Taxol resistance in breast cancer cells is mediated by the Hippo pathway component TAZ and its downstream transcriptional targets Cyr61 and CTGF

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ABSTRACT

Taxol resistance represents a major challenge in breast cancer treatment. The TAZ oncogene is a major component of the novel Hippo-LATS signaling pathway and a transcriptional co-activator that interacts with and activates multiple transcription factors to regulate various biological processes. Here we report that elevated levels of TAZ found in human breast cancer cells is responsible for their resistance to Taxol. DNA microarray analysis identified the oncogenes Cyr61 and CTGF as downstream transcriptional targets of TAZ. shRNA-mediated knockdown of both Cyr61 and CTGF reversed TAZ-induced Taxol resistance in breast cancer cells. Interaction of TAZ with the TEAD family of transcription factors was essential for TAZ to activate the Cyr61/CTGF promoters and to induce Taxol resistance. Our findings define the TAZ-TEAD-Cyr61/CTGF signaling pathway as an important modifier of the Taxol response in breast cancer cells, also highlighting it as a novel therapeutic target to treat drug-resistant breast cancers that arise commonly at advanced stages of disease.
INTRODUCTION

Breast cancer is the most frequently diagnosed cancer and second leading cause of cancer-related deaths in women worldwide (1). However, due to the multi-factor and multi-stage nature of mammary tumorigenesis (2), the successful diagnosis and treatment of breast cancer remains a difficult task for oncologists. One of the major obstacles for successful breast cancer therapy is that, although mammary tumors can sometimes be suppressed by therapeutic drugs, they often recur and acquire resistance to therapy. Therefore, identification of proteins or biomarkers responsible for drug resistance is critical for planning and designing alternative breast cancer treatment strategies.

TAZ (Transcriptional co-activator with PDZ-binding motif) is a WW-domain-containing protein that functions as a co-activator of many transcription factors that are critical for the development of various tissues (3-7). Recently, TAZ was identified as a component of the emerging Hippo-LATS tumor suppressor pathway, which plays important roles in regulating cell proliferation and apoptosis in both Drosophila and mammals (8-10). The LATS tumor suppressor can phosphorylate and inhibit TAZ function in mammary cells (11). In addition, TAZ has been found to be over-expressed in about 70% of breast cancer cell lines and 20% of invasive breast cancer tissues (12). Over-expression of TAZ has been shown to cause enhanced cell proliferation and cell migration, transformation, and EMT in immortalized mammary epithelial cells (11, 12), suggesting that TAZ may function as an oncogene in breast cancer. In this study, we provided the first evidence that TAZ is also involved in drug resistance in breast cancer.
EXPERIMENTAL PROCEDURES

Plasmid construction and site-directed mutagenesis

The DNA of Cyr61 [nucleotide (nt.) position –163 to +57] and CTGF (nt. -250 to –1) promoters were amplified by PCR from genomic DNA extracted from MCF10A mammary cells (Table 1S) and subsequently cloned into pGL3-basic luciferase reporter vector (Promega). Site-directed mutagenesis was performed using the QuickChange Mutagenesis Kit (Stratagene) according to the manufacture’s protocol.

Cell culture, transfection, trypan blue exclusion assay for cell death

The general methods for cell culture and cell transfection are as described (13, 14). Human mammary epithelial cells (HMEC) and Hs574-Mg mammary epithelial cells were cultured in Mammary Epithelial Growth Media (MEGM, Clonetics). Trypan blue exclusion assay for Taxol-induced cell death was performed as described previously (15).

Antibodies, GST-pull down assay, co-immunoprecipitation (Co-IP) and western blot

Mouse monoclonal antibodies to FLAG and HA were M2 (Sigma) and 12C5 (Santa Cruz), respectively. Rabbit polyclonal antibody to TAZ and mouse monoclonal antibody to E-cadherin were purchased from Cell Signaling and Transduction Lab, respectively, whereas rabbit polyclonal antibody to Cyr61, mouse monoclonal antibody to Vimentin (V9), and goat polyclonal antibody to CTGF were purchased from Santa Cruz. Mammalian cell protein extraction, GST-pull down assay, Co-IP, and western blot are as described (13, 14).
**Lentiviral production, infection, and establishment of stable cell lines over-expressing or knocking down cellular genes**

Lentiviral production, titering, and infection are as described (14). Two MDA-MB231 cell lines stably expressing shRNAs [shTAZ1: 5’-GCGATGAATCAGCCTCTGAAT-3’ (sense); shTAZ2: 5’-GCCCTTTTCTAACCTGGCTGTA-3’ (sense), Open Biosystems] with the best TAZ knockdown were established and subsequently used for further experiments. Similar to TAZ knockdown, a set of pGIPZ lentiviral vector expressing shRNAs against different regions of Cyr61 or CTGF mRNAs (Open Biosystems) were also used for screening Cyr61 or CTGF knockdown in MCF10A-TAZ cells. MCF10A-TAZ cells expressing shRNAs with the best knockdown for Cyr61 [5’-GGCAGACCCTGTGAATATA-3’ (sense)] or CTGF [5’-CCCAGACCCAACTATGATT-3’ (sense)] or Cyr61/CTGF were expanded and used for further experiments.

**RNA isolation, microarray analysis, and qRT-PCR**

RNA extraction, microarray, and qRT-PCR analysis was performed as described (14). The RNAs were labeled, amplified and used for the following microarrays: Array#1: WPI/Cy3-CTP, TAZ-1/Cy5-CTP; Array#2: TAZ-1/Cy3-CTP, WPI/Cy5-CTP (flip color); Array#3: WPI/Cy3-CTP, TAZ-2/Cy5-CTP (biological replicate).

**Luciferase assay**

Triplicates of 5×10^4 SK-BR3 cells in a 12-well plate were transfected with Cyr61-luc or CTGF-luc or their mutants (0.1μg) alone or together with TAZ (0.2μg) or TAZ (0.2μg) plus TEAD (0.2μg) using Lipofectamine 2000 (Invitrogen). As an internal transfection control, 10 ng
of Renilla luciferase vector (pRL-TK) was also co-transfected in each sample. Luciferase activity was measured 2 days after transfection using the Dual-Luciferase Reporter Assay System (Promega) and Turner Biosystems 20/20 luminometer.

**Chromatin immunoprecipitation (ChIP) assay**

A ChIP-IT Express kit (Active Motif) was used for ChIP analysis of TAZ and Cyr61 promoter interaction. In brief, MCF10A cells expressing WPI vector or TAZ-HA were treated with 1% formaldehyde, lysed and homogenized using a Dounce homogenizer. DNA was sheared by sonication and the sheared chromatin was incubated with 2 µg of mouse IgG (Sigma) or anti-HA (F7) monoclonal antibody (Santa Cruz Biotechnology), followed by PCR using the primers used for amplification of the Cyr61 promoter. The PCR products were run on a 3% ethidium bromide-agarose gel and visualized under UV.
RESULTS

Levels of TAZ in mammary epithelial cells are negatively correlated with their sensitivity to Taxol

To explore the roles of TAZ in drug resistance of breast cancer cells, we first examined the level of TAZ in normal, immortalized, and tumorigenic mammary cells representing multistage tumorigenesis (Fig. 1A). While TAZ levels were low in both normal and immortalized mammary epithelial cells, they were significantly higher in most of the breast cancer cell lines examined (Fig. 1A). We subsequently examined the responses of two mammary cell lines MCF10A and MDA-MB231, representing low and high TAZ levels, respectively, to increasing concentrations of Taxol, a chemotherapeutic drug commonly used for the treatment of breast cancer and other cancers (16). Compared to TAZ-low MCF10A, TAZ-high MDA-MB231 were significantly resistant to apoptosis induced by Taxol (Fig. 1B), suggesting that the higher level of TAZ in mammary cells may be responsible for their resistance to Taxol. To confirm that over-expression of TAZ is directly responsible for Taxol resistance in mammary cancer cells, we carried out the following two experiments. First, we stably overexpressed TAZ in TAZ-low/drug sensitive MCF10A cells (Fig. 1A), using lentivirus expressing HA-tagged TAZ. Significantly, compared to MCF10A-WPI control, over-expression of TAZ in MCF10A (MCF10A-TAZ) causes significant resistance to apoptosis induced by Taxol (Fig. 1C). Second, we knocked down TAZ in TAZ-high/drug resistant MDA-MB231 using lentiviruses expressing shRNAs against different regions of TAZ mRNA (Fig. 1D). Significantly, knockdown of TAZ by both shTAZs in MDA-MB231 cells sensitizes their response to Taxol treatments (Fig. 1D). In summary, our findings strongly suggest that TAZ is a novel biomarker for the resistance of breast cancer cells to Taxol.
Identification of Cyr61 and CTGF as major downstream targets of TAZ

To understand the molecular mechanism underlying TAZ-induced drug resistance in mammary epithelial cells, we aimed to identify the downstream targets of TAZ. Since TAZ is a transcriptional co-activator (4), we used a whole human genome microarray to identify the transcriptional targets of TAZ. HA-tagged TAZ was stably expressed in TAZ-low MCF10A cells (Fig. 2A). Over-expression of TAZ in MCF10A causes EMT (Fig. 2B) with reduced levels of the epithelial marker E-cadherin and increased levels of the mesenchymal marker Vimentin (Fig. 2C). Gene expression profiles were subsequently compared between MCF10A-WPI and the two lines of MCF10A-TAZ (Fig. 2A) using 44K whole human genome microarray analysis. After statistical analysis, 389 cellular genes were transcriptionally activated after overexpression of TAZ (Table 2S). We further confirmed some of the transcriptional targets, which have been previously shown to play important roles in mammary tumorigenesis, by real time qRT-PCR using the RNAs extracted from MCF10A-WPI and MCF10A-TAZ. Significantly, 8 cellular genes identified have higher levels of mRNA after TAZ overexpression (Fig. 2D).

Next, we further characterized two of the most highly activated genes, Cyr61 and CTGF (Fig. 2D). Cyr61 and CTGF are two members of the connective tissue factor CCN (Cyr61, CTGF, Nov) family, which are secreted cysteine-rich extracellular matrix proteins that function as ligands of the integrins to regulate cell proliferation, apoptosis, cell migration/adhesion, and angiogenesis (17). Similar to TAZ, Cyr61 and CTGF have previously been identified as oncogenes that are activated in breast cancers and cause resistance to apoptosis induced by Taxol or hypoxia when over-expressed in mammary epithelial cells (18-28). Recently, CTGF has been identified as a transcriptional target of TAZ (29). However, the functional significance of its...
activation by TAZ is unknown. Moreover, Cyr61 has not been identified as a transcriptional target of TAZ. To confirm that both Cyr61 and CTGF are indeed *bona fide* downstream targets of TAZ, we carried out the following experiments. First, we used western blot analysis to show that both Cyr61 and CTGF protein levels were much higher in MCF10A-TAZ compared to those in MCF10A-WPI (Fig. 3A). Most interestingly, enhanced Cyr61 and CTGF protein were reduced back to their original levels when over-expressed TAZ in MCF10A-TAZ was knocked down by shTAZ (Fig. 3A). Second, we knocked down TAZ in TAZ-high MDA-MB231 cells to assess whether endogenous TAZ is essential for maintaining enhanced levels of Cyr61 and CTGF in these cells. Contrary to TAZ-over-expression, knockdown of TAZ by two shRNAs (shTAZ-1 and shTAZ-2) reduced the expression of both Cyr61 and CTGF in MDA-MB231 cells (Fig. 3B). Third, we found that TAZ significantly activated the luciferase activity of both Cyr61 and CTGF promoters (Cyr61-luc or CTGF-luc) 6.8- and 14.3-fold, respectively (Fig. 3C-D). Co-transfection of a constitutively active TAZ, TAZ-S89A (a mutant lacking LATS phosphorylation site), further enhanced Cyr61 and CTGF promoter activity to 9- and 20.7- fold, respectively, whereas co-transfection of TAZ-Δ227, a mutant lacking the transactivating domain, abolished activation of the Cyr61 and CTGF promoters (Fig. 3C-D), suggesting that the transactivating function of TAZ is essential for its activation of Cyr61 and CTGF. Finally, our ChIP assay showed that TAZ can be co-immunoprecipitated with the Cyr61 promoter DNA *in vivo* (Fig. 3E). Collectively, these studies strongly suggest that Cyr61 and CTGF are indeed *bona fide* transcriptional targets of TAZ.
**TAZ activates Cyr61 through interaction with TEADs**

Since TAZ is a transcriptional co-activator, it should activate downstream genes through interaction with transcription factors. Recently, the TEAD family of proteins including TEAD1, 2, 3, and 4 (TEADs) have been identified as the transcription factors mediating TAZ functions in cell growth, oncogenic transformation, and EMT (6, 29, 30). In addition, TEADs have also been shown to enhance TAZ-induced transcriptional activation of CTGF (29). To examine whether TEADs mediate TAZ-induced activation of Cyr61, we transfected Cyr61-luc alone, along with each of the TEADs, or with both TAZ/TEADs into SK-BR3 cells. While transfection of any member of the TEAD family alone has no effect on Cyr61 promoter activity (data not shown), co-transfection of TEAD with TAZ significantly enhanced TAZ-induced activation of the Cyr61 promoter. On the other hand, co-transfection of Runx2, another TAZ interacting transcription factor, has no effect (Fig. 4A), suggesting that TAZ may directly interact with the TEADs to activate the Cyr61 promoter.

Next, we further examined whether the interaction of TEAD with TAZ is essential for TAZ-induced transcriptional activation of the Cyr61 promoter. Since TEAD4 has been shown to be the most important TEAD in TAZ-induced tumorigenesis (29, 30), we chose to use TEAD4 in the following experiments. First, our co-immunoprecipitation assay clearly showed that, although TEAD4-FLAG interacts strongly with TAZ-HA in vivo, a single amino acid mutation in TEAD4, TEAD4-Y429H corresponding to TEAD1-Y421H (31), abolished binding to TAZ (Fig. 4B). In addition, the TEAD4-Y429H mutant also failed to enhance TAZ-induced activation of the Cyr61 promoter (Fig. 4C), suggesting that the interaction of TAZ with TEAD is critical for its effect on activation of Cyr61 transcription.
Identification of the TEAD Response Element (TRE) in the Cyr61 promoter

Previous studies have shown that TEAD activates CTGF through binding to three TREs in the CTGF promoter (32). Therefore, we wanted to determine whether TAZ activates the Cyr61 promoter through TEAD interaction with the TREs. We have also identified two putative TREs in the Cyr61 promoter region (Fig. 4D) and mutated the two TREs individually (TRE1M or TRE2M) or in combination (TRE1/2M)(Fig. 4E). Our luciferase assay showed that mutation of TRE1, rather than TRE2, completely abolished TAZ/TEAD-induced activation of the Cyr61 promoter (Fig. 4F), suggesting that TAZ/TEAD may bind TRE1 to activate Cyr61 transcription.

TAZ and TEAD interaction is essential for its effects on the Cyr61 and CTGF promoter and drug response in mammary cells

Although TEADs have been identified as the critical transcription factors mediating TAZ-induced transformation, it is still unknown whether TEADs are essential for TAZ-induced drug resistance in breast cancer cells. To answer this question, we performed the following experiments. First, our GST pull-down assay showed that, while equal amounts of fusion protein were used (Ponceau S staining for proteins), wild-type TAZ-GST rather than TAZΔ72-GST mutant (corresponding to TAZ paralog YAP mutant lacking interaction with TEADs (33)) was able to interact with TEAD4-FLAG in vitro (Fig. 5A). In addition, although over-expression of wild-type TAZ increased the levels of Cyr61 and CTGF mRNA and protein, over-expression of TAZΔ72 had no effects (Fig. 5B and 5E). Moreover, TAZΔ72 also failed to activate Cyr61 and CTGF promoter activity (Fig. 5C-D) and its overexpression in MCF10A failed to induce resistance to Taxol in these cells (Fig. 5F).
Knockdown of Cyr61 and CTGF reverses the drug resistant phenotypes caused by TAZ

Since enhanced levels of Cyr61 and CTGF have also been shown to cause drug resistance in breast cancers (17, 23, 25, 34), we wanted to confirm that Cyr61 and CTGF are the major downstream transcriptional targets mediating TAZ-induced Taxol resistance. We produced lentiviruses expressing shRNA against different regions of Cyr61 (shCyr61) or CTGF (shCTGF) mRNA, which were used for single (TAZ/shCyr61 or TAZ/shCTGF) or double knockdown (TAZ/shCyr61/shCTGF) in MCF10A-TAZ cells (Fig. 6A-B). As shown in Figure 6C, while knockdown of Cyr61 or CTGF alone partially, but significantly, sensitized MCF10A-TAZ cells to Taxol, knockdown of both Cyr61 and CTGF completely blocks TAZ-induced resistance to Taxol. Together, these results strongly suggest that Cyr61 and CTGF are two of the major downstream proteins mediating TAZ-induced Taxol resistance in breast cancer cells.
DISCUSSION

*TAZ as a novel gene inducing drug resistance*

Although tremendous progress has been made towards understanding the molecular mechanism underlying breast cancer development and treatment, the overall survival of breast cancer patients is still significantly hindered due to the evolution of drug resistant tumors. Therefore, the identification of proteins responsible for drug resistance is critical for successful breast cancer treatment. In this study, we have for the first time identified TAZ as a novel gene responsible for drug resistance in breast cancer. By over-expressing TAZ in TAZ-low/drug sensitive MCF10A mammary epithelial cells, we have shown that enhanced levels of TAZ can directly cause resistance of mammary epithelial cells to apoptosis induced by the chemotherapeutic drug Taxol. On the other hand, knockdown of endogenous TAZ in TAZ-high/drug resistant MDA-MB231 breast cancer cells sensitized these cells to Taxol. We are currently examining whether TAZ can be used as a biomarker in predicting chemotherapeutic drug response in breast cancer in clinical setting using tissue microarray samples obtained from breast cancer patients treated with chemotherapeutic drugs such as Taxol. If TAZ levels are indeed correlated with the drug-resistance of breast cancer, targeting TAZ in TAZ-over-expressed drug-resistant patients will be a novel therapeutic strategy for successful breast cancer treatment.

Recently, TAZ and its paralog YAP have been identified as two major proteins mediating the effects of the novel Hippo-LATS tumor suppressor pathway (10, 35). Consistent with our finding that TAZ is a novel protein responsible for drug resistance of breast cancer, some of the proteins in the Hippo-LATS pathway have also been shown to be involved in the drug resistance seen in human cancers. For example, we have recently reported that loss of LATS1 and LATS2
tumor suppressor genes, two negative regulators of TAZ (11), induced resistance of cervical cancer cells to Taxol (15). On the other hand, over-expression of YAP, a TAZ paralog, also caused resistance of breast cancer cells to multiple chemotherapeutic drug treatments (36). In addition, loss of Mst or RASSF1A, which are upstream activators of LATS, have also been shown to cause drug resistance in prostate cancer and hepatocellular carcinoma (37, 38). Altogether, these studies suggest that the emerging Hippo-LATS tumor suppressor pathway, which has been shown to play important roles in tumorigenesis, may also have significant roles in drug resistance of human cancers. Therefore, it will be very interesting to examine if and how TAZ and other components of the Hippo-LATS pathway interact to induce drug resistance in breast cancer.

Identification of Cyr61 and CTGF as transcriptional targets of TAZ

Although TAZ has been shown to be involved in regulating various biological functions, the downstream transcriptional targets mediating TAZ function remain largely unknown. By using a 44K whole genome microarray and real time qRT-PCR, we have identified and confirmed many important cellular genes as novel downstream transcriptional targets of TAZ. Most interestingly, many of these genes including BMP4, Cyr61, CTGF, FGF1, and PDGFβ are growth factors secreted from the cells to promote cell proliferation, cell migration/adhesion, and tumorigenesis of mammary epithelial cells (17, 27, 39-42). Other TAZ downstream genes identified such as IRS-1, MYLK/MLCK, and PLK2 are also important genes in tumor development and metastasis (43, 44). Therefore, it will be very interesting to examine whether these genes mediate TAZ-induced functions in mammary cells.
In this study, we have characterized and confirmed Cyr61 and CTGF as two major bona fide transcriptional targets of TAZ by the following experiments: First, we have shown that over-expression of TAZ in MCF10A mammary epithelial cells caused increased mRNA and protein levels of Cyr61 and CTGF. Second, we have also shown that knockdown of TAZ in these TAZ over-expressing MCF10A reduced the increased Cyr61 and CTGF protein back to normal levels, whereas reduction of endogenous TAZ by shTAZ in TAZ-high MDA-MB231 reduces Cyr61 and CTGF levels in these cells. Third, we have shown that TAZ activates Cyr61 and CTGF transcription by binding to and activating Cyr61 and CTGF promoters.

After confirming that Cyr61 and CTGF are indeed downstream transcriptional targets of TAZ, we then examined whether Cyr61 and CTGF mediate TAZ-induced drug resistance in human mammary epithelial cells. Significantly, we found that individual knockdown of Cyr61 or CTGF by shRNA partially but double Cyr61/CTGF knockdown completely reversed TAZ-induced Taxol resistance. These studies suggest that Cyr61 and CTGF are two critical TAZ transcriptional targets mediating TAZ-induced drug resistance in breast cancer cells. Together, our studies provided the first biological evidence that over-expression of the TAZ oncogene can cause drug resistance of breast cancer cells through direct activation of two secreted and matrix-associated proteins Cyr61 and CTGF.

Consistent with our findings, previous studies have also shown that Cyr61 and CTGF are indeed oncogenes that caused resistance of breast cancers to various chemotherapeutic drugs (17, 23, 25, 34). Further studies also showed that both Cyr61 and CTGF caused drug resistance by activating integrin αvβ3 (Fig. 7), which subsequently activates both MAPK/ERK and PI3K/Akt signaling pathways or by up-regulation of the anti-apoptotic proteins Bcl-XL and cIAP1/XIAP (23, 25, 34). We have also found that over-expression of TAZ activated both ERK and PI3K
pathways (Lai and Yang, unpublished results). Therefore, further characterization of how integrin and MAPK/PI3K pathways mediate TAZ-induced drug resistance will enhance our understanding of this signaling pathway in mediating TAZ-induced drug resistance in breast cancer cells.

**Identification of TEADs as transcription factors mediating TAZ-induced drug resistance**

In this study, we have identified the TEAD family of transcription factors as the critical mediators of TAZ-induced Cyr61 and CTGF transcriptional activation and drug resistance. The interaction between TAZ and TEAD is essential for its effect on Cyr61 and CTGF transcription and TAZ-induced drug resistant phenotypes. Although the roles of TEADs in breast cancer has not been reported, TEAD1 and TEAD2 have been shown to increase both cell proliferation and survival (45), whereas TEAD4 was found to be the major TEAD mediating TAZ-induced transformation (29, 30). However, it remains unknown whether TEADs are also directly involved in the response of breast cancer cells to chemotherapeutic drug treatments. Therefore, further characterization of TEADs in breast cancer development and drug response will be invaluable for our understanding of the roles of TAZ in mammary tumorigenesis and drug resistance.

In conclusion, we have provided convincing evidence that TAZ is a novel gene causing Taxol drug resistance through activation of Cyr61 and CTGF in breast cancer cells as illustrated in our proposed model (Fig. 7). Further confirmation of our findings using an *in vivo* mouse model and clinical breast cancer patient samples will greatly facilitate our efforts in the treatment of drug resistant breast cancers in the future.
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REFERENCES


FIGURE LEGENDS

Figure 1. Correlation of TAZ expression levels with response of breast cancer cells to chemotherapeutic drug treatments. (A) Western blot analysis of TAZ protein levels in normal [HMEC and Hs574-Mg], immortalized (MCF10A), and tumorigenic (BT20, MCF7, SK-BR3, Hs578T, MDA-MB231, MDA-MB436, and MDA-MB468) mammary cells. About 10 μg of cell lysate extracted from mammary cells using lysis buffer (50 mM Tris-HCl, pH7.4, 150 mM NaCl, 1 mM EDTA, 1.0% NP40, and 1 × protease inhibitor) were subjected to western blot using rabbit polyclonal anti-TAZ antibody (Cell signaling). β-actin was used as an internal protein loading control. (B) Trypan blue exclusion analysis of apoptosis induced by Taxol in MCF10A and MDA-MB231 cells. About 2.5×10^4 cells were seeded into each well of 24 well plate, followed by treatment with increasing amounts of Taxol (0, 0.1, 1, 2, 5, 10, 25, 50, 100 nM) for 72 hr. Since Taxol induces apoptotic cell death in breast cancer cells (16), the trypan blue exclusion assay is used for measuring apoptosis. Dead cells were stained with 0.2% trypan blue and the percentage of trypan blue positive (dead) cells was calculated. Taxol concentrations are shown in Log_{10} scale. The mean and standard error of three independent experiments for each cell line are shown. (C) Over-expression of TAZ caused Taxol resistance in MCF10A cells. Protein lysate extracted from MCF10A cells stably expressing WPI lentiviral vector or TAZ were subjected to western blot using anti-TAZ antibody (upper panel). Cell death assay (lower panel) was performed as described in (B). (D) Enhanced sensitivity of MDA-MB231 cells to Taxol after TAZ knockdown. shRNAs against different regions of TAZ mRNA (shTAZ-1 and shTAZ-2) were stably expressed in MDA-MB231 cells. Duplicate protein lysate extracted from MDA-MB231 cells stably expressing shTAZ were subjected to western blot using anti-TAZ antibody (upper panel). Protein lysate from MDA-MB231 cells stably expressing shGFP was used as a
Figure 2. Identification of transcriptional targets of TAZ by microarray. (A) Expression of TAZ in MCF10A cells. Duplicate MCF10A cells were individually infected with lentivirus expressing TAZ (TAZ-1 and TAZ-2). MCF10A infected with lentivirus expressing WPI vector control was used as a negative control. (B) Cell morphology. Cell morphology was examined using white light (left) or fluorescent light (right) at 10× magnification. GFP expressed from the lentiviral vector was used as a marker for infection efficiency. (C) Western blot analysis of EMT markers. (D) qRT-PCR analysis of cellular genes up-regulated by TAZ. The fold increase at the mRNA level in MCF10A-TAZ cells relative to those in MCF10A-WPI (control) cells are presented here. The mean and standard deviation (SD) were calculated from Ct values of triplicate real-time RT-PCR reactions for each RNA sample.

Figure 3. Activation of Cyr61 and CTGF by TAZ. (A) Expression of Cyr61 and CTGF after TAZ-over-expression and knockdown. Protein lysate extracted from MCF10A cells expressing WPI vector, TAZ, or TAZ together with shTAZ (TAZ/shTAZ) were subjected to western blot analysis (see legend of Fig. 1A for details). (B) Reduced expression of Cyr61 and CTGF in MDA-MB231 cells after TAZ knockdown. MDA-MB231 cells were stably infected with lentivirus expressing shGFP, shTAZ-1, or shTAZ-2. Protein lysate extracted from these cell lines were subjected to western blot. (C and D) Activation of Cyr61 and CTGF promoters by TAZ. SK-BR3 cells were transfected with luciferase reporter plasmid expressing Cyr61 (C) or CTGF (D) promoters (Cyr61-luc or CTGF-luc) together with plasmids expressing vector, TAZ, TAZ-
S89A (constitutively active TAZ), or TAZ-Δ227 (TAZ lacking transactivating domain).

Luciferase assays were carried out using a Dual Luciferase Assay Kit. The fold changes in luciferase activity were calculated by normalizing SK-BR3 cells transfected with Cyr61-luc or CTGF-luc together with TAZ, TAZ-S89A, or TAZ-Δ227 to those transfected with Cyr61-luc or CTGF-luc alone. (E) ChIP analysis of TAZ interaction with the Cyr61 promoter in vivo. DNA and protein were cross-linked by treatment of MCF10A-WPI or MCF10A-TAZ-HA cells with 1% formaldehyde. After purification of chromatin and DNA-binding proteins by homogenization, sonication and centrifugation, they were subjected to immunoprecipitation using rabbit IgG (negative control) or rabbit polyclonal anti-HA (F7) antibody, followed by PCR and agarose-electrophoresis. About 0.2% input chromatin (1 μl) extracted from MCF10A-WPI or MCF10A-TAZ cells were used as positive PCR controls.

**Figure 4. TAZ activates Cyr61 through interaction with TEADs.** (A) Luciferase assay. Procedures for measurement and calculation are as described in Fig. 3C-D. (B) Co-IP analysis of interaction of TAZ and TEAD4 in vivo. Cos-7 cells were mock transfected or transfected with TAZ-HA alone or together with TEAD4-FLAG (wild-type) or TEAD4-Y429H-FLAG. About 500 μg of protein lysate extracted from transfected cells were precipitated using mouse anti-FLAG (M2) monoclonal antibody. The precipitated proteins were subjected to western blot using rabbit anti-HA (A14) polyclonal antibody (1st) and HRP-conjugated light-chain specific anti-rabbit IgG (2nd). Expression of TAZ-HA and TEAD4-FLAG/TEAD4-Y429H-FLAG were detected by western blot using cell lysate from transfected cells, and anti-HA and anti-FLAG antibodies, respectively. (C) Luciferase assays. Procedures and labels are as described in (A). (D) Sequence of the Cyr61 promoter. Two TEAD-response elements (TRE1 and TRE2) were
identified (bold/underlined). (E) Constructs used for luciferase assay in (F). The structures of Cyr61-luc with wild-type (WT) or mutated (TRE1M, TRE2M, TRE1/2M) TRES are shown. Mutated nucleotides in TRE1 or TRE2 are bolded and underlined. (F) The constructs shown in (E) were transfected together with TAZ/TEAD into SK-BR3 cells. Luciferase assays were carried out as described in Fig. 3C-D.

Figure 5. Interaction of TAZ with TEAD is essential for its activation of Cyr61/CTGF and induction of Taxol resistance. (A) GST pulldown analysis of the functional domain of TAZ interacting with TEAD. About 10 μg of GST (control), TAZ-GST or TAZΔ72-GST (lacking TEAD-interacting domain) fusion proteins were incubated with 100 μg of cell lysate extracted from cells expressing TEAD4-FLAG, washed with lysis buffer, and subjected to western blot along with 1/10 of the amount of cell lysate used for GST pull-down assays (1/10 input) using mouse anti-FLAG monoclonal antibody. The membrane was stained with 1% Ponceau S to visualize the GST fusion proteins used in the GST-pull-down assays. (B) Loss of TAZ and TEAD interaction abolishes activation of Cyr61 and CTGF transcription. qRT-PCR analysis of Cyr61 and CTGF mRNA levels were performed using mRNAs extracted from MCF10A cells expressing WPI (vector), wild-type TAZ, or TAZΔ72. (C and D) Loss of activation of Cyr61 (C) and CTGF (D) promoters by TAZΔ72. Luciferase assays were carried out as described in Fig. 3C-D. (E) Loss of Cyr61 and CTGF protein expression by TAZΔ72. (F) Loss of resistance to Taxol in MCF10A-TAZΔ72 cells. Conditions and procedures for the experiment are as described in Fig. 1B.
Figure 6. Knockdown of Cyr61 and CTGF reverses TAZ-induced drug resistant phenotype. (A, B) Western blot analysis of Cyr61 (A) or CTGF (B) expression after shRNA knockdown of Cyr61 (TAZ/shCyr61), CTGF (TAZ/shCTGF) or both (TAZ/shCyr61/shCTGF) in MCF10A-TAZ cells. (C) Cell death analysis after treatment of cells with increasing concentration of Taxol. Conditions and procedures are as described in Fig. 1B.

Figure 7. A proposed model for TAZ-induced drug resistance in breast cancer cells. In this model, TAZ and TEAD forms a complex, which translocates to the nucleus and binds to the TEAD-response element (TRE) on the promoter regions of Cyr61 or CTGF that leads to their transcriptional activation. After proteolytic processing, Cyr61 and CTGF are subsequently secreted out of the cells and activate integrin heterodimers on the cell membrane, consequently resulting in enhanced cell survival and resistance to chemotherapeutic drug-induced apoptosis.
Figure 4

A

B

TEAD4-Y429H-FLAG
TEAD4-FLAG
TAZ-HA

IP: α-FLAG
IB: α-HA

α-HA
α-FLAG

TAZ-HA
IgG light chain

Cell lysate

C

D

-165 TGGAGCCAGGGAGGCCTTGAGCAAGCCCGGCAGCCACCGA
   AAGCATTCTTGA
   TRE1

-111 TGTTTGAGAATTCTGAGACGAGACGGGACGTCACTGCAACACG
   GGG
   TRE2

-58 CGCCTCCGGCAGCCGCTGCTGAGGGGCCTGGGCTGACG
   GAC
   TATA box

-4 GAGC (transcription initiation)

E

F

-163 TRE1 TRE2

Cyr61-TRE-WT -163

Cyr61-TRE1M -163

Cyr61-TRE2M -163

Cyr61-TRE1/2M -163

TRE1-WT: AAGCATT
TRE1M: AAAAAT

TRE2-WT: AAGCATT
TRE2M: AAAAAT

Cyr61-luc TRE-WT
Cyr61-luc TRE1M
Cyr61-luc TRE2M
Cyr61-luc TRE1/2M

Fold change

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Figure 7
Taxol resistance in breast cancer cells is mediated by the Hippo pathway component TAZ and its downstream transcriptional targets Cyr61 and CTGF

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