The Transcription Factor ZNF217 Is a Prognostic Biomarker and Therapeutic Target during Breast Cancer Progression

Laurie E. Littlepage\(^1,2\), Adam S. Adler\(^3\), Hosein Kourosoh-Mehr\(^1\), Guiqing Huang\(^1,2\), Jonathan Chou\(^1,2\), Sheryl R. Krig\(^4\), Obi L. Griffith\(^5\), James E. Korkola\(^5\), Kun Qu\(^5\), Devon A. Lawson\(^1,2\), Qing Xue\(^1\), Mark D. Sternlicht\(^1,2\), Gerrit J. P. Dijkgraaf\(^1\), Paul Yaswen\(^5\), Hope S. Rugo\(^2\), Colleen A. Sweeney\(^4\), Colin C. Collins\(^2\), Joe W. Gray\(^2,5\), Howard Y. Chang\(^3,6\), and Zena Werb\(^1,2\)

**Authors’ Affiliations:**
- \(^1\)Department of Anatomy, \(^2\)Helen Diller Family Comprehensive Cancer Center, University of California, San Francisco; \(^3\)Program in Epithelial Biology, Stanford University School of Medicine, Stanford; \(^4\)Division of Basic Sciences, University of California at Davis Cancer Center, Sacramento; \(^5\)Life Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California; and \(^6\)Howard Hughes Medical Institute, Chevy Chase, Maryland

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Corresponding Author: Zena Werb, Department of Anatomy, University of California, 513 Parnassus Avenue, San Francisco, CA 94143. Phone: 415-476-4622; Fax: 415-476-4565; E-mail: zena.werb@ucsf.edu

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INTRODUCTION

In the most aggressive breast tumors, neoplastic cells activate or amplify oncogenes or inactivate or delete tumor suppressor genes to promote invasive growth and poor prognosis in patients. Amplification of the human chromosomal region 20q13 occurs in 20% to 30% of primary human breast cancers, as well as in other cancers, and its amplification correlates with poor patient prognosis (1, 2).

The ZNF217 gene on human 20q13.2 encodes a transcription factor that is overexpressed in all breast tumors and cell lines in which the gene is amplified, as compared with normal mammary tissue and epithelial cells (1, 2). The ZNF217 protein is a member of the C2H2 family of transcription factors and contains 8 predicted Kruppel-like C2H2 zinc finger motifs and a proline-rich region. It is a component of a human histone deacetylase complex (CoREST-HDAC) and is found in complexes with the transcriptional co-repressor C-terminal binding protein (CtBP), the histone demethylases LSD1 (H3K4, H3K9) and KDM5B/JARID1B/PLU-1 (H3K4), and the methyltransferases G9a (H3K9, H3K27) and EZH2 (H3K27; refs. 3–8). Its overexpression in human mammary epithelial cells (MEC) overcomes senescence and promotes immortalization accompanied by increased telomerase activity, increased resistance to TGFβ-induced growth inhibition, and amplification of c-MYC (9). ZNF217 binds to the promoters of genes involved in differentiation and is repressed following retinoic acid treatment of pluripotent embryonal cells (10).

In this study, we investigated whether and how ZNF217 promotes tumor progression and poor prognosis using cultured cells, in vivo transplant models, and human patient expression data sets.

RESULTS

ZNF217 Is Prognostic of Poor Survival in Breast Cancer Patients

Using microarray expression data from primary breast tumors and corresponding clinical data (11, 12), we found that high ZNF217 amplification and expression correlate with shorter overall, disease-specific, and relapse-free survival (Fig. 1A and B; Supplementary Fig. S1A and S1B). To determine whether ZNF217 overexpression overlapped with another poor prognostic subtype, we compared ZNF217 expression levels across patient subtypes [e.g., estrogen receptor (ER)−, ER−, ERBB2/HER2−, ERBB2/HER2+, luminal, and basal patient cohorts] and found that ZNF217 expression levels are highest in ER− tumors and lowest in basal subtype tumors (data not shown).

We next determined whether ZNF217 had prognostic value across breast cancer subtypes. We compared survival and ZNF217 expression by univariate analysis across ER+, ER+, HER2+, luminal, and basal subtype patients. Patients with tumors expressing high ZNF217 consistently had reduced survival compared with patients with tumors expressing lower ZNF217 across multiple breast cancer subtypes (Fig. 1C and data not shown). For example, in a meta-analysis of relapse-free survival across 9 published studies that included 858 patients [ER+/HER2− lymph node (LN)+] with ZNF217 expression, we found that ZNF217 expression was significantly associated with 5-year (P = 0.012) and 10-year (P = 0.023) relapse status (Mann–Whitney), and patients with relapse had higher ZNF217 expression. Similarly, patients grouped into the high-expression tertile had significantly worse survival than low-expression groups. These data show that ZNF217 is prognostic of poor survival in patients by univariate
analysis. Moreover, ZNF217 was a better predictor of survival than ER status by multivariate analysis (Supplementary Fig. S1C).

Overexpression of Znf217 Accelerates Loss of Adhesion and Increased Motility in Mouse MECs

To determine the consequences of Znf217 overexpression, we generated mouse mammary epithelial cell lines that overexpressed Znf217 by retroviral and lentiviral infection. Mouse mammary epithelial cell lines (SCp2, NMuMG, EpH4) overexpressing Znf217 had altered motility showing a more scattered phenotype than adherent, clustered control cells (Fig. 2A–C). Supplementary Fig. S2A–S2C). In a wound-healing/scratch assay, individual SCp2 cells (Fig. 2D) and NMuMG cells (data not shown) overexpressing Znf217 showed increased motility, forward extended lamellipodia, and independent migration (i.e., separate from other cells) toward the middle of the scratch (Fig. 2D, Supplementary Movie S1). In contrast, vector-treated cells migrated as a sheet predominantly with a single leading edge. In keeping with the increased motility, cells overexpressing Znf217 reorganized their actin cytoskeleton with reduced cortical actin and increased actin stress fibers (Fig. 2E) and upregulated epithelial-to-mesenchymal transition (EMT) markers including Snail1 and Twist (Fig. 2F).

Consistently, we found that Znf217 expression levels correlated with expression of EMT markers, including Snail1, Snail2, and Vimentin, genes that have Znf217 enriched at their promoters in human breast cancer cell lines and tumors (Supplementary Table S1). Taken together, these results indicate that the early effects of increased ZNF217 expression would lead to premalignant changes of enhanced mammary epithelial migration.

We used gene expression microarrays of the mouse Scp2 MECs overexpressing Znf217 to identify altered processes and molecular targets of Znf217 (Fig. 2G). In these cells, 176 genes were upregulated and 243 genes downregulated following Znf217 overexpression. We used DAVID software to classify the gene sets with Gene Ontology (GO) terms (Supplementary Table S2). The GO terms suggested that Znf217 overexpression promoted increased cell motility, decreased epithelial differentiation, increased vasculature development, and changes at the membrane.

We also assayed for clonogenicity and transformation potential in vitro. Znf217 overexpression in NIH3T3 cells stimulated anchorage-independent growth in a soft agar assay, with increased number and size of colonies (Fig. 3A–C).

Znf217 Overexpression in Normal Primary Mammary Epithelium Promotes Increased Mammosphere Formation in Culture

Because we found that Znf217 overexpression in culture promoted increased motility, decreased epithelial marker expression/increased mesenchymal marker expression, and increased clonogenicity/transformation potential in vitro, we reasoned that these changes were consistent with a change in differentiation toward a less differentiated or more mesenchymal phenotype. Znf217 gene expression was enriched in the CD24highCD49fhigh cell population, which includes basal, myoepithelial, and progenitor cells, compared with CD24highCD49flow cells, which include luminal and luminal progenitor cells (Fig. 3D and E).

To determine whether ZNF217 could promote progenitor cell phenotypes, we overexpressed Znf217 in normal primary MECs and analyzed clonogenicity potential in the mammosphere assay. Primary MECs infected with Znf217-overexpressing lentivirus and grown in serum-free nonadherent culture conditions showed increased self-renewal capacity (Fig. 3F and G).

Gene Expression Analysis of MECs Following Znf217 Overexpression Predicts Changes in Epithelial Proliferation, Cell Adhesion, and Motility

We next determined the impact of Znf217 overexpression on global gene expression in normal primary mouse MECs by gene expression microarrays (Fig. 3H). Primary MECs were infected with a Znf217-overexpressing lentivirus, passaged to expand the population, and confirmed to overexpress Znf217 by quantitative reverse transcription PCR (qRTPCR; Fig. 3I). In these MECs, 340 genes were upregulated and 401 genes downregulated following Znf217 overexpression (Fig. 3H). The GO terms classified by DAVID software (Supplementary Table S2) suggested that Znf217 overexpression altered the gene expression profile of genes involved in cell proliferation,
ZNF217 Overexpression Promotes Malignancy

**Figure 2.** Znf217 overexpression promotes increased cell motility and aberrant epithelial marker expression. A, relative Znf217 expression levels by qRT-PCR in SCp2 mammary epithelial cell lines infected with virus to overexpress vector or Znf217 with comparable results in 3 experiments. Each sample was tested by qRT-PCR in triplicate relative to the reference TATA box binding protein (Tbp), with similar results for other reference genes. Graphs show the mean ± SEM. B, Western blot analysis of ZNF217 protein (anti-ZNF217) and loading control (anti-HDAC1) in SCp2 cells. Images are representative of multiple experiments using retrovirus or lentivirus overexpression of Znf217. Arrows mark the indicated proteins. C, brightfield images of SCp2 cells ± Znf217 display increased cell scattering in culture after Znf217 overexpression. D, frames from movies of SCp2 cells infected with vector or ZNF217 following a scratch with a pipette tip. The movies ran 20.25 hours. Note the lamellipodia (arrow) extending from the cells by 5.5 hours and the increased number of Znf217-expressing cells in the middle of the scratch by 10.5 hours (arrow). E, phalloidin staining of SCp2 cells ± Znf217. F, relative expression of Znf217 and selected genes by qRT-PCR from NMuMG (top) and SCp2 (bottom) cells ± Znf217 in vitro. Graph shows the mean ± SEM, relative to the reference Gapdh. Similar results were seen with the reference Hprt. For each gene, samples for Znf217 were compared with vector by Mann–Whitney tests, and significant P values <0.02 were marked with *. G, heat map of selected genes enriched following Znf217 overexpression in SCp2 cells. Gapdh, glyceraldehyde-3-phosphate dehydrogenase; Hprt, hypoxanthine phosphoribosyltransferase.

Cell adhesion, cell migration, G-protein–coupled receptor signaling pathways, and ribosomal function.

Genes identified by microarray analysis suggested that overexpressing Znf217 in vivo would promote increased epithelial growth or progenitor cell expansion (Fig. 3H; Supplementary Table S2). These genes included a number of TGFβ and Wnt pathway genes (Axud1/Csnrp-1, Bcl9, Bmpr2, follistatin, Samd9l, Sfrp1, Tcf4, Tgfb2, Tgfrk3, Wnt5a). We validated selected genes including Wnt5a and Sfrp1 by qRT-PCR (Fig. 3J). These results are consistent with ZNF217 promoting differentiation toward a less differentiated cell-like phenotype via aberrant signaling in the TGFβ and Wnt pathways. We also found that ZNF217 was required for cell proliferation (Supplementary Fig. S2D).
**Figure 3.** Znf217 overexpression causes an increase in soft agar colonies and in mammosphere formation. A, Western blot analysis of ZNF217 protein in NIH3T3 cells infected with vector or Znf217 retrovirus. B, Znf217 overexpression increases the number of colonies by anchorage-independent growth in soft agar assay. Relative number of colonies per well by soft agar with vector or Znf217 overexpression (P = 0.001; Student t test). Graph compiled from 3 experiments, each done in triplicate. C, brightfield images of anchorage-independent colonies from soft agar assay. Arrows mark examples of colonies. The large colonies were only seen with the Znf217-overexpressing cells, whereas much smaller colonies were seen with vector-expressing cells. D, relative expression of Znf217 by qRT-PCR from normal adult mammary gland (FVB/n), relative to the reference Hprt with line marking the mean. Glands were sorted by flow cytometry for CD24 brightCD49f dim (basal/myoepithelial/progenitor cells) and CD24 dimCD49f bright (luminal/luminal progenitor) fractions. RNA was isolated and used to generate cDNA from each population. Each dot represents one mouse sorted, collected, and processed by qRT-PCR. Graph shows relative epithelial Znf217 expression in the CD24 brightCD49f dim versus CD24 dimCD49f bright populations. Similar results were seen with the reference Gapdh. E, relative expression of Znf217 by qRT-PCR in primary mouse MECs following lentiviral infection with either pEiT vector or Znf217-pEiT in 3 separate samples. Each sample was tested by qRT-PCR in triplicate relative to the reference Tbp. These samples were used for microarray analysis. Graph shows the mean ± SEM. F, fold change over vector.
ZNF217 Overexpression Promotes Malignancy

We also examined epithelial marker expression in our microarray data set. We found increased expression of both K17 (myoepithelial marker) and K18 (luminal epithelial marker; Fig. 3H). Consistent with these results, we found that ZNF217 expression levels correlated with expression of K19 and K8/18, genes with ZNF217 enriched at their promoters in human breast cancer cell lines and tumors and with downregulated expression after ZNF217 knockdown in MCF7 cells (Supplementary Tables S1 and S3).

**Znf217 Overexpression in Primary MECs Represses an Adult Stem Cell Expression Signature Downregulated in Cancers**

Because the aberrant differentiation markers seen both in vivo and in culture suggest that ZNF217 may push MECs to a more progenitor cell–like phenotype, we compared our microarray data set expression pattern with our previously defined gene expression signature that we found expressed in adult stem cells (13). Many of these adult stem cells are slowly cycling and show balanced differentiation versus self-renewal during normal homeostasis. Adult stemness as defined by this adult stem cell signature is not correlated with self-renewal. This signature has high expression in normal tissues, where cells predominantly are quiescent and have limited self-renewal, but low expression in cancerous tissues, where cells can self-renew. Therefore, reduced expression of the signature correlates with increased self-renewal (13).

Similar to that seen in cancers, primary MECs overexpressing Znf217 significantly repressed genes of the adult stem cell signature (Supplementary Table S4; P = 1.89 × 10\(^{-18}\)), thus making normal cells like renewing cancer cells at the expression level. Consistent with the increased clonogenicity by mammosphere assay, this alteration in the expression signature suggests that ZNF217 may block differentiation and/or promote self-renewal.

**Tumors Overexpressing Znf217 Have a More Basal Pathology with Increased Dual-Positive Luminal and Basal Cell Marker Expression**

Our finding that Znf217 overexpression promoted decreased differentiation in normal and immortalized mammary epithelium prompted us to determine whether these changes are also followed in tumorigenic mammary epithelium both in culture and in vivo. We overexpressed Znf217 by lentiviral delivery of Znf217 into primary luminal-type mammary epithelial tumor cells isolated from 18-week-old MMTV-PyMT mice (PyMT MEC) or an MMTV-PyMT cell line (Vo-PyMT), sorted the cells for the IRES-Tomato reporter gene, and confirmed Znf217 overexpression by qRT-PCR (Fig. 4A). In culture, ZNF217 induced mesenchymal marker expression, reduced expression of E-cadherin, increased expression of EMT markers Snail2 and Twist (Fig. 4A), and produced a more scattered phenotype (Supplementary Fig. S2C). In addition, cells overexpressing Znf217 readily formed increased numbers of mammospheres compared with vector control cells (Fig. 4B and C).

When the sorted cells were transplanted into syngeneic mouse mammary fat pads cleared of epithelium, Znf217 overexpression accelerated the rate of tumor formation, reduced the tumor-free survival, and increased both tumor volume and final tumor weight (Fig. 4D–F; Supplementary Fig. S3A). Tumors overexpressing Znf217 had a markedly altered, heterogeneous histology compared with tumors from vector-treated cells (Fig. 4G). Control tumors had little to no smooth muscle actin (SMA) staining with predominantly luminal K8+ epithelium, whereas Znf217-overexpressing tumors expressed higher levels of myoepithelial and myofibroblast SMA protein (Fig. 4H).

Tumor cells from vector-treated cohorts were predominantly K8+ with few K14+ cells; most of the K14+ cells were K8 and were located basal to the K8+ tumor cells. Znf217 overexpression increased numbers of K14+ cells in tumors, with many double-positive K8/K14+ cells (Fig. 4I and J and data not shown). The K8/K14+ cells may be a bipotent progenitor population capable of forming both luminal and myoepithelial cells, also seen by others as K18/K19+ cells (14–18).

We also assayed for epithelial E-cadherin expression in these tumors. In vivo Znf217 overexpression resulted in heterogeneous staining of E-cadherin with a large number of regions containing a marked reduction in E-cadherin expression, whereas control tumors had E-cadherin localized to the plasma membrane throughout the epithelium (Fig. 5A; Supplementary Fig. S3B). Together, these phenotypic changes seen within tumors are consistent with Znf217 promoting the acquisition of a mesenchymal/progenitor cell phenotype.

**Overexpression of Znf217 Promotes Metastasis**

Because metastasis in vivo often is accompanied by increased motility, invasion, and mesenchymal/basal phenotypes, we next asked whether ZNF217 promotes metastasis in vivo. In mice transplanted with either PyMT or Vo-PyMT cells, Znf217 overexpression significantly increased the percentage of mice with lung metastases, increased metastatic burden, and increased the number of spontaneous lung metastases per mouse (Fig. 5B–D; Supplementary Fig. S3C). In keeping with these results, high ZNF217 expression was prognostic of reduced metastasis-free survival in patients with breast cancer (Fig. 5E; ref. 19).

**ZNF217 Promotes Resistance to Chemotherapy**

Patients with tumors expressing stem cell–like/progenitor cell markers have increased resistance to chemotherapy (20). We determined whether ZNF217 was a prognostic predictor of treatment response by comparing clinical data with expression data from patients who received neoadjuvant chemotherapy. In one data set, patients received either doxorubicin or a combination of 5-fluorouracil and mitomycin (FUMI) before surgical removal and microarray gene expression analysis of the tissue (12). Tumors that responded to treatment (i.e., became smaller) expressed less ZNF217 than did nonresponsive tumors (Fig. 6A).

We also found that tumors with low ZNF217 expression responded better to treatment (pathologic complete response) than did tumors with high ZNF217 expression. In a second data set, fine needle aspirate samples were collected before treatment and used for gene expression (21). All patients received similar preoperative treatments (paclitaxel and fluorouracil-doxorubicin-cyclophosphamide). We found ZNF217 expression levels higher in nonresponsive tumors that did not respond to therapy than in tumors that responded (Fig. 6A). Therefore, ZNF217 is a prognostic predictor of patient outcome in response to chemotherapy.
**Figure 4.** Znf217 overexpression in vivo increases rate of tumor progression, tumor heterogeneity, and differentiation state. **A,** relative expression of Znf217 and EMT genes by qRT-PCR in the Vo-PyMT cell line overexpressing either vector or Znf217. The assay used the reference Gapdh. Similar results were seen using Hprt or Tbp references. The cells used in this experiment had previously been sorted for fluorescent marker expression and were used for the Vo-PyMT transplants throughout this study. **B,** mammosphere assay of primary MECs infected with vector or Znf217-overexpressing lentivirus. **C,** quantification of mammosphere formation in primary MECs expressing vector or Znf217 after 1 week. Graph shows mean ± SEM, and samples were compared by unpaired t test. **D,** tumor-free survival over time in Vo-PyMT transplants (P = 0.01; log-rank). **E,** tumor volume over time in Vo-PyMT transplants of Znf217 (n = 8) versus vector (n = 10; P = 0.007; ANOVA, repeated measures). **F,** final tumor weight in Vo-PyMT transplants (P = 0.02; Mann-Whitney). Line represents median of vector (n = 9) versus Znf217 (n = 8). **G,** H&E staining of MMTV-PyMT (PyMT MEC) tumors from transplants overexpressing vector (top) or Znf217 (middle, bottom). Insets are enlarged images of boxed regions and show heterogeneous pathology. **H,** immunofluorescence staining with anti-Keratin-8 (green), anti-α-SMA (red; arrows), and DNA (Hoechst; blue) in tumors derived from PyMT MEC transplants. **I,** immunofluorescence staining with anti-Keratin-8 (green), keratin-14 (red), and DNA (blue) from PyMT MEC transplants. Arrows mark cells double-positive for K8 and K14. **J,** quantification of a progenitor cell population: K8+K14+ (P = 0.002), percentage of K8+K14+ (P = 0.0002; unpaired t tests). Bar graphs show mean representation [n (%)] of K8+K14+ cells ± SEM per HPF. Gapdh, glyceraldehyde-3-phosphate dehydrogenase; HPF, 3 high-powered fields. Hprt, hypoxanthine phosphoribosyltransferase.
ZNF217 overexpression promotes malignancy

**Figure 5.** Znf217 overexpression in vivo increases lung metastasis. **A,** immunofluorescence with anti-E-cadherin (green) and DNA (blue) from Vo-PyMT transplants. Arrows mark regions with low E-cadherin expression. **B,** number of lung metastases per 3 (i) or 5 (ii) high-powered fields from (i) PyMT MEC (P = 0.008) or (ii) Vo-PyMT transplants (P = 0.01; Mann-Whitney) with vector or Znf217 overexpression. **C,** metastatic burden from PyMT and Vo-PyMT transplants. Number of lung metastases per 3 (PyMT) or 5 (Vo-PyMT) high-powered fields divided by tumor weight (i) PyMT MEC (P = 0.003; Mann-Whitney) or (ii) Vo-PyMT (P = 0.32; Mann-Whitney) transplants with vector or Znf217 overexpression. **D,** E-cadherin DNA expression by immunofluorescence with anti-E-cadherin (green) and DNA (blue) from Vo-PyMT transplants. Arrows mark examples of metastases. **E,** metastasis-free survival based on high (n = 41) versus low (n = 41) Znf217 expression (P = 0.01; log-rank) from the work of Minn and colleagues (19).

**ZNF217 Levels Are Related to Levels of Activated AKT, Mitogen-Activated Protein Kinase, and ERBB3**

ERBB3 is a direct target of ZNF217 (22). We found significant correlation between ZNF217 and ERBB3 expression levels in human breast tumors (Fig. 6B). To determine the mechanism underlying the effects of ZNF217, we analyzed several downstream signaling molecules downstream of ERBB3 in 2 human breast cancer cell lines (MCF7, ZR-75-1) that express high levels of ZNF217. Using both wild-type cells and cells after knockdown for ZNF217 expression by siRNA, as described previously (22), we treated serum-starved cells with the growth factor ligand for ERBB3, heregulin, and validated for reduced protein expression (Supplementary Fig. S4A-S4D). These data indicate that these pathways are downstream of ZNF217 and that ZNF217 sensitizes cells to heregulin.

**ZNF217 Is a Drug Target for Individualized Therapy**

Because ZNF217 is overexpressed in poor prognostic and chemoresistant patients with breast cancer, we sought to identify drugs that kill tumor cells overexpressing ZNF217. We first used a candidate approach to determine whether AKT pathway inhibitors promoted cell death in a ZNF217-dependent manner, because ZNF217 is required for and promotes AKT activation (Fig. 6C; ref. 23). MCF7 cells were infected with virus expressing short hairpin RNAs (shRNA) to ZNF217 and validated for reduced protein expression (Supplementary Fig. S4E and S4F). Assaying cell death of MCF7 cells infected with lentivirus expressing scrambled or ZNF217-shRNA, we observed that the phosphoinositide 3-kinase (PI3K) inhibitor GDC0941 and the AKT inhibitor MK2206 did not induce ZNF217-dependent cell death (Fig. 6D).

We next used an in silico screening approach to identify candidate therapeutics that inhibit growth of cancer cells expressing high ZNF217 at low drug concentrations. We determined ZNF217 expression by qRT-PCR in the NCI60 panel of cell lines. We then used a drug data set from a panel of approximately 50,000 drugs generated by the NCI Developmental Therapeutics Program (http://dtp.nci.nih.gov/). Correlation of ZNF217 expression in the cell line panel with the drug panel identified 15 drugs that selectively inhibited growth of cells expressing high levels of ZNF217, as assessed by GI₅₀, with a low drug concentration (Supplementary Table S5).

To determine whether ZNF217 contributes to the drug-induced growth inhibition, we assayed cell death of MCF7...
cells infected with lentivirus expressing stably integrated scrambled or ZNF217-shRNA knockdown constructs. As proof-of-concept, we tested bisacodyl, triciribine, nogalamycin, and 2E3E for their ability to influence cell death in culture in a ZNF217-dependent manner. Cells expressing reduced levels of ZNF217 (ZNF217-shRNA) required higher concentrations of bisacodyl or triciribine for cell killing (Fig. 6E and F). Three different ZNF217-shRNA constructs gave similar results (Fig. 6 and data not shown). Nogalamycin or 2E2E treatment did not promote ZNF217-dependent cell death at a therapeutically possible concentration range (data not shown).

We focused on triciribine (also known as API-2), which is a nucleoside analogue and DNA synthesis inhibitor that has been tested in phase I clinical trials in patients with cancer as well as in one phase II clinical trial in patients with metastatic breast cancer (24–27). Cancer cells expressing high levels of ZNF217 required lower concentrations of triciribine to inhibit growth than cells with low ZNF217 expression (Fig. 6G and H). We then assayed triciribine on a panel of breast cancer cell lines that we previously analyzed for gene expression (28). The GI₅₀ significantly correlated with ZNF217 expression levels ($r = -0.39$, $P = 0.035$; Spearman; Fig. 6I), consistent with a selective effect of triciribine on cell lines that express the highest ZNF217 levels.

**Triciribine Kills Cells In Vivo in Tumors That Overexpress ZNF217**

To test the effects of triciribine in vivo, we transplanted vector control and Znf217-overexpressing tumorigenic Vo-PyMT cells orthotopically to contralateral mammary fat pads cleared of epithelium. At 3 weeks, we injected mice with either triciribine or vehicle solution for 5 d/wk. Triciribine treatment significantly reduced to baseline levels the increase in tumor burden seen as a result of Znf217 overexpression and led to reduced phospho-AKT expression, reduced phospho-MAPK expression, and increased cell death in vivo (Fig. 7A–C; Supplementary Fig. S4G). In culture, triciribine inhibited only phospho-AKT and did not inhibit phospho-MAPK or ErbB3 activation after heregulin stimulation (Fig. 7D). The observed differences between signaling events inhibited by triciribine in culture versus in vivo suggest that cells within a tumor microenvironment respond differently to triciribine than do cells in culture.

Triciribine also was effective in vivo at inhibiting tumor growth in mice xenografted with the human tumorigenic cell line MCF7 compared with control-treated mice (Fig. 7E).

**Triciribine Overcomes ZNF217-Induced Doxorubicin Resistance**

Tumor cells overexpressing ZNF217 are resistant to doxorubicin-induced cell death (23). Several groups have found triciribine to be an effective, synergistic therapy in combination with other drugs (e.g., trastuzumab, farnesyltransferase inhibitors) to reduce tumor burden (29, 30). Similarly, we found that the addition of triciribine with doxorubicin to cells in culture generated a synthetic lethality in which cells overexpressing ZNF217 were no longer resistant to doxorubicin and instead were killed (Fig. 7F). Interestingly, the parent mammary epithelial cell line HBL100 expresses low levels of adenosine kinase, which is required for the phosphorylation and activation of triciribine in patients. This suggests that ZNF217 may be a sufficiently predictive biomarker of triciribine efficacy, even in patients with low adenosine kinase, if patients are also treated in combination with a drug such as doxorubicin.

**DISCUSSION**

**ZNF217 Is a Biomarker of Disease Progression and Treatment Response and Is a Therapeutic Target Inhibited by Triciribine**

In this study, we identified ZNF217 as a prognostic biomarker of reduced survival, metastasis, and chemoresistance in patients with breast cancer. Using both cultured cells and in vivo mouse transplant models, we found that ZNF217 overexpression contributes to multiple aspects of carcinogenesis including increased proliferation/decreased cell death, increased invasiveness, increased motility, immortalization, chemotherapy resistance, metastasis, and progenitor cell expansion. Our data show that ZNF217 promotes carcinogenesis by driving a differentiation gene expression signature toward a less differentiated/progenitor state indicative of expanding a multipotent progenitor population.

We identified a panel of drugs that inhibit the growth of cell lines that overexpress ZNF217 and validated two that induced ZNF217-dependent cell death.

**Triciribine: A Component of Therapy for Poor Prognostic Breast Cancer Patients**

Triciribine is a nucleoside analogue and DNA synthesis inhibitor that has been tested in phase I clinical trials in patients with cancer as well as in one phase II clinical trial in patients with metastatic breast cancer (24–27). In the phase II study, one of 14 patients had stable disease and the other patients progressed (27). The phase II studies and subsequent studies found that triciribine was not readily bioactive in all patients, possibly due to the requirement for expression of multiple genes for triciribine bioactivation. Triciribine is also an allosteric inhibitor of AKT activation: it physically interacts with AKT to prevent AKT recruitment to the plasma membrane and to block the phosphorylation and activation of AKT (31, 32).

Although several studies identified triciribine as an AKT inhibitor, triciribine is not always redundant with other AKT pathway inhibitors in treating tumors: often triciribine is more effective in vivo than other PI3K/AKT pathway inhibitors at inhibiting tumor progression (29). Indeed, we found that triciribine inhibited not only AKT activation but also MAPK activation in vivo (Fig. 7B and C). We hypothesize that triciribine inhibits both AKT and MAPK pathways, both of which are downstream of ERBB3/ERBB2 activation. This could provide a rationale for inhibition of ZNF217-induced tumor burden by triciribine because ZNF217 drives the overexpression of ERBB3 and leads to the activation of both AKT and MAPK pathways. Alternatively, triciribine could inhibit these pathways after activation of other receptor tyrosine kinases (Fig. 7G).
ZNF217 Overexpression Promotes Malignancy

Figure 6. Identification of triciribine as a candidate inhibitor of ZNF217-induced growth. A, response to neoadjuvant chemotherapy in patients with breast cancer with high versus low ZNF217 expression in tumors (i) from the work of Sorlie and colleagues (12). Patients had responsive (n = 27) or nonresponsive (stable/progressive) disease (n = 28) in response to treatment (P = 0.01; Mann-Whitney). Lines mark means. (ii) from Hess and colleagues (ref. 21; P < 0.001; Mann-Whitney). Tumors were responsive (pathologic complete response; n = 34) or nonresponsive (residual disease; n = 34) to treatment. Lines mark means. B, ZNF217 and ERBB3 expression levels in human breast tumors (n = 118) from Chin and colleagues (11). ZNF217 and ERBB3 strongly correlate (Pearson r = 0.47; P < 0.001; ANOVA). Similar results were obtained with a second shRNA and in at least 3 experiments. C, MCF7 cells (left) or ZR-75-1 cells (right) were transiently transfected with scrambled or ZNF217-siRNA. Forty-eight hours after transfection, cells were serum-starved 24 hours and treated for 15 minutes with heregulin. Lysates were blotted for the indicated proteins. D, PI3K and AKT inhibitors do not promote ZNF217-dependent cell death. Fluorescence-activated cell-sorting (FACS) analysis of cell death by Annexin V staining in MCF7 cells with ZNF217 shRNA or scramble control and treated for 2 days with control, 2 μmol/L GDC-0941, or 10 μmol/L MK2206. E, treatment of MCF7 cells ± ZNF217-shRNA with bisacodyl in triplicate at the indicated concentrations (P = 0.001; ANOVA). Similar results were obtained in at least 3 experiments. F, treatment of MCF7 cells ± ZNF217-shRNA with 10 μmol/L triciribine at the indicated concentrations (P = 0.001; ANOVA). Similar results were obtained with a second shRNA and in at least 3 experiments. ZNF217 (G) expression levels and related triciribine GI50 concentrations (H) in NCi60 panel breast cancer cell lines. Inset, chemical structure of triciribine. I, ZNF217 expression levels (Neve data set, ref. 28) across triciribine GI50s in 30 breast cancer cell lines (15 each of cell lines expressing highest/lowest ZNF217; r = −0.39; P = 0.035; Spearman correlation). Two outliers circled are identified by cell type and relevant mutations. DMSO, dimethyl sulfoxide.
Figure 7. Triciribine inhibits ZNF217 in vivo and in human cells. A, tumor burden growth rate of Vo-PyMT transplants treated with dimethyl sulfoxide (DMSO) solution (solid lines) or triciribine (dotted line; P < 0.0001 by genotype; \( P = 0.02 \), genotype over time; ANOVA). B, Vo-PyMT transplants overexpressed vector (blue) or Znf217 (orange). Shown are the mean ± SEM. C, triciribine can block these phenotypes of Znf217 overexpression. D, MCF7 cells ± triciribine were serum-starved overnight and stimulated with heregulin/neuregulin-1β for the indicated times. Graph shows mean ± SEM. E, other RTKs HER3/ERBB3, other factors.

Our study suggests that ZNF217 may be a sufficiently predictive biomarker of triciribine efficacy if patients are also treated in combination with a drug such as doxorubicin or another drug that offers synergy with triciribine. In part, ZNF217 may act by inducing upregulation of its target ERBB3 (22). Thus, cells resistant to triciribine treatment might independently activate multiple signaling pathways, making them less responsive to inhibitors that act upstream in the signaling pathway.

Combinatorial pathway activation may be therapeutically important in treating patients with high ZNF217 expression, as concurrent activation of the PI3K/AKT and RAS/MAPK pathways causes resistance to AKT inhibition in cells (33). Interestingly, in the panel of immortal cell lines expressing ZNF217 and tested for triciribine sensitivity, all outlier cell lines (i.e., lines with high GI50 and high ZNF217 expression) contained previously identified mutations in the PI3K/AKT and/or RAS/MAPK pathways (34–36). Because triciribine does not inhibit upstream activators PI3K or PDK1 or related family members directly (31), future studies will be required to sort out mechanistically how ZNF217...
ZNF217 Overexpression Promotes Malignancy

activates and triciribine inhibits signaling. Whether combination therapies will be more effective in vivo remains to be tested.

ZNF217 Reprograms Tumor Cells to Express Luminal and Myoepithelial Cell Markers

We found that ZNF217 promotes phenotypes suggestive of expansion of progenitor cells in vivo and in culture and drives reprogramming of an adult stem cell gene expression signature that is also downregulated in many epithelial cancers. Consistent with a progenitor phenotype, ZNF217 promotes increased telomerase, resistance to TGFβ growth inhibition, amplified c-MYC (9, 37), and chemotherapy resistance (23). That ZNF217 may drive a less differentiated gene expression signature is supported by the observation that Znf217 is upregulated in the somite following the transition from the presomitic mesoderm and before the differentiation into the skeleton, muscle, and dermis (38). Moreover, Zn217 is repressed concurrently with Oct4 following differentiation of a teratocarcinoma cell line to neuronal cells and binds to the promoters of a number of genes involved in differentiation (10). Thus, in tumors, ZNF217 may promote transdifferentiation to or expansion of a pool of progenitor-like cells by aberrantly suppressing differentiation pathways.

Znf217 overexpression in tumor cells derived from mice expressing the oncogene PyMT switched their phenotype from a predominantly luminal to a more heterogeneous pathology characterized by expression of both luminal and myoepithelial cell markers. This phenotype is similar to that seen following Wnt1 overexpression or activation of the AKT pathway by PTEN deletion in vivo (39, 40). Interestingly, the PyMT oncogene can give rise to tumors expressing both luminal and myoepithelial markers, depending on the cell type into which it is introduced. Expression of PyMT by intraductal injection of avian retrovirus (RCAS-PyMT) induces tumors with markers of luminal, myoepithelial, and progenitor cells (41). Recently, a connection has emerged between the un differentiated, stem-cell-like phenotype in breast cancer cells and transdifferentiation of the tumor cells toward a mesenchymal phenotype (reviewed in refs. 42–44). Induction of EMT in cultured MECs not only increases the population of cells with mesenchymal markers but also increases those with progenitor cell characteristics (CD44high/CD24low; ref. 45).

CONCLUSIONS

We used an integrated biologic approach to model the multiple contributions of ZNF217 to carcinogenesis during tumor progression, metastasis, and neoadjuvant treatment. We propose that ZNF217 is a biomarker that is prognostic of disease progression and is a therapeutic target. Our data suggest that triciribine may be a component of an effective treatment strategy in patients who have tumors expressing high ZNF217, possibly by targeting a progenitor population and reducing signaling in the AKT and MAPK pathways. Because ZNF217 is amplified in numerous cancers, this work has implications for other cancers as well.

METHODS

Additional descriptions of materials and methods, including cell lines, antibodies, and staining procedures used, are in the Supplementary Data.

Cell Lines

Cell lines used in this study include mouse MECs NMuMG (source: Rik Derynck), SCp2 (source: Mina Bissell), and Vo-PyMT-Luc (source: Conor Lynch) and human MEC lines MCF7, ZR-75-1, and HBL100 (source: American Type Culture Collection for all 3 lines). MCF7 was authenticated by SNP6.0 copy number analysis. Other cell lines were not authenticated.

Mouse Lines

Mice used in this study were maintained on the FVB/n background under pathogen-free conditions in the University of California, San Francisco (San Francisco, CA; UCSF) barrier facility. Our animal protocols were reviewed and approved by the UCSF Institutional Animal Care and Use Committee.

Metastasis Analysis

Both PyMT MEC and Vo-PyMT transplants were analyzed for lung metastasis. To determine metastasis frequency, lung tissue blocks were sectioned into 5-μm sections and stained by hematoxylin and eosin. For each mouse analyzed, one section was scored for number of metastases seen at ×100 magnification in 3 (PyMT MECs) or 5 (Vo-PyMT cell line) high-powered fields in regions of the tissue section with the highest density of metastases. Each cohort had 6 to 11 mice analyzed.

Statistical Analysis

Statistical analysis was conducted using Prism 4 software (GraphPad Software, Inc.) or SPSS Statistics software (IBM) for Cox proportional hazard tests. Cohorts of 3 or more samples were compared using one-way ANOVA. All tests used and P values specified are in the figure legends. P < 0.05 was considered significant.

Accession Numbers

Microarray data were deposited to the NCBI’s GEO Repository and are accessible to readers through GEO series accession number GSE24727.

Disclosure of Potential Conflicts of Interest

J.W. Gray has a Commercial Research Grant from GlaxoSmithKline, Pfizer and Susan G. Komen and is a consultant/advisory board member for New Leaf Ventures, Agenda, and KromaTiD. No potential conflicts of interests were disclosed by the other authors.

Authors’ Contributions

Conception and design: L.E. Littlepage, H. Kouroso-Mehr, D.A. Lawson, H.S. Rugo, Z. Werb


Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): L.E. Littlepage, A.S. Adler, J. Chou, S.R. Krig, J.E. Korkola, D.A. Lawson, Q. Xue, C.C. Collins, Z. Werb


Writing, review, and/or revision of the manuscript: L.E. Littlepage, H. Kouroso-Mehr, J. Chou, O.L. Griffith, J.E. Korkola, K. Qu,

Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): L.E. Littlepage, C.A. Sweeney, Z. Werb

Study supervision: L.E. Littlepage, Z. Werb

Made reagents available before they were published: G.J.P. Dijkgraaf

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