Introduction

Breast cancer (BC) remains a significant health threat for women despite extensive research and progress in understanding its mechanisms. BC ranks first in incidence and fatality rates among all cancer types in women (1), with 1.7 million new cases diagnosed per year worldwide (2,3). The BC incidence rate increased slightly by 0.3% per year (4). The incidence of BC is higher along with poorer outcomes in developing countries, and the incidence is expected to increase by 55% with a 58% increase in mortality in the next 20 years (5). Therefore, there is an urgent need to identify more reliable prognostic biomarkers and potential drug targets to improve personalized treatments and the prognosis prediction of BC patients.

The metabolic characteristics of tumor cells are distinct from those of normal cells, with tumor cells exhibiting continuous glucose uptake and aerobic glycolysis, i.e., the Warburg effect (6). Glucose transporters (GLUTs) are the most critical rate-limiting enzymes in aerobic glycolysis;
however, different GLUT forms show different affinities for glucose, with the strongest affinities reported for GLUT1, GLUT3, and GLUT4, which also transport glucose at high rates under typical physiological or pathological conditions (7-9). To date, 14 GLUT factors have been identified in mammals, which all belong to the solute carrier 2A (SLC2A) family (10,11). Among them, GLUT1-4 play roles in the regulation of cellular and systemic glucose homeostasis (12), and GLUT1/3 expression has been detected in various normal human tissues and malignancies (12-15). A study comprising 118 patients with BC showed that GLUT1 was expressed in 42% of breast tumors, particularly in high-grade and proliferating tumors (16). Grover-McKay [1998] also found that the expression level of GLUT1 increased according to the increasing invasiveness of three human BC cell lines (17). A meta-analysis showed that the combination of GLUT1 and GLUT3 could be valuable in predicting the malignancy of the cancer (18). GLUT4 was originally considered to primarily regulate the insulin signaling pathway (19), but was recently found to be amplified in prostate cancer tissues and suggested to play a role in tumorigenesis (20,21). Therefore, GLUT1/3/4 show promising potential as new biomarkers for improving the prognosis prediction and/or personalized treatment for patients with BC.

Despite numerous studies on the relationship between GLUT factors and cancer, the underlying mechanisms by which they are activated or inhibited in tumorigenesis and the unique roles of GLUT factors in BC have not been completely clarified to date. Therefore, in the present study, we analyzed available transcriptome and clinical data from patients with BC in online public databases, and used bioinformatics approaches to explore the expression patterns, potential functions, and differential prognosis ability of GLUT1/3/4 with BC.

**Methods**

**Oncomine analysis**

We analyzed the expression levels of GLUT1, GLUT3, and GLUT4 between various types of tumors and their corresponding normal tissues using the online Oncomine database (22). All datasets met the following criteria: (I) threshold (fold change): 2.0; (II) Student’s t-test was used to determine the significance level of the difference in the expression of GLUTs between tumor and normal tissues; P<0.01 was considered statistically significant.

**Gene expression profiling interactive analysis (GEPIA) dataset**

We further utilized GEPIA data to determine the expression patterns of GLUTs specifically in BC. GEPIA includes RNA sequence expression data from 8,587 normal samples and 9,736 tumors collected from the GTEx project and The Cancer Genome Atlas (TCGA) (23). The analyses were conducted according to the instructions on the GEPIA website.

**Kaplan-Meier (KM) plotter**

We used KM analysis to assess the relationship between GLUT1/3/4 expression and the prognosis of BC patients (24), including gene expression information and clinical data for 6,234 BC patients. We divided the BC patients into a high expression group and low expression group based on the median GLUT expression level. The associations of GLUT expression with overall survival (OS), relapse-free survival (RFS), and distant metastasis survival (DMFS) were determined according to the KM survival plot; a log-rank test was used to analyze the significance of a KM plot, P<0.05 represented statistical significance.

**cBioPortal**

The Breast Cancer (METABRIC, Nature 2012 & Nat Commun 2016) dataset (25), including data from 1,904 pathologically reported cases, were utilized to analyze the genomic profiling information (including mutation and mRNA enrichment) of GLUT1, GLUT3, and GLUT4 in BC patients with cBioPortal online tools (26,27). In addition, networks were constructed following standard processing procedures to obtain the 50 neighboring genes with the highest frequency of alteration between BC and normal tissues.

**TCGA and Gene Expression Omnibus (GEO) dataset analysis**

GDC TCGA Breast Cancer (BRCA) (15 datasets) was downloaded from UCSC Xena (http://xena.ucsc.edu/). The matrix data of each TCGA dataset were normalized and converted into TPM. GSE109169 and GSE9574 were downloaded from GEO. The expression level of GLUTs between normal and tumor tissue was analyzed via the Student's t-test, P<0.05 represented statistical significance.
Cells were cultured in Dulbecco’s modified Eagle’s medium (Thermo Fisher Scientific, USA) with 10% fetal bovine serum (Gibco, USA), 100 U/mL penicillin (Beyotime, China), and 100 mg/mL streptomycin (Beyotime, China). All cell lines were incubated at 37 °C at 5% CO₂.

Western blot

Cells were lysed with RIPA buffer (Beyotime, China). Equal amounts of protein in cell lysates were measured by standardization with the BCA Protein Assay Kit (Beyotime, China). Proteins were resolved by SDS-PAGE and transferred to nitrocellulose membranes (Whatman, Dassel, Germany). After blocking with 5% skimmed milk in TBST, membranes were incubated with primary antibodies overnight in 4 °C, followed by 2 h incubation with HRP-conjugated secondary antibodies. Protein bands were visualized with ECL. Antibodies against GLUT1/3/4 were purchased from ABclonal (Hubei, China). Antibodies against beta-tubulin were purchased from Cell Signaling Technology (Beverly, MA, USA). The grey of the protein bands was measured using ImageJ software. A two-tailed Student’s t-test was applied to assess the statistical significance of the difference between two independent groups.

Results

Transcription levels of GLUTs in patients with BC

Comparison of the transcription levels of GLUTs in BC and normal breast tissues from the Oncomine datasets showed different patterns of differential expression depending on the GLUT considered (Figure 1). Abundant upregulation of GLUT1 expression was found in BC samples in 11 datasets (Figure 1). In the dataset of Zhao et al. (28), the transcription level of GLUT1 was higher in invasive ductal (ID) and invasive lobular (IL) BC than in normal breast tissue, with fold changes (FC) of 2.800 and 2.075, respectively (Table 1). By contrast, the transcription levels of GLUT3 and GLUT4 were significantly reduced in 14 and 8 BC patient datasets, respectively (Figure 1). In the TCGA Breast dataset, GLUT4 expression was also down-regulated in all BC types compared to that of breast tissues, with an FC of −5.889 for ID BC and FC of −6.020 for IL BC (Table 1).

GLUT transcription levels and clinicopathological parameters of patients with BC

Comparison of the transcription levels of GLUTs between BC samples and non-cancer breast samples in the GEPIA dataset confirmed that the GLUT1 level was higher in BC tissues, whereas the transcription levels of GLUT3/4 were lower in the BC samples (Figure 2). Moreover, the
transcription levels of GLUT1 and GLUT3 were correlated with clinical cancer stage, whereas the GLUT4 levels were not (Figure 3).

**Association of GLUT transcription levels with patient prognosis**

Online KM tools indicated that the expression levels of GLUTs could provide reliable predictions of survival in BC patients. KM plotter and the log-rank test suggested that up-regulated GLUT1 expression and down-regulated GLUT4 expression were significantly related to a poor OS, RFS, and DMFS in BC patients (P<0.05; Figure 4). Moreover, BC patients with a relatively high transcription level of GLUT3 were predicted to have a high RFS (P<0.05; Figure 4).

**Predicted functions and pathways of the changes in GLUT factors and their associated gene networks in patients with BC**

GLUT expression was altered in 336 of the 1,904 (18%) BC

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**Table 1** Transcription levels of glucose transporters (GLUTs) in different types of breast cancer (BC) and normal tissues

<table>
<thead>
<tr>
<th>GLUTs</th>
<th>Type of BC vs. normal tissues</th>
<th>Fold change (FC)</th>
<th>P value</th>
<th>t-statistic</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLUT1</td>
<td>Invasive ductal breast carcinoma (ID BC)</td>
<td>2.800</td>
<td>1.03E-11</td>
<td>9.276</td>
<td>Zhao et al., 2004</td>
</tr>
<tr>
<td></td>
<td>Invasive lobular breast carcinoma (IL BC)</td>
<td>2.075</td>
<td>6.62E-6</td>
<td>5.631</td>
<td>Zhao et al., 2004</td>
</tr>
<tr>
<td>GLUT3</td>
<td>ID BC</td>
<td>−2.753</td>
<td>3.52E-44</td>
<td>−19.000</td>
<td>Curtis et al., 2012</td>
</tr>
<tr>
<td></td>
<td>IL BC</td>
<td>−2.665</td>
<td>5.64E-34</td>
<td>−13.812</td>
<td>Curtis et al., 2012</td>
</tr>
<tr>
<td>GLUT4</td>
<td>ID BC</td>
<td>−5.889</td>
<td>2.14E-26</td>
<td>−16.643</td>
<td>The Cancer Genome Atlas (TCGA)</td>
</tr>
<tr>
<td></td>
<td>IL BC</td>
<td>−6.020</td>
<td>1.82E-16</td>
<td>−9.886</td>
<td>TCGA</td>
</tr>
</tbody>
</table>

GLUTs, glucose transporters; BC, breast cancer; ID BC, invasive ductal breast carcinoma; IL BC, invasive lobular breast carcinoma; FC, fold change.
patients in the Breast Cancer (METABRIC, Nature 2012 & Nat Commun 2016) dataset of the cBioPortal database. The highest frequency of mutation was 9.14% (Figure 5A), with mutation frequencies in GLUT1, GLUT3, and GLUT4 of 8%, 7%, and 5%, respectively (Figure 5B). The network showed that the five most frequently altered genes associated with GLUT alterations were MYC, YWHAZ, ARNT, CREBBP, and CLTC (Figure 5C).

The GLUTs and 50 neighboring genes were annotated, and the results were visualized using Gene Ontology (GO) and Kyoto Encyclopedia of Genes and Genomes (KEGG) analysis in the DAVID tool (31,32). GO analysis showed an enrichment of GLUT mutations in BC in the biological function terms like negative/positive regulation of RNA polymerase II promoter transcription, cellular response to insulin stimulation, and signal transduction (Figure 6A), along with other terms of the cytoplasm like cellular exosome, protein binding, protein domain-specific binding, and transcription factor binding (Figure 6B,C). KEGG analysis identified 10 pathways associated with the functions of GLUTs mutations in BC (Figure 6D), including hsa04110 (cell cycle), hsa04151 (PI3K-AKT signaling pathway), hsa04330 (Notch signaling pathway), and hsa05200 (cancer pathway), which are critical pathways in the tumorigenesis and pathogenesis of BC (Figure 7) (33).

Enrichment of mutation and differential expression mRNA between GLUTs

The BC samples showing differences in GLUT expression from normal samples also showed altered mutation frequencies of TP53, PIK3CA, and MAP2K4 compared to those of BC samples without altered GLUT expression (Figure 8A). Aberrant mutations in both TP53 and PIK3CA have been reported to be associated with the development of BC (34-36).

A total of 80 differentially expressed genes (DEGs: logFC ≥0.5, odds ratio ≤−1.5) between the groups with altered and unaltered GLUT expression were identified (Figure 8B). GO analysis of these 80 DEGs showed enrichment in signal transduction, negative regulation of cell proliferation, cellular response to tumor necrosis factor, and cell differentiation, indicating the regulation of these processes by GLUTs in BC (Figure 8C). Moreover, extracellular exosome, identical protein binding, structural constituent of the cytoskeleton, and microtubule binding were significantly regulated by these GLUT mutations (Figure 8D,E).

The expression of GLUTs between normal tissues and tumors in TCGA and GEO datasets

Comparison of the expression levels of GLUTs between normal breast tissues and BC tissues in the TCGA dataset confirmed that GLUT1 level was higher in BC tissues, whereas the expression levels of GLUT3/4 were lower in the BC samples (Figure 9A). By analyzing the GEO datasets (GSE109169 and GSE9574), we also found that BC tissues had higher expression levels of GLUT1, whereas lower GLUT3/4 levels were found in the normal breast tissues (Figure 9B). Moreover, the expression levels of GLUT4 were correlated with OS, whereas the GLUT1/3 levels were not (Figure 9C).

Expression of GLUTs between luminal and basal-like BC cell lines

We compared the expression levels of GLUTs between luminal (MCF-7/T47D/BT474) and basal-like BC cells (SUM159/BT549/MDA-MB-231) and found that the
GLUT1 levels were higher in basal-like BC cells and T47D cells, whereas the levels of GLUT3/4 were higher in luminal BC cells (Figure 10).

**Discussion**

Aberrant expression of GLUT has been reported in several types of tumor tissues (9,37-41). Although a role of GLUT in predicting the prognosis has been demonstrated for some cancers (42-44), the detailed associations with BC and underlying mechanisms have remained unclear so far. By the comprehensive analysis of available public data and bioinformatics, we demonstrated clear and distinct patterns of up-regulated GLUT1 expression, and down-regulated
Figure 5 GLUT1/3/4 mutation analysis and network construction in breast cancer patients.

GLUT3 and GLUT4 expression in BC, which can help guide personalized treatment and improve the accuracy of prognosis for BC patients.

In line with the present results, GLUT1 has been reported to be overexpressed in many cancers (15), and was associated with poor survival in BC (16), lung cancer (45,46), oral squamous cell carcinoma (47,48), esophageal cancer (49,50), rectal cancer (51), tongue squamous cell carcinoma (52) and pancreatic cancer (53). GLUT1 was higher in TNBC cases than in non-TNBC cases (54). Moreover, high expression levels of GLUT1 were suggested to contribute to the tumorigenesis of BC (16,55), and a recent study
Figure 6 Functions of GLUT1, GLUT3, and GLUT4, and the 50 most frequently mutated neighboring genes predicted by Gene Ontology (GO) analysis and Kyoto Encyclopedia of Genes and Genomes (KEGG) analysis in The Database for Annotation, Visualization and Integrated Discovery (DAVID). GO analysis included biological processes (A), cellular components (B), molecular functions (C). KEGG analysis included KEGG pathways (D).
Figure 7 Breast cancer signal pathways regulated by the GLUT1, GLUT3, and GLUT4 alteration in breast cancer.
Figure 8 Functions of GLUT1, GLUT3, and GLUT4 and enrichment of mutation and differentially expressed mRNAs with GLUT alterations predicted by GO analysis and KEGG analysis in DAVID. Enrichment of mutation (A) and differentially expressed mRNAs (B). GO analysis included biological processes (C), cellular components (D), and molecular functions (E).
showed a link between the overexpression of GLUT1 and the hypoxic condition of the tumor microenvironment (56). The transcription factors c-Myc and sinoculis homeobox 1 (Six1) have been reported to directly activate GLUT1 transcription (57,58). The analysis of miRNA-mRNA network reveals miR-140-5p as a suppressor of BC glycolysis via targeting GLUT1 (59). Among colorectal cancer cell lines, those with KRAS/BRAF mutations also showed a higher transcription level of GLUT1 than wild-type cells (60). By contrast, thioredoxin-interacting protein (TXNIP) and p53 repress GLUT1 transcription (61-64).

GLUT3 has also been reported to be overexpressed in many tumors (65), and was considered a potential marker of poor prognosis in oral squamous cell carcinoma and non-small cell lung cancer (16,47). However, we found an opposite pattern of a reduced transcription level of GLUT3 in BC than in non-cancer tissues, which was associated with a worse OS and clinical cancer stage.

GLUT4 expression was also found to be down-regulated in BC in the present study, and was a significant predictor of poor OS, RFS, and DMFS. Loss of GLUT4 induces metabolic reprogramming and impairs viability of BC cells (66). Previous studies have shown diverse patterns of GLUT4 expression, with overexpression reported in gastric cancer (67,68) and reduced transcription levels in pancreatic cancer (69).

In summary, we have provided new insight to clarify the expression pattern and prognosis-related features of GLUT1, GLUT3, and GLUT4 in BC.

Figure 9 Analysis of GLUT1/3/4 with The Cancer Genome Atlas (TCGA) and Gene Expression Omnibus (GEO) datasets. Expression levels of GLUT1/3/4 between BC and normal breast tissues in TCGA dataset (A), and GEO datasets (C), The relationship between the expression levels of GLUT1/3/4 and OS in TCGA dataset (B). P<0.05 represented statistical significance, *, P<0.05; ****, P<0.0001; ns means P>0.05.
GLUT1, GLUT3, and GLUT4 in BC by integrating the data of online databases. These results demonstrate that the amplified transcription of GLUT1 might play a critical role in BC tumorigenesis. Moreover, a high transcription level of GLUT1 can be considered as a reliable marker for discerning high-risk subtypes of BC, suggesting an effective therapeutic target for BC. In addition, the high transcription of GLUT3/4 can serve as a potential prognostic marker for BC patients, implying a better prognosis.

Acknowledgements

None.

Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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