DACH1 suppresses breast cancer as a negative regulator of CD44.

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Recommended Citation  
Xu, Hanxiao; Yu, Shengnan; Yuan, Xun; Xiong, Jing; Kuang, Dong; Pestell, Richard; and Wu, Kongming, "DACH1 suppresses breast cancer as a negative regulator of CD44." (2017).  
Department of Cancer Biology Faculty Papers.  
Paper 116.  
https://jdc.jefferson.edu/cbfp/116

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DACH1 suppresses breast cancer as a negative regulator of CD44

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Dachshund homolog 1 (DACH1), a key cell fate determination factor, contributes to tumorigenesis, invasion, metastasis of human breast neoplasm. However, the exact molecular mechanisms for the anti-tumor roles of DACH1 in breast carcinoma are still lack of extensive understanding. Herein, we utilized immunohistochemistry (IHC) staining and public microarray data analysis showing that DACH1 was higher in normal breast, low-grade and luminal-type cancer in comparison with breast carcinoma, high-grade and basal-like tumors respectively. Additionally, both correlation analysis of public databases of human breast carcinoma and IHC analysis of mice xenograft tumors demonstrated that DACH1 inversely related to cancer stem cells (CSCs) markers, epithelial-mesenchymal transition (EMT) inducers and basal-enriched molecules, while cluster of differentiation 44 (CD44) behaved in an opposite manner. Furthermore, mice transplanted tumor model indicated that breast cancer cells Met-1 with up-regulation of DACH1 were endowed with remarkably reduced potential of tumorigenesis. Importantly, meta-analysis of 19 Gene Expression Omnibus (GEO) databases of breast cancer implicated that patients with higher DACH1 expression had prolonged time to death, recurrence and metastasis, while CD44 was a promising biomarker predicting worse overall survival (OS) and metastasis-free survival (MFS). Collectively, our study indicated that CD44 might be a novel target of DACH1 in breast carcinoma.

In spite of significant achievement made in early diagnosis and therapeutic strategies, breast cancer still draws great attention from the worldwide because of its high incidence rate and mortality1–3. The unsatisfactory clinical outcome is mostly due to tumor recurrence, metastasis and therapy-resistance1. Identifying novel biomarkers related to molecular subtypes, aggressive phenotypes and prognosis of breast cancer is essential for drug development, disease surveillance and precise therapy.

The retinal determination gene network (RDGN), including DACH1, EYA1 and SIX1, plays crucial roles in the development of multiple organs1. SIX1 and EYA1, two important RDGN members, exert favorable effects on tumor initiation and progression5–7, and high expression of SIX1 and EYA1 is an adverse factor for clinical outcomes for breast cancer patients8–9. On the contrary, another key RDGN member DACH1 behaved as a tumor suppressor and reduced expression of DACH1 predicts poor survival performance of breast cancer patients9. Several lines of evidence have demonstrated that the hypermethylation of promoter region leads to the down-regulation of DACH1, which is closely associated with proliferation, invasion and metastasis of various tumors, including breast cancer10–13, lung cancer14, esophageal cancer15, renal cell carcinoma16 and hepatocellular carcinoma17. DACH1 antagonizes the transcription and translation of oncogenes and induces epithelial-mesenchymal transition (EMT) in breast cancer, resulting in the inhibition of tumor growth, invasion and migration6,10. Recent studies prove that cancer stem cells (CSCs) possess potent self-renewal ability and are responsible for tumor relapse and metastasis and endogenous DACH1 participates in the negative regulation of CSCs18,19.

Cluster of differentiation-44 (CD44), a ubiquitously present glycoprotein on the membrane of mammalian cells, plays essential roles in a variety of biological function such as cell division, adhesion and migration20. During the past decades, the role of CD44 in cancer development has been revealed and valued. As a well-known marker of CSCs, CD44 promotes carcinogenesis, invasion, metastasis and therapy-resistance21–23. It promotes proliferation and suppresses apoptosis by regulation of relative pathways, including Ras-Raf-Mek-Erk-Cyclin D1
pathway and phosphoinositide 3-kinase (PI3K)-Akt signaling, as well as stimulates EMT, which contributes to tumor invasion and metastasis

Previous study has demonstrated that endogenous reduction of DACH1 was accompanied by down-regulation of CSC markers, such as SOX2, Nanog, KLF4. To further evaluate the correlation between DACH1 and CSC markers and EMT inducers in breast cancer, we performed a comprehensive analysis of immunohistochemistry (IHC) staining, publicly available microarray data, RNA profiling and western blot. Our study indicated that DACH1 was inversely correlated with CD44 and CD44 might be a novel target of DACH1 in breast cancer.

Results
DACH1 and CD44 associated with tumorigenesis and histological grade of breast cancer. In order to evaluate the expression of DACH1 and CD44 in normal breast and breast malignant tissues, we carried out IHC analysis on two TMAs (BR1502–97 and BR1502–98) with normal breast and human breast cancer tissues. DACH1 was majorly found in nucleus and CD44 was mostly detected on the membrane of breast cancer cells. Representative images of IHC staining for noncancerous and cancerous tissues were shown in Fig. 1a, showing that DACH1 decreased and CD44 increased in breast neoplasm tissues in comparison with normal breast.

Additionally, we also explored the correlation between the protein abundance of DACH1 and CD44 and histological grade. Representative images of IHC staining for low-grade and high-grade breast cancer tissues were showed in Fig. 1b, which indicating that DACH1 was inversely correlated with tumor grade, while CD44 was positively associated with histological grade.

Expression of DACH1 and CD44 correlated with molecular subtypes of breast cancer. We also carried out IHC staining to assess the protein abundance of DACH1 and CD44 in luminal-type and basal-like
breast cancer tissues. Representative images for the expression of DACH1 and CD44 in luminal and basal-like breast cancer tissues were shown in Fig. 2a. Furthermore, expression analysis of GSE20711 including a total of 45 luminal and 22 basal-like breast tumor cases was also interrogated to evaluate the mRNA levels of DACH1 and CD44 in luminal and basal-like breast neoplasm tissues, which showed that DACH1 was enriched in luminal breast carcinoma in comparison with basal-like breast cancer (P < 0.001) (Fig. 2b), while CD44 exhibited an opposite tendency (P < 0.001) (Fig. 2c) at mRNA level. Altogether, our results indicated that luminal breast carcinoma was most likely to be DACH1 high/CD44 low type, and basal-like breast tumor tissues were majorly DACH1 low/CD44 high type.

DACH1 down-regulated some CSC and EMT markers in vitro, as well as blocked Met-1 tumor growth in vivo. Breast cancer Met-1 cells were transduced with a DACH1 expression vector resulting in an ∼4.5-fold increase in DACH1 expression (Fig. 3a) and subsequent reduction of CSC markers CD44, KLF4 and MYC as well as EMT markers including FN1 and VIM (Fig. 3b) by mRNA analysis. Western blot also demonstrated the presence of the DACH1-tagged FLAG epitome, and the effects of DACH1 overexpression on the protein abundance of CD44, Fibronectin, Vimentin, p21 and p27, which were showed in Fig. 3c. Ectopic expression of DACH1 contributed to remarkable reduction of CD44, Fibronectin, Vimentin and significant up-regulation of p21 and p27 in Met-1 cells. Mammary tumor growth in vivo was assessed by subcutaneous implantation of Met-1 cells in nude mice (Fig. 3f). Met-1 cells with engineered expression of DACH1 were endowed with remarkably reduced potential of tumorigenesis in xenograft tumors. Up-regulation of DACH1 significantly reduced the volume of tumors by ∼90% and slowed down tumor growth (Fig. 3d). Tumor weight was also reduced by ∼90% in comparison with the control tumors (Fig. 3e). The results implicated that DACH1 suppressed the expression of some CSCs and EMT markers and serves as a potent anti-tumor factor in xenograft tumors.
DACH1 reduced the expression of CD44, Fibronectin, Vimentin, Myc, Sox2, EGFR, Ki-67 in vivo. Immunohistochemistry analysis was conducted to assess the protein abundance of DACH1, CD44, Myc, Sox2, Fibronectin, Vimentin, EGFR, and Ki-67 in nude mice xenograft tumor tissues with overexpression of DACH1 and the GFP controls. Additionally, we also employed IHC scoring to quantize the levels of these proteins in both DACH-overexpressing and the control tumors by using semi-quantitative criteria. About six 200 magnification images of each kind of protein were selected for IHC scoring by two experienced pathologists independently. Representative images of IHC staining and scoring results for DACH1, CD44, Myc, Sox2, Fibronectin, Vimentin, EGFR and Ki-67 were shown in Fig. 4a,b,c,d,e,f,g and h, respectively. Our results displayed that over-expression of DACH1 (P < 0.001) remarkably reduced the expression of CD44 (P < 0.001), Myc (P < 0.001), Sox2 (P < 0.001), Fibronectin (P < 0.001), Vimentin (P < 0.001), EGFR (P < 0.001) and Ki-67 (P < 0.001), demonstrating that DACH1 could potently down-regulated the expression of some CSCs and EMT markers, basal-like factor EGFR and proliferative biomarker Ki-67 in vivo at protein level.
Correlation between the expression of DACH1 and CD44 and the levels of FN1, VIM, YBX1, FOXA1, EGFR and MKI67. Previous study has implicated that DACH1 enriched in luminal A breast cancer and its expression fluctuated in direct proportion to the level of luminal-like marker FOXA1. Previously experimental study demonstrated that DACH1 participated in the inhibition of Snail-induced EMT through suppressing the activity of the Y box-binding protein (YB-1). Herein, public dataset GSE20685 was interrogated to assess the association between DACH1 and CD44, FN1, VIM, FOXA1, EGFR and MKI67, as well as evaluate the correlation between CD44 and the above genes. The results showed that DACH1 mRNA expression was inversely correlated with CD44 (R = −0.341, P < 0.001) (Fig. 5a), FN1 (R = −0.214, P < 0.001) (Fig. 5b), VIM (R = −0.229, P < 0.001) (Fig. 5c), EGFR (R = −0.390, P < 0.001) (Fig. 5e) and MKI67 (R = −0.376, P < 0.001) (Fig. 5f), but...
positively associated with the mRNA expression of FOXA1 ($R = 0.608$, $P < 0.001$) (Fig. 5d). Conversely, CD44 was found to be positively correlated with FN1 ($R = 0.253$, $P < 0.001$) (Fig. 5g), VIM ($R = 0.237$, $P < 0.001$) (Fig. 5h), YBX1 ($R = 0.446$, $P < 0.001$) (Fig. 5i), EGFR ($R = 0.336$, $P < 0.001$) (Fig. 5k) and MKI67 ($R = 0.215$, $P < 0.001$) (Fig. 5l), while there was a significantly negative association between CD44 and FOXA1 ($R = -0.402$, $P < 0.001$) (Fig. 5j).

Breast cancer cell line data reported by Neve RM, including a total of 51 different breast cancer lines from luminal-type ($N = 25$) or basal-like ($N = 26$), were also employed to evaluate the correlation between the expression of DACH1 and CD44 and the levels of FN1, VIM, YBX1, FOXA1, EGFR and MKI67. The results displayed

**Figure 5.** The expression of DACH1 and CD44 correlated with VIM, FN1, YBX1, FOXA1, EGFR and MKI67 in breast cancer tissues. Correlation analysis of public dataset GSE 20685 showed that DACH1 was inversely correlated with cancer stem cell marker CD44 (a), mesenchymal markers FN1 (b) and VIM (c) as well as basal-like markers EGFR (e) and MKI67 (f), while positively associated with luminal marker FOXA1 (d). CD44 was parallel with FN1 (g) and VIM (h), YBX1 (i), EGFR (k) and MKI67 (l), while negatively associated with FOXA1 (j).
that DACH1 mRNA expression was inversely correlated with CD44 \( (R = -0.507, P < 0.001) \) (Fig. 6a), FN1 \( (R = -0.354, P = 0.011) \) (Fig. 6b), VIM \( (R = -0.419, P < 0.001) \) (Fig. 6c), EGFR \( (R = -0.523, P < 0.001) \) (Fig. 6e) and MKI67 \( (R = -0.391, P = 0.005) \) (Fig. 6l) but negatively associated with FOXA1 \( (R = 0.689, P < 0.001) \) (Fig. 6j), supporting the conclusion from the correlation analysis of human breast tumor samples (GSE20685).
Importantly, DACH1, as an important member of RDGN, is widely expressed in epithelial cells and plays critical roles in carcinogenesis of various tumor types, including human breast cancer. Previous studies have implicated that overexpression of DACH1 reduced the levels of CSC and EMT markers in breast cancer cell line and potently inhibited the ability of tumorgenesis in xenograft model. Besides, correlation analysis exhibited that DACH1 negatively regulated cellular proliferation and tumor growth by repressing cell cycle protein cyclin D1 expression types of DACH1 and CD44 were opposite in breast cancer.

### Discussion

DACH1, as an important member of RDGN, is widely expressed in epithelial cells and plays critical roles in normal organ development and tumor growth by repressing cell cycle protein cyclin D1 in both breast cancer and renal clear cell cancer. Restoration of DACH1 suppressed clone formation of renal clear cell cancer cells in vitro as well as tumor growth in vivo through the inhibition of cyclin D1 transcription via associating with AP-1 protein. Furthermore, hypermethylation of DACH1 promoter region itself led to carcinogenesis and it also exerted inhibitory effects on tumor initiation through activating transforming growth factor-beta (TGF-beta) signaling. Besides, DACH1 inhibited cellular growth in an NAD and p53-dependent manner by direct protein-protein association in breast cancer. On the contrary, CD44, a family of transmembrane glycoproteins, exerted promoting roles in tumorigenesis of various cancer types. Up-regulation of the cleaved intracellular domain of CD44 (CD44ICD) enriched the mammosphere formation, while the blockage of CD44ICD reversed the effects. Immunohistochemistry analysis on human breast cancer tissues and expression analysis of GSE42568 indicated that CD44 remarkably increased in breast carcinoma in comparison with normal breast tissues. CD44 functions in carcinogenesis through binding to extracellular matrix components and messenger molecules in tumor environment.

### Table 1. Characteristics of the included public microarray datasets in the meta-analysis.

| First Author | GSE accession | Year | Duration (Months) | Patient Number | Detection | Platform |
|--------------|---------------|------|-------------------|----------------|-----------|----------|
| Desmedt C^26 | GSE7390       | 2007 | 143.2             | 198            | Microarray | GPL96    |
| Pawitan Y^27 | GSE1456       | 2005 | 102               | 159            | Microarray | GPL96    |
| Hennesey BT^28 | GSE10885 | 2009 | 106               | 89             | Microarray | GPL887   |
| Diederwaarder S^29 | GSE20711 | 2011 | 169               | 88             | Microarray | GPL570   |
| Kao KJ^30    | GSE20865      | 2011 | 156               | 327            | Microarray | GPL570   |
| Clarke C^31  | GSE42568      | 2013 | 100.9             | 104            | Microarray | GPL570   |
| Desmedt C^32 | GSE16446      | 2011 | 60                | 120            | Microarray | GPL570   |
| Loi S^33     | GSE6532       | 2010 | 176.8             | 327            | Microarray | GPL96    |
| Bili AH^34   | GSE3143       | 2006 | 156               | 158            | Microarray | GPL8300   |
| Terunuma A^35 | GSE9004     | 2014 | 120               | 61             | Microarray | GPL6244 |
| Heikinnen T^36 | GSE24450   | 2011 | 120               | 183            | Microarray | GPL6947 |
| Hatzi C^37   | GSE25066      | 2011 | 120               | 508            | Microarray | GPL96    |
| Symmans WF^38 | GSE17705   | 2010 | 196               | 298            | Microarray | GPL96    |
| Wang Y^39    | GSE2034       | 2005 | 180               | 286            | Microarray | GPL96    |
| Tofigh A^40  | GSE58644      | 2014 | 145               | 321            | Microarray | GPL6244 |
| Minn AF^41   | GSE2603       | 2005 | 130               | 99             | Microarray | GPL96    |
| Minn AF^42   | GSE5327       | 2007 | 156               | 58             | Microarray | GPL96    |
| Sircoulomb F^43 | GSE17907   | 2010 | 112               | 51             | Microarray | GPL570   |
| Nagalla S^44 | GSE45255      | 2013 | 127.4             | 139            | Microarray | GPL96    |

**The opposite roles of DACH1 and CD44 in clinical outcomes of breast cancer patients.** In order to assess the prognostic value of DACH1 and CD44 in breast cancer, a meta-analysis enrolling a total of 19 published Gene Expression Omnibus (GEO) databases and including 3574 breast cancer patients was performed. The characteristics of these 19 GEO databases were displayed in Table 1. The results indicated that patients with higher mRNA expression of DACH1 tended to enjoy longer time to death (HR: 0.72 (0.57–0.92), I² = 22.9%, P = 0.323) (Fig. 7a), relapse (HR: 0.73 (0.56–0.97), I² = 64.1%, P = 0.003) (Fig. 7c) and metastasis (HR: 0.73 (0.56–0.95), I² = 27.2%, P = 0.202) (Fig. 7e). On the contrary, higher mRNA expression of CD44 was directly related to worse OS (HR: 1.27 (1.03–1.57), I² = 48.4%, P = 0.012) (Fig. 7b) and MFS (HR: 1.40 (1.02–1.93), I² = 48.4%, P = 0.050) (Fig. 7f), but did not insignificantly contribute to worse RFS (HR: 1.19 (0.94–1.51), I² = 45.7%, P = 0.056) (Fig. 7d). Our results demonstrated that DACH1 was a promising biomarker predictive of better clinical outcomes, while CD44 was an adverse factor for the survival performance of breast cancer patients.
Several lines of evidence indicated that DACH1 expression correlated with tumor differentiation. Immunohistochemistry analysis of clear cell renal cancer tissues displayed that DACH1 was inversely correlated with tumor grade. About 60% of cells in low-grade tumors expressed DACH1, and less than 20% cells in grade III tumors expressed DACH1. Similar phenomenon was also found in breast cancer. DACH1 was remarkably enriched in low-grade breast tumors. In contrast, CD44 positively correlated with breast tumor grade. Our previous study displayed a positive association between CD44 expression and breast tumor grade at both mRNA and protein levels. This paper further supported this opposite tendency of DACH1 and CD44 in low-grade and high-grade breast carcinoma, respectively.

Majorly according to the status of ER, PR and Her2, breast cancer is grouped into four distinct subtypes including luminal, Her2-positive, basal-type and normal-like. Among these, luminal tumor patients accounted for the most part of breast carcinoma population and have relatively good clinical outcomes, while patients...
with basal-like tumor endowed with malignancy features have significantly poor prognosis. Previous study has demonstrated that nuclear DACH1 is a biomarker of luminal breast cancer. Breast tumors with positive ER-alpha and co-expressing PR-alpha were most likely to highly express DACH1, and nuclear DACH1 expression was positively correlated with luminal marker FOXA1 and inversely associated with basal-like markers EGFR. In contrast, our previous meta-analysis showed that CD44 mRNA was remarkably enriched in basal-like breast cancer compared with luminal-type breast tumor. CD44 was also positively correlated with basal markers EGF, KRT5 and KRT17, and inversely associated with luminal marker FOXA1. Our results supported that luminal breast neoplasm tended to be with high DACH1 expression and low CD44 level, while basal-like tumors were most likely to be the inverse type. The correlation analysis further indicated that DACH1 was significantly inversely associated with CD44.

CSCs were composed of a subset of tumor cells with the expression of stem cell-associated markers and enhanced capacity for tumorigenesis, metastasis and therapy-resistance. It has been implicated that endogenous DACH1 participated in the negative regulation of CSCs. DACH1 suppressed the expression of stem cell markers SOX2, Nanog and KLF4 through binding to the promoters of these genes. On the contrary, CD44, as a well-known CSCs marker, positively monitored the levels of CSCs markers. Nuclear location of cleaved CD44 intracellular domain transcriptionally activated stemness factors Nanog, Sox2 and Oct4.

EMT is a complex and highly conserved process which enhances cellular invasiveness, being critical for metastasis of various solid tumors and considered to be promising therapeutic targets. EMT was dysregulated by a complex network during tumor development. Knock-down of DACH1 in breast cancer cells MCF-7 and T47D promoted the morphology change from epithelial phenotype to mesenchymal pattern and interfered with cell-cell contact, accompanied by down-regulation of epithelial marker E-cadherin, resulting in cell migration and invasion. DACH1 also transcriptionally suppressed the activity of Snail, leading to the activation of E-cadherin in breast cancer cells, but the complex of DACH1 and Snail could bind to the E-box of E-cadherin promoter then contributing to the reduction of E-cadherin. In addition, DACH1 reduced the expression of the mesenchymal marker Snail through suppressing the activity of the Y box-binding protein, an important EMT inducer. Besides, previous study has revealed that DACH1 decreased both in breast cancer cell lines and tissues accompanied by relatively high proportion of CSCs. Inversely, CD44 not only promoted EMT, but also was upregulated by some mesenchymal markers. Previous studies have demonstrated that mesenchymal genes including ZEB1, TWIST1, SNAI1 and SLUG were positively correlated with CD44 expression. The switch from CD44 variant isoforms to its standard isoform is essential to undergo EMT for normal epithelial cells.

DACH1 played important roles in invasion and migration of various neoplasms, such as lung adenocarcinoma, gastric cancer, pancreatic cancer and breast cancer. Several lines of evidence showed that DACH1 is absent or suppressed in poor prognosis breast cancer. Breast cancer patients with reduced DACH1 expression had three years shorter time to death in comparison to those with normal DACH1 levels. Immunohistochemistry analysis showed that higher nuclear level of DACH1 was predictive of longer disease-free interval, cancer relapse-free survival and distant metastasis-free survival over 5 years post diagnosis. In consistency, our analysis of GSE databases showed that higher mRNA level of DACH1 was parallel with better OS, DFS and MFS. The protected effect of DACH1 in the prognosis of breast cancer patients could be explained partly by negatively interplaying CSCs and EMT. Besides, DACH1 inhibited breast cancer migration and invasion also via suppressing oncogene function through targeting interleukin-8. Altogether, these studies suggested that DACH1 could be a valuable molecular marker for prognosis, thereby detection of DACH1 level is useful for therapeutic stratification of breast cancer patients. In contrast, CD44 contributed to tumor formation and progression predictive of poor clinical outcome. CD44 functioned as an oncogene and knockdown of CD44 remarkably attenuated the migration and invasion of breast cancer cells MDA-MB-231 and Hs578T by modulating c-Src transcription. According to the analysis of 448 primary breast tumors, CD44 was parallel with enhanced distant recurrence and decreased disease-free survival.

In this study, 19 public datasets were enrolled to assess the correlation between the mRNA levels of DACH1 and CD44 and the survival performance of breast cancer patients. However, there are still some limitations: 1) the overall sample size is limited. Some data were not available when the meta-analysis was conducted; 2) the platforms used to evaluate the mRNA expression of DACH1 and CD44 are different; 3) the results at the mRNA levels might not be consistent with those at protein abundance because there is a complex regulation network from mRNA to protein.

In conclusion, this study confirmed that DACH1 and CD44 inversely related in breast cancer, different grade tumors and different subtypes. DACH1 was negatively associated with CD44 in vitro and vivo. DACH1 served as a good prognostic marker, and CD44 was an unfavorable element of breast cancer patients. Thus, we concluded that CD44 might be a novel target of DACH1.

Materials and Methods

Immunohistochemical staining. To evaluate the expression of DACH1 and CD44 in normal breast versus breast tumor tissues, grade 1–2 versus grade 3 tissues as well as luminal-type and basal-like human breast carcinoma tissues, two commercially available tissue microarray (TMA) slides (BR1502–97 and BR1502–98, US Biomax, Inc, Rockville, MD) containing histologically confirmed tissues were purchased for immunohistochemistry (IHC) analysis. In addition, IHC was also employed to compare the expression of CD44, Fibronectin, Vimentin, Sox2, Myc, EGFR and Ki-67 in Met-1 nude mice xenograft tumors with overexpression of DACH1 and the controls. The Specific primary antibodies against DACH1 (10914-1-AP, ProteinTech Group), CD44 (15675-1-AP, ProteinTech Group), Fibronectin (sc-8422, Santa Cruz), Vimentin (5741, Cell Signaling Technology), Sox2 (AB5603, Millipore), Myc (sc-40, Santa Cruz), EGFR (sc-03, Santa Cruz) and Ki-67 (ab15680, Abcam) were utilized for IHC with a 2-step protocol.
Analysis and quantification of staining. For quantification, a total of six 200× magnifications of each kind of protein were selected for IHC scoring. Two experienced pathologists assessed the immunohistochemical score independently. Scores were calculated on intensity and proportion of positive staining tumor cells in the whole tissue stains according to the Fromowitz Standard as described above. The staining intensity was scored as 0 (no staining), 1 (weak staining, light yellow), 2 (moderate staining, yellow brown) and 3 (strong staining, brown). The proportions of stained tumor cells were classified as 1 (0–25% positive cells), 2 (26–50% positive cells), 2 (51–75% positive cells) and 3 (76–100% positive cells). The multiplication for intensity and proportion was utilized to represent the protein levels of DACH1, CD44, Myc, Sox2, Fibronectin, Vimentin, EGFR and Ki-67.

Cell culture. The breast cancer cell line Met-1, was cultured in high-glucose Dulbecco's modified Eagle's medium (DMEM) supplemented with 10% fetal bovine serum (FBS, Life Technologies, Inc.). All cells were grown 37°C in a humidified incubator with 5% CO2.

Western blot. Cells were washed with cold PBS, scraped into RIPA buffer and centrifuged. The cell lysates were subjected to 10% SDS-PAGE and transferred to a polyvinylidene fluoride (PVDF) hybridization transfer membrane. The primary antibodies used were as follows: HA (Sc-7392, Santa Cruz), CD44 (15675-1-AP, ProteinTech group), Fibronectin (sc-8422, Santa Cruz), Vimentin (5741, Cell Signaling Technology), p21cip1 (sc-6246, Santa Cruz), p27kip2 (sc-1641, Santa Cruz) and β-actin (Sc-47778, Santa Cruz). Secondary staining and detection were carried out in accordance with standard protocols.

RNA profiling by microarray. DNA-free total RNA isolated from Met-1 cells expressing GFP or DACH1 were used to probe Affymetrix Gene 1.0 arrays (Affymetrix, Santa Clara, CA). RNA quality was determined by gel electrophoresis. Analysis of the arrays was performed using GeneSpring. Arrays were normalized using robust multi-array analysis, and the p value of 0.05 was applied as a statistical criterion for differentially expressed genes.

Meta-analysis for DACH1 on published Gene Expression Omnibus (GEO) databases. We carried out a comprehensive search of relevant GEO databases for mRNA expression of DACH1 and CD44 through ArrayExpress and Oncomine. The datasets meeting the following criteria were included: 1) the datasets were about human breast cancer; 2) the mRNA expression of DACH1 and CD44 was measured in these databases; 3) clinical outcomes of patients were showed in these databases; 4) the sample capacity was more than 50. Only the latest and most complete datasets were included when several databases shared common patients. At last, a total of 19 independent human breast cancer microarray databases with the mRNA expression of DACH1 and CD44 and required the survival information of breast cancer patients were enrolled in this systematic analysis.

Cutoff value for DACH1 and CD44 was median expression. OS, RFS and MFS were evaluated by Cox proportional hazard ratio (HR) and 95% confidence interval (95% CI). HRs was employed to assess the survival outcome of breast cancer patients with high mRNA expression of DACH1 and CD44 and HR > 1 indicated that high expression of DACH1 and CD44 predicted worse survival of patients. The random-effect model was employed when heterogeneity was present, and the fixed-effect model was used when homogeneity was demonstrated. Heterogeneity of publication was evaluated by means of the Chi-square-based-Q statistic and inconsistency index (I²) statistic. Statistical analysis was performed based on the guidelines of Meta-Analysis of Observational Studies. The STATA software package (version 12.0) (Stata Corp LP, College Station, TX, USA) was employed to perform the meta-analysis.

Analysis of gene expression data. GSE20711, available through GEO databases and containing 45 luminal-type and 22 basal-like breast carcinoma cases, was analyzed to evaluate the mRNA expression of DACH1 and CD44 in basal-like carcinoma in comparison with that in luminal-type tumors.

GSE20685, containing a total of 327 patients of breast cancer, was interrogated to assess the correlation between DACH1 and CD44, FN1, VIM, FOXA1, EGFR, MKI67 as well as the correlation between CD44 and FN1, VIM, YBX1, FOXA1, EGFR and MKI67 in breast cancer tissues.

Breast cancer cell line data of 51 breast cancer cell lines of different molecular subtypes published by Neve RM, et al. were also employed to evaluate whether the correlation in breast cancer cells was consistent with that in breast tumor tissues.

Nude Mice Study. The animal protocols were approved by the ethics committee of the Tongji Hospital of Huazhong University of Science and Technology. The methods used in this section were in accordance with the relevant guidelines and regulations. 1 × 10⁶ Met-1 cells expressing GFP control or DACH1 were implanted subcutaneously in 4–6-week-old athymic female nude mice purchased from Wuhan Hamilton Biological Polytron Technologies Inc. The tumor growth was measured twice weekly for 3 weeks by using a digital caliper. Tumor weight was measured when mice were sacrificed on day 27 after cells implantation.

Statistical analysis. Correlation analyses were performed using SPSS 20 statistical software (SPSS Inc., Chicago, IL, USA). The Student’s t-test was applied to evaluate the differences in groups as appropriate and the significance level was set at 0.05. The correlation analysis was evaluated by a χ²-test. A two-tailed p value < 0.05 was considered statistically significant.

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Acknowledgements
This work was supported by the National Natural Science Foundation of China (NSFC) No. 81572608 and 81172422 (KW), 81502296 (JX), and was also supported by NIH grant R01CA132115 (RGP).

Author Contributions
H.X.X. collected and analyzed the data, did experiments and wrote the manuscript. S.N.Y., X.Y., J.X., and D.K. carried out immunohistochemical analysis. K.M.W. and R.G.P. designed the study and revised the manuscript. All authors edited and approved the final manuscript.

Additional Information
Competing Interests: The authors declare that they have no competing interests.

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