments.

Recent data suggest that the regulation of pH by CAIX may be important for cell survival in conditions of hypoxic stress (22, 42) and previous studies have demonstrated a reduction in clonogenic survival in hypoxia of MDA-MB-231 cells treated with siRNA to CAIX (41). To examine whether depletion of CAIX may be influencing cell survival in the 4T1 system, we cultured control and CAIX-depleted 4T1 cells in hypoxia and assessed the amount of cell death by using a TUNEL assay. 4T1 shCAIX cells showed a significant increase in cell death compared shNS cells (Figure 3C). To determine whether the increase in TUNEL-positive cells was due to an increase in apoptosis, we analyzed the levels of active caspase-3 and PARP. No clear evidence of increased caspase-3 cleavage (Supplemental Figure 2A) or PARP cleavage (Supplemental Figure 2B) was observed, suggesting that cell death in the CAIX-depleted cells may be occurring by a caspase-independent mechanism, possibly related to depletion of the intracellular ATP concentration (Supplemental Figure 2C). While the decrease in ATP concentration was modest, it was statistically significant and similar in magnitude to data reported previously (43).

CAIX is functionally linked to the control of tumor pH (18, 22, 42), and hypoxia-induced, extracellular acidosis is a measure of the biological activity of
CAIX in cultured cells (30). Therefore, we examined the effect of CAIX depletion on pHe in hypoxia. Acidification of the extracellular medium in hypoxia was inhibited in the shCAIX-expressing 4T1 clones relative to the parental and shNS-expressing 4T1 cells (Figure 3D), suggesting that silencing CAIX gene expression induces functional inhibition of pHe regulation in this cell line.

**Depletion of CAIX expression results in regression or growth inhibition of mouse and human breast tumors**

Having evaluated the biological response of 4T1 cells to CAIX depletion in vitro, we next tested the impact of silencing CAIX expression on the growth of these tumors in vivo. We observed that whereas control 4T1 cells formed tumors that grew steadily over 30 days, tumors established from CAIX-depleted cells regressed significantly after initial tumor growth (Figure 4A). The regression of the tumors appeared to be stable, as there were only two mice with primary tumor recurrence appearing towards the end of the study (Table S4). Examination of the primary tumors confirmed downregulation of CAIX expression in the tumors (Supplemental Figure 3). The reduction of CAIX expression had a dramatic effect on the overall survival of the mice (Figure 4B). While the animals bearing tumors that express CAIX did not survive, the survival rate of animals inoculated with CAIX-depleted 4T1 cells remained at 100% over the course of the study.

To validate the observed in vivo effects of CAIX depletion on primary breast tumor growth, we performed similar experiments using the MDA-MB-231 cells expressing human shCAIX (see Figure 3B). Depletion of CAIX significantly
attenuated tumor growth of MDA-MB-231 xenografts (Figure 4C). Importantly, both the parental cells and the cells expressing the non-silencing construct (shCAIX 1 NS) formed tumors at a similar rate (Figure 4C), demonstrating the specificity of the effect of CAIX depletion on tumor growth. These data provide strong evidence for an important functional role of CAIX in the growth of hypoxic primary breast tumors.

To demonstrate that the tumor regression seen with the 4T1 shCAIX cells was dependent specifically on CAIX, we attempted to rescue the tumor growth by introducing human CAIX (resistant to mouse CAIX shRNA) into 4T1 cells expressing mouse-specific shCAIX. Human CAIX expression was readily detectable on the cell surface, together with stable expression of mouse shCAIX (Figure 4D). Cell cultures expressing human CAIX in tandem with shRNA to mouse CAIX showed low numbers of TUNEL-positive cells (Supplemental Figure 4), similar to control 4T1 cells (see Figure 3C). Furthermore, the mammary tumors established from these cells grew at rates similar to those of the parental 4T1 tumors (Figure 4D), confirming the specificity of CAIX-targeting in the regression of the 4T1 tumors.

Previous work in a xenograft model of colon cancer reported a requirement of hypoxia-induced CAIX and CAXII in the regulation of tumor growth (22). In this model, shRNA-mediated depletion of CAIX expression resulted in a partial reduction in tumor growth and compensatory upregulation of CAXII, while depletion of expression of both proteins resulted in greater inhibition of tumor growth (22). Our current findings suggest that, in breast cancer, CAIX
alone is important for the growth of breast tumors. Our data demonstrating that overriding CAIX depletion by constitutive expression of human CAIX can rescue tumor growth strongly implicates the dependency of these metastatic tumors on CAIX function. In addition, CAIX depletion in MDA-MB-231 human breast cancer cells, a cell line which is deficient in CAXII expression (44), also significantly reduced tumor growth. The reasons for the lack of CAXII dependence in these models are not known, but it is possible that the relative expression of CAIX versus CAXII in different cell types may be an important factor.

**Inhibition of CAIX inhibits metastasis of 4T1 breast tumors**

While a reduction in colon tumor growth in response to CAIX depletion has been demonstrated previously (22) and CAIX has been shown to influence cell migration in vitro (45), CAIX has not been previously linked to metastasis in vivo. Given the metastatic potential of the 4T1 cells, in particular, we were interested in determining whether inhibition of CAIX expression or activity also inhibited breast tumor metastasis. To investigate the effects of CAIX depletion on spontaneous metastasis of primary breast tumors in vivo, we employed bioluminescent imaging to detect metastases arising from control (parental and shNS) and CAIX-depleted 4T1 tumors (Figure 5A). Whereas the mice implanted with control cells showed clear evidence of metastasis to several organs, IVIS-detectable metastases were not observed in mice that had been implanted with the CAIX-depleted cells.

To demonstrate that the observed effects on the formation of metastases were not simply due to primary tumor regression, we injected the various 4T1
tumor cell lines intravenously and assessed the ability of the cells to form lung metastases (Figure 5B). We found that, whereas the shNS cells formed robust lung metastases, cells depleted of CAIX showed almost no visible metastasis to the lungs. 67NR cells also showed little evidence of experimental metastasis (Figure 5B). Quantification of bioluminescent signal at 2 weeks and 3 weeks post-injection demonstrated a significant increase in signal in the shNS group, but not in the shCAIX and 67NR groups (Figure 5B). Examination of the gross lungs revealed that animals injected with shNS cells exhibited large numbers of lung surface nodules, while nodules were largely absent in mice injected with shCAIX cells or 67NR cells (Figure 5C). Quantification of surface nodules showed that mice harboring shNS cells had significantly higher counts than mice harboring shCAIX or 67NR cells (Figure 5C). Membrane-localized CAIX expression was also evident in some of the metastatic foci in histologic sections taken from control animals, but not from mice inoculated with CAIX-depleted cells (Figure 5D). Taken together, these data suggest that CAIX may be required for colonization and growth of metastatic cells at secondary sites.

**Pharmacologic inhibition of CAIX reduces the growth and metastasis of mouse and human tumors.**

Our data showing the requirement of CAIX expression for survival and eventual metastasis of primary breast tumor cells suggested to us that targeting the activity of CAIX with specific pharmacologic inhibitors may be useful for inhibiting disease progression. In previous studies, treatment of renal clear cell carcinoma xenografts with fluorescein- and albumin-based membrane-
impermeant derivatives of acetazolamide, a general carbonic anhydrase inhibitor, resulted in inhibition of tumor growth compared to vehicle-treated controls (24). These data have provided initial proof of principle for sulfonamide-based antitumor effects, but acetazolamide lacks specificity for CAIX. First, we investigated the ability of the metastatic and non-metastatic cells to bind to a previously described, highly selective sulfonamide-based inhibitor of CAIX (CAI17) with a Ki in vitro of 24 nM (8). This fluorescent inhibitor (Figure 6A) interacts only with active CAIX in hypoxic conditions (8) and has been used successfully to image hypoxic xenografts (15). Similar to findings in MDCK cells expressing CAIX (30), we observed that the inhibitor was not able to bind appreciably 4T1 or 67NR cells in normoxia (Figure 6A). In contrast, CAI17 bound to the cell surfaces of metastatic, CAIX-expressing 4T1 cells cultured in hypoxia, but not the non-metastatic, CAIX-negative 67NR cells cultured in similar conditions (Figure 6A). We next tested the effect of CAI17 on hypoxia-induced changes in pHe in these two cell types. In the absence of the inhibitor, the pHe of cultured 4T1 cells decreased significantly in hypoxia, but remained unchanged in the 67NR cultures (Figure 6A). Treatment of the 4T1 cells with CAI17 reversed the hypoxia-induced decline of pHe, indicating functional inhibition of CAIX activity (Figure 6A).

To evaluate the effect of pharmacologic inhibition of CAIX activity in vivo, we treated mice harboring established 4T1 tumors with CAI17. We observed significant inhibition of tumor growth in mice treated with the inhibitor, compared to vehicle controls (Figure 6B). To test for the possibility of non-specific cytotoxic
activity of CAI17, we took advantage of the 67NR tumor model as a negative control. We treated 67NR cell-derived tumors using a dosing schedule and concentrations of CAI17 identical to those used for the 4T1 model (Figure 6C). There was no effect of the CAI17 compound relative to the vehicle control, even at the highest concentration of the inhibitor (Figure 6C). The inhibitor concentrations and the dosing schedule were well-tolerated, and no significant weight reduction was noted in any of the treated mice (Supplemental Figure 5A and 5B). In addition to CAI17, we tested the effect of a novel ureido-sulfonamide inhibitor of CAIX, U-104 (Figure 6D, Table 1), on primary breast tumor growth using a highly metastatic variant of the MDA-MB-231 cell line (27). These cells were observed to induce robustly CAIX in hypoxia (Figure 6D, inset). Tumor volume measurements showed significant inhibition of primary tumor growth in the mice treated with the U-104 compound compared to vehicle controls (Figure 6D). Taken together, these data suggest the ability of sulfonamide-based CAIX inhibitors to specifically target CAIX-expressing tumors.

Having demonstrated that selective sulfonamide-based compounds inhibit the growth of primary breast tumors, we next tested U-104 for its ability to inhibit metastasis formation in the 4T1 experimental metastasis model. Intravenous injection of 4T1 cells into mice and subsequent daily treatment of these animals beginning 24 hours post-injection with U-104 resulted in inhibition of metastases formation (Figure 7A). Quantification of the bioluminescent signal revealed a statistically significant decrease in the formation of metastases in the treated mice (Figure 7A), suggesting that CAIX-specific inhibition may be useful in
treating metastatic disease in breast cancer. Further structure/function analyses for the ureido-sulfonamide compounds will be described elsewhere (46).

Finally, we also tested the ability of 2 additional selective inhibitors of CAIX, GC-204 and GC-205 (Figure 7B, Table 1), to inhibit metastasis in the same model. These two novel compounds are glycosylcoumarins and are representatives of the coumarin class of CAIX inhibitors. GC-204 and GC-205 were effective in limiting colonization in the lungs (Figure 7B). Quantification of the bioluminescent signal revealed a statistically significant decrease in the formation of metastases in the treated mice (Figure 7C), with GC-205 being particularly efficacious at 15 mg/kg (Figure 7C). Collectively, these pharmacologic studies provide strong "proof of principle" data for the therapeutic inhibition of CAIX activity for breast tumor growth and metastasis formation. Moreover, our results suggest that perturbation of CAIX function reduces metastasis both by inhibiting cell survival in hypoxia and perhaps also by preventing migration and invasion, as inhibition of CAIX reduced the metastatic burden in models of experimental metastasis.

In conclusion, our results not only solidify CAIX as a poor prognostic biomarker for human breast cancer, but also show it to be a promising therapeutic target for breast tumor growth and metastasis. Our data demonstrate that CAIX is an essential factor in the survival of tumor cells in hypoxic regions of breast tumors and, in addition, its activity contributes to metastasis in breast cancer. Its use would allow for the identification and selection of patients whose tumors are likely to metastasize, and for treatment with CAIX inhibitors to prevent...
this deadly process. Although CAIX expression is elevated in about 16% of breast cancer patients, this percentage falls in with the frequency of upregulation of Her-2 and of basal breast cancers which have the highest expression of CAIX (Table S2). Since these subgroups of breast cancers are the most difficult to treat and are also the most aggressive in terms of metastatic potential, we suggest that CAIX inhibitors, such as those described here, should be used to treat hypoxic breast tumors with elevated CAIX expression. The development of small molecule inhibitors of CAIX activity (8), anti-CAIX neutralizing antibodies, and CAIX imaging agents, should accelerate clinical translation of our findings. Finally, our findings are likely to be applicable to other CAIX-expressing tumors.

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References


Table 1. $K_i$ values for ureido-sulfonamide and glycosylcoumarin inhibitors of CAIX

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<th>Compound</th>
<th>$K_i$ (nM)*</th>
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<tr>
<td></td>
<td>CA I</td>
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<tr>
<td>U-104</td>
<td>5080</td>
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<td>GC-204</td>
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*$K_i$ values were derived using in vitro assays for CA activity as described in (47).
Figure Legends

Figure 1

**CAIX expression is an independent prognostic factor in a large cohort of breast cancer patients.** The Kaplan-Meier plots show cumulative survival (Cum Survival) as a function of time to event cut off at 10 years post-diagnosis. CAIX expression was significantly associated with poor relapse-free survival (RFS) (A), distant RFS (B), and disease specific (breast cancer) survival (C). DSS = distant site survival. $P<10^{-17}, P<10^{-16}, P<10^{-13}$ for A, B, and C, respectively. CAIX expression on the TMA was binarized as 0 and 1 for analysis.

Figure 2

**The metastatic 4T1 primary tumor is a valid preclinical model of hypoxia-induced CAIX expression.** (A) Representative composite, pseudocolored images of 4T1 and 67NR tumor tissue sections showing the distribution of the indicated parameters. Scale bar = 150 μm. (B) Quantification of the parameters outlined in (A) using whole tumor tissue sections. n = 10 animals/group. *$p \leq 0.02$, **$P<10^{-5}$. (C) Differential gene expression data derived from tumor tissue from each cell model (25) was analyzed bioinformatically for expression of hypoxia-induced genes (high expression, red; low expression, green). n = 3/group. (D) The indicated cell lines were cultured in normoxia or hypoxia and levels of CAIX expression were analyzed by Western blot. β-actin served as a loading control.

Figure 3
Silencing CAIX expression in metastatic 4T1 cells inhibits cell survival and alters \( p\text{He} \) in hypoxia. (A) Cells expressing non-silencing shRNA (shNS) or shRNA targeting mouse CAIX (shCAIX) were cultured in normoxia (N) or hypoxia (H) and analyzed for CAIX expression. Two independent clones (C2, C5) expressing a single, identical shCAIX construct were tested. (B) MDA-MB-231 cells expressing either of 2 different shRNA constructs targeting human CAIX (shCAIX 1 and shCAIX 2) were cultured as above and analyzed for CAIX expression. (C) 4T1 cells expressing shNS or shCAIX were cultured in hypoxia and the amount of cell death was analyzed. Left panel, representative images of TUNEL-positive cells (arrows). Scale bar = 100 \( \mu \text{m} \). Right panel, quantification of the TUNEL-positive cells. Data are expressed as fold change in TUNEL-positive cells, compared to control cells cultured in normoxia. \( n = 5 \). \( *P<0.01 \), compared to the controls. (D) Cells were cultured in normoxia or hypoxia and \( p\text{He} \) was measured. \( n = 3 \). Data show the mean change in \( \text{pH} \pm \text{s.e.m.} \). Changes in the \( p\text{He} \) in hypoxia are assessed relative to the baseline \( p\text{He} \) values in normoxia. \( *P<0.01 \), compared to the 4T1 cells expressing shNS in hypoxia.

**Figure 4**

Growth of primary breast tumors characterized by hypoxia requires the expression of CAIX. (A) Parental 4T1 cells, or 4T1 cells expressing shNS or shCAIX were implanted orthotopically into BALB/c mice and tumor volume was monitored over time. \( n = 10 \) for each group. Arrows denote changes in the \( n \) due to surgery and revised values are indicated. \( * \) denotes completion of primary tumor excision from the control groups. Results are expressed as mean ± s.e.m
for each group. ***P<10⁻¹¹, compared to the shNS group. (B) The groups of mice described in (A) were monitored for the percentage of mice surviving (pooled control and shCAIX groups) over time. n=18/group. (C) Parental MDA-MB-231 cells or cells expressing shCAIX 1 or shCAIX 2 were implanted subcutaneously into the flank of NOD/SCID mice and tumor growth was monitored. Note that shCAIX 1 does not silence CAIX expression (see Figure 3B) and is used as a non-silencing (NS) control. n=7 for each group. *P<0.01, compared to NS control tumors. (D) 4T1 cells expressing mouse shCAIX were transfected with human CAIX (hCAIX) and immunocytochemistry was performed to assess levels of human CAIX expression (red, arrowheads) in these cells (shCAIX + hCAIX). Cells are simultaneously positive for GFP (mouse shCAIX) and are counterstained with DAPI (blue). Cells were implanted orthotopically in BALB/c mice and monitored for tumor growth. n=9 for each group. *P<0.04, compared to the shCAIX group.

**Figure 5**

**Inhibition of CAIX expression or activity attenuates metastasis of 4T1 mouse mammary tumors.** (A) Using the experimental design detailed in Figure 4A, mice were examined for evidence of spontaneous metastasis. Primary tumors in the control arm were removed by day 30 post implantation, while primary tumors in the CAIX-depleted groups either regressed or were removed in a similar fashion to control tumors. Representative bioluminescent images are shown as heat maps (blue, least intense; red, most intense;) overlaid on gray-scale body images. (B) 4T1 cells expressing shNS or shCAIX, or 67NR cells
were injected directly into the tail vein of BALB/c mice. Representative images of tumor cell bioluminescence at 20 days post inoculation are shown. The graph shows quantification of bioluminescence at week 2 and week 3 post injection of tumor cells. n = 8/group. *P<0.02. (C) Comparison of surface nodules on gross lungs resected from animals at 3 weeks post-injection. The graph shows quantification of the number of metastatic foci (nodules) on the lung surface. n = 8. *P=0.0001. (D) Representative images of lung metastases stained immunohistochemically for CAIX (arrowheads). Scale bar = 50 µm.

Figure 6
Targeting CAIX activity with selective small molecule inhibitors of CAIX attenuates the growth of mouse and human breast tumors. (A) Left panel, chemical structure of sulfonamide-based CAIX inhibitor CAI17 (formally called CAI17 (8). Center panel, cells were cultured with 10 µM CAI17. Shown are representative images of the FITC-tagged inhibitor (green) bound to cells in normoxia and hypoxia. Right panel, cells were cultured with or without 400 µM CAI17. The mean changes in pH ± s.e.m. are shown. Changes in pH in hypoxia were assessed relative to the baseline pH values measured in parallel cultures grown in normoxia. n = 3. *P<0.001. (B) BALB/c mice were inoculated orthotopically with 4T1 cells and tumors were grown for 14 days. Animals then received CAI17 3 times per week for 2 weeks and tumor growth was monitored. Treatment initiation and termination are indicated. Vehicle-treated and untreated animals served as controls. n = 6 to 8. *P<0.02, **P<0.01, compared to vehicle.
controls. (C) Animals were implanted with 67NR cells, treated as described in (B) and monitored for tumor growth. n = 5 to 6. (D) Top, chemical structure of U-104. Bottom, MDA-MB-231 LM2-4\textsuperscript{Luc+} cells were implanted orthotopically into NOD/SCID mice. When tumors reached an average of 200 mm\textsuperscript{3}, animals received the indicated doses of U-104 daily and tumor growth was monitored. n = 8/group. *P<0.03, **P<0.001. Inset, hypoxia-induced CAIX expression by LM2-4\textsuperscript{Luc+} cells.

Figure 7

Novel selective small molecule inhibitors of CAIX inhibit metastasis formation by 4T1 mammary tumor cells. (A) 4T1 cells were injected directly into the tail vein of BALB/c mice. Daily treatment for 5 days with vehicle or U-104 was initiated 24 hours post inoculation of cells and mice were imaged 24 hours following the final dose. The graph shows quantification of bioluminescence. n = 6 per group. *P<0.01. (B) Left panel, chemical structures for the 2 glycosylcoumarins, GC-204 and GC-205. Right panel, using the experimental design outlined in A, mice were treated daily for 6 days with GC-204 or GC-205. Mice were imaged 24 hours following the final dose. (C) Quantification of bioluminescence shown in (B). Data are reported as the mean ± s.e.m. n = 8/group. *P<0.02.
Figure 4
Targeting Tumor Hypoxia: Suppression of Breast Tumor Growth and Metastasis by Novel Carbonic Anhydrase IX Inhibitors

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