



# Construction of a prognostic score model for breast cancer based on multi-omics analysis of study on bone metastasis

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**Background:** Breast cancer (BRCA) is the most common type of cancer and the second leading cause of cancer-related death in women all over the world. Metastasis to bone is an indicator of poor prognosis in BRCA patients. This study aimed to develop a prognostic score model for predicting bone metastasis in patients with BRCA.

**Methods:** BRCA-related RNA sequencing datasets and corresponding clinical information were downloaded from the Gene Expression Omnibus (GEO) and The Cancer Genome Atlas (TCGA). Differentially expressed genes (DEGs) were screened using Limma package of R software. A risk score based predictive model was constructed based on the key genes identified through univariate Cox regression and the least absolute shrinkage and selection operator (LASSO) Cox regression. The gene expression profiles in BRCA patients were analyzed by gene set variation analysis (GSVA) and gene set enrichment analysis (GSEA). Random survival forest (RSF) analysis of BRCA patients with bone metastasis was conducted to identify the key DEGs.

**Results:** Based on DEG analysis, a total of 677 genes were identified as genes related to bone metastasis in BRCA. By univariate Cox regression and LASSO regression, 28 DEGs were identified as signature genes to develop the prognostic model. A risk score for each patient was created by incorporating the expression values of each specific gene and weighting them with the corresponding estimated regression coefficients. Patients were divided into a low-risk and a high-risk group based on the median risk score. Overall survival (OS) was significantly lower in the high-risk group. The receiver operating characteristic (ROC) curve and multi-omics analysis indicated that the model had high training/testing accuracy and a good clinical predictive value. We used extra data from GEO database to verify the robustness of the prognostic model, and the lower OS in high-risk group and area under the curve (AUC) value indicated the model had strong predictive efficacy for prognosis of BRCA.

**Conclusions:** A prognostic prediction model was constructed based on 28 key DEGs identified through multi-omics analysis of studies on bone metastasis. The model may provide a promising method for distinguishing the high-risk BRCA patients and help on decision making in addition to prognosis prediction for BRCA patients.

**Keywords:** Breast cancer (BRCA); bone metastasis; prognosis; prognostic score model; risk score

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## Introduction

Breast cancer (BRCA) is the most common type of cancer, with an estimated 2.26 million cases recorded in 2020. The global age standardized incidence rate in females is estimated to be 48/100,000 and has been rising in the past four decades (1). During the most recent data years [2010–2019], the rate increased by 0.5% annually. At present, BRCA is the second leading cause of cancer-related death among women overall, second to lung cancer, posing a serious threat to women's health (2,3).

It is a heterogeneous disease with significant differences between patients and even within each tumor (4). Based on cancer statistics, in the United States, the average 5-year and 10-year survival rates for women with non-metastatic invasive BRCA are 90% and 84%, respectively (5). Although the median survival and 5-year relative survival for *de novo* metastatic BRCA increased over the years, especially in younger women, the 5-year relative survival was not more than 40% (6). Moreover, a large percentage of cancer survivors who were initially diagnosed with

early-stage (I–III) cancer later experienced a recurrence or progression to metastatic disease according to the analysis of US mortality data from the National Center for Health Statistics and US Census Bureau populations (3). Approximately 4% of women with a history of BRCA have metastatic disease, more than half of whom were initially diagnosed with early-stage BRCA (3,6). The common sites of metastasis include bone, lung, liver, and brain. Among the above metastatic sites, bone metastasis is most common, accounting for approximately 65–75% of metastasis cases, with the 5-year overall survival (OS) rate being about 20% (7–9). Therefore, bone metastasis is an indicator of poor prognosis in BRCA patients. Current treatments for bone metastasis include systemic therapies such as chemotherapy and endocrine therapy to slow the proliferation of cancer cells; bone-targeted treatments such as potent bisphosphonates or denosumab to inhibit the excessive bone destruction associated with cancer; and the use of bone-seeking radionuclides (10). However, even these treatments for many patients result in a major reduction in skeletal complications, reduced bone pain and improved quality of life, they are only palliative (10). New treatment markers and targets are needed to achieve better prognosis.

Although BRCA subtypes partly indicate the preferential site of metastasis and help to guide clinical therapeutics, the development of more effective treatments against BRCA metastases depends on a systematic and deepened understanding of the molecular mechanism of metastatic heterogeneity (7). Bone metastasis of BRCA is associated with activation of several pathways, including epithelial-mesenchymal transition (EMT), angiogenesis, and interleukin 1 beta (IL-1 $\beta$ ) pathway (11–13). However, the genetic and molecular mechanism of bone metastasis of BRCA remains unclear. With the development of gene expression profiling, such as RNA-seq and single-cell RNA-seq, researchers have identified gene expression signatures that are associated with bone metastasis or survival outcomes of BRCA (14,15). Recently, public database bioinformatics analysis has been widely used to investigate prognostic biomarkers in disease progression, and predictive models can also be used to assess prognosis in BRCA patients (16–18). As a result, identifying reliable signature genes and clinical factors will serve as a guide for clinical decision-making. In this study, we comprehensively analyzed the RNA-seq data from a BRCA cohort to construct a BRCA prognostic model based on differentially expressed genes (DEGs) in bone metastasis, and it can help identify patients at high risk of bone metastasis for early

### Highlight box

#### Key findings

- A prognostic prediction model was constructed based on 28 key differentially expressed genes (DEGs) identified through multi-omics analysis of studies on bone metastasis in breast cancer (BRCA).

#### What is known and what is new?

- BRCA is the most common type of cancer and the second leading cause of cancer-related death in women all over the world. Many prognostic models for BRCA have been developed, but only a few have been extensively validated in various settings. Furthermore, their performance is suboptimal in independent populations, particularly in patients with high risk and in young and elderly patients.
- Bone is the most common site of metastasis for BRCA, with the 5-year overall survival rate being about 20%. Therefore, bone metastasis is an indicator of poor prognosis in BRCA patients. We developed a prognostic score model for prognostic prediction in BRCA based on the genes associated with bone metastasis of BRCA and externally validated the reproducibility and generalizability of this prognostic model.

#### What is the implication, and what should change now?

- The prognostic prediction model of BRCA in this study can provide a promising method for clinical helping on clinical decision making and prognosis prediction for BRCA patients. Meanwhile, screening for prognostic biomarker genes and pathways in BRCA may provide potential therapeutic targets for future treatment.

intervention. We present this article in accordance with the TRIPOD reporting checklist (available at <https://tcr.amegrouppublishing.com/article/view/10.21037/tcr-23-1881/rc>).

## Methods

### *Data and patient samples extraction*

This study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). We downloaded the raw mRNA expression and clinical data of BRCA patients from The Cancer Genome Atlas (TCGA) database including normal group (n=113), tumor group (n=1,109). Limma package of R software was used to identify DEGs, with a significance threshold of  $P < 0.01$ . Additionally, we downloaded the Series Matrix File data files of GSE20685 (annotation platform was GPL570), GSE2034 (annotation platform was GPL96), GSE124647 (annotation platform was GPL96), and GSE39494 (annotation platform was GPL6840) from the NCBI Gene Expression Omnibus (GEO) database. In GSE20685, a total of 327 BRCA patients with complete expression profiles and survival information were collected. GSE2034 was comprised of 286 samples, including 217 patients without bone metastasis and 69 patients with bone metastasis. GSE124647 featured 30 samples, consisting of 19 patients without bone metastasis and 11 patients with bone metastasis. Lastly, GSE39494 encompassed expression profile data of 10 samples, including 5 patients without bone metastasis and 5 patients with bone metastasis.

### *Gene Ontology (GO) and Kyoto Encyclopedia of Genes and Genomes (KEGG) pathway enrichment analysis*

Enrichment analyses of DEGs were performed using Metascape ([www.metascape.org](http://www.metascape.org)). We conducted biological pathway analysis of specific genes through GO terminology and KEGG pathways. A Min overlap  $\geq 3$  &  $P \leq 0.01$  was considered statistically significant.

### *Construction of a prognosis-predicting model based on the bone metastasis-related DEGs in BRCA*

The DEGs associated with bone metastases were carefully selected, and a prognostic-predicting model was constructed using the least absolute shrinkage and selection operator (LASSO) Cox regression. In the LASSO regression analysis, a risk score for each patient was calculated for each patient

by incorporating the expression values of specific genes and weighting them with the corresponding estimated regression coefficients. Based on their risk scores, the patients were categorized into low- and high-risk groups, using the median risk score as the cut-off point. The survival differences between the two groups were evaluated using Kaplan-Meier and compared using log-rank statistical methods. Moreover, the predictive capability of the risk score model for patient prognosis was examined using LASSO regression analysis and stratified analysis. Additionally, to assess the prediction accuracy of the model, the receiver operating characteristic (ROC) curve was plotted.

### *Drug sensitivity analysis*

Based on the Genomics of Drug Sensitivity in Cancer (GDSC) databases (<https://www.cancerrxgene.org/>), we used pRRophetic to predict the chemosensitivity of each tumor sample. Cox regression was employed to acquire estimated half maximal inhibitory concentration (IC50) values for individual chemotherapy drug treatment, and 10-fold cross-validations were conducted with the GDSC training dataset to evaluate the accuracy of regression and prediction.

### *Infiltrating immune cells analysis*

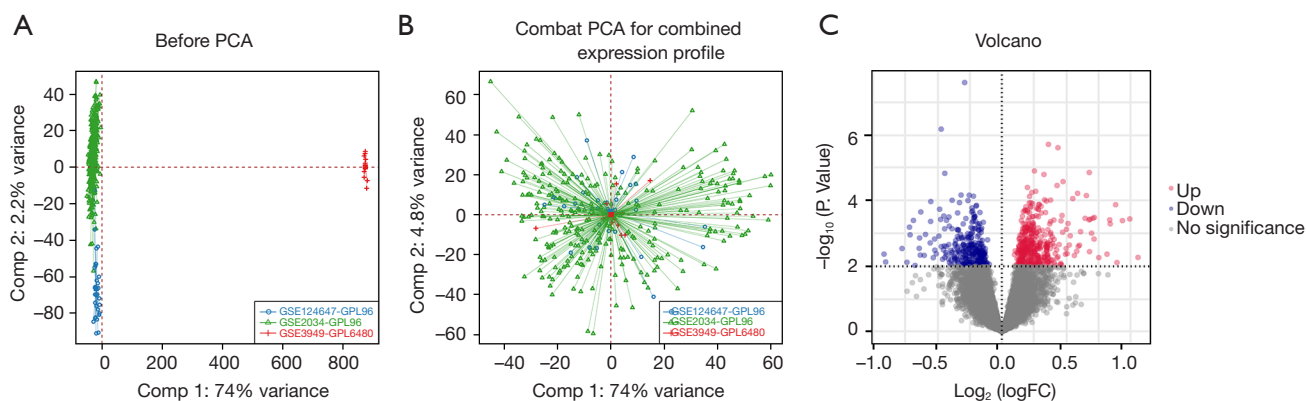
The CIBERSORT algorithm was employed to estimate the relative proportions of 22 types of infiltrating immune cells using normalized gene expression data obtained from various subgroups of BRCA patients.  $P < 0.05$  was considered statistically different.

### *Gene set variation analysis (GSVA)*

GSVA was used to estimate variation of gene set enrichment through the samples in an unsupervised manner. Gene sets were downloaded from the Molecular signatures database (v7.0). GSVA algorithm was used to score each gene set to evaluate the potential biological function changes of different samples.

### *Gene set enrichment analysis (GSEA)*

GSEA (<http://www.broadinstitute.org/gsea>) of BRCA patients' expression profiles was conducted on the TCGA database to identify genes showing differential expression between patients in the low- and high-risk groups. Gene sets



**Figure 1** The volcano plot of the DEGs in BRCA with bone metastasis after correction of combat-seq. (A) The before-PCA data contains a strong batch effect, as samples clearly separated by batch in the principal components indicated the lower gene expression values. (B) In the Combat-seq corrected data, variation explained by batch is greatly reduced compared to that in unadjusted data. (C) Volcano plot of 677 DEGs in BRCA with bone metastasis. Blue dots: downregulated genes; red dots: upregulated genes. PCA, principal component analysis; FC, fold change; DEGs, differentially expressed genes; BRCA, breast cancer.

were filtered using the maximum and minimum gene set sizes of 500 and 15 genes, respectively. After performing 100 alignments, enriched gene sets were obtained based on a P value <0.05 and a false discovery rate (FDR) value of 0.25.

### Random survival forest (RSF)

The gene selection process was executed using the randomForestSRC. We applied the RSF algorithm to prioritize the significance of prognosis-related genes (nrep=1000, which indicated a number of 1,000 iterations in the Monte Carlo simulation).

### Statistical analysis

Survival curves were generated by the Kaplan-Meier method and subsequently compared using the log-rank test. The Cox proportional hazards model was employed to conduct multivariate analysis. All statistical analyses were performed in R (version 3.6). All statistical tests were two-sided, and  $P < 0.05$  was statistically significant.

## Results

### DEGs for bone metastasis in BRCA

We downloaded GSE2034, GSE124647, and GSE39494 BRCA-related databases from the GEO database and included expression profile data from 326 patients, with 241 having no metastasis and 85 having bone metastasis.

Combat-seq was employed to mitigate for batch effects within databases (Figure 1A,1B). A total of 677 DEGs were identified using Limma ( $P < 0.01$ ), comprising 379 upregulated genes and 298 downregulated genes. Volcano plots revealed the expression patterns of these differentially expressed genes between bone metastasis and non-metastasis BRCA (Figure 1C).

### Construction of prognostic model for BRCA

Univariate Cox regression and LASSO regression were used to identify key DEGs in BRCA with bone metastasis based on clinical data from BRCA patients. Univariate Cox analysis ( $P < 0.05$ ) identified 77 genes significantly associated with bone metastasis BRCA. These genes are tabulated in Table 1. The functional enrichment analysis performed using Metascape revealed a significant enrichment of the DEGs in processes such as peptide metabolic process, regulation of B cell activation, intestinal immune network for IgA production (Figure 2A). Then protein-protein interaction (PPI) network was conducted using Cytoscape (Figure 2B).

The partial likelihood deviance of validation included lower and upper standard deviations (SDs) as a function of log (lambda) for the dataset of the BRCA patients (Figure 3A). LASSO-Cox regression analysis revealed that the model built with 28 key DEGs performed better in both the training and test sets, and the OS was significantly lower in the high-risk group than in the low-risk group (Figure 3B). In LASSO regression analysis, a risk score for

**Table 1** A total of 77 DEGs identified by univariate Cox regression with P value <0.01 in BRCA with bone metastasis

Gene expression level	Genes
Upregulated	CPT1A, RPL27, TM9SF3, TFF1, RPA3, GPN3, GGCX, AATK, CACYBP, SEC24A, BLVRA, KANSL2, SLC1A1, CRIP1, NDUFB1, GAPVD1, SNW1, SLC22A18, TOR1B, GSTO1, GSTK1, METTL17, ATP7B, SLC19A2, SLC30A5, WDR41, RACGAP1, ATG12
Downregulated	VDAC1, BRD4, ZFP36L2, TNFRSF17, NONO, GSTM4, IGLL5, AARS, SLC25A28, MED17, CIR1, UGP2, CCNC, RPL29, N4BP2L1, UBXN7, MED15, CD79A, GSTK1, TNFRSF13B, APC2, SOCS3, PRKG2, HLA-DMA, RDX, UBTF, MZB1, LCP1, TNFAIP2, CXCL13, OSBPL1A, APOBEC3C, FRS3, CD74, KRT5, HYAL2, MAP3K6, CD27, GUSBP11, SGPP1, RABIF, IL27RA, KRT15, WAC, HLA-J, PIGR, RASAL2, MPST, MTPAP

DEGs, differentially expressed genes; BRCA, breast cancer.

each patient was created by incorporating the expression values of each specific gene and weighting them with the corresponding estimated regression coefficients [risk score = SGPP1  $\times$  (-0.101225800921312) + CXCL13  $\times$  (-0.0990602304262338) + TFF1  $\times$  (-0.0761355688305833) + GSTM4  $\times$  (-0.0701245664074805) + OSBPL1A  $\times$  (-0.0697959194240498) + SOCS3  $\times$  (-0.0697408751094871) + SLC1A1  $\times$  (-0.0626539083827484) + SNW1  $\times$  (-0.0613959366359668) + UBTF  $\times$  (-0.0532038393937342) + SLC19A2  $\times$  (-0.0522506821431928) + IGLL5  $\times$  (-0.050589292470364) + KRT15  $\times$  (-0.0275896594668161) + RPL3  $\times$  (-0.0221797643103188) + ATP7B  $\times$  (-0.0191263079888773) + LCP1  $\times$  (-0.0182193631834509) + MZB1  $\times$  (-0.0180883496044173) + IL27RA  $\times$  (-0.0111516113130218) + TNFAIP2  $\times$  (-0.0066362926318615) + CIR1  $\times$  (-0.00522630755396113) + PRKG2  $\times$  0.00628130837936622 + GGCX  $\times$  0.00672477812884809 + UGP2  $\times$  0.00901642206667127 + APC2  $\times$  0.0502830638605627 + CPT1A  $\times$  0.0755668823957223 + VDAC1  $\times$  0.0804574886170706 + RPA3  $\times$  0.0929797695524507 + TOR1B  $\times$  0.125112100662822 + MED17  $\times$  0.132621345321979] (Figure 3C). A prognostic score model for BRCA was developed based on the above 28 genes. The median risk score in the clinical cohort is firstly determined based on the model. Subsequently, enrolled patients are grouped into high-risk group ( $\geq$  the median risk score) and low-risk group ( $<$  the median risk score).

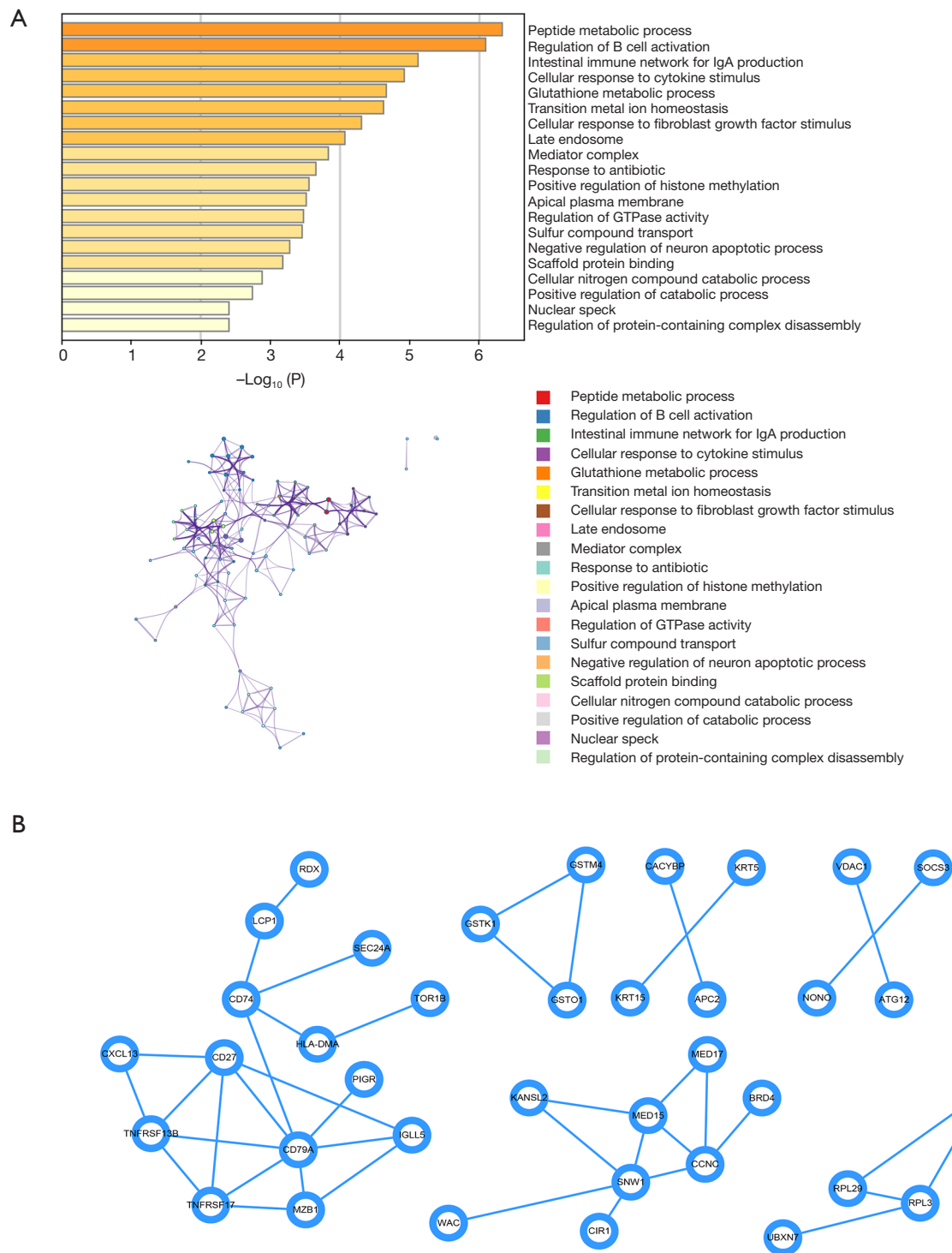
We randomly divided BRCA patients from TCGA database into training and testing sets in the ratio of 4:1. Patients were divided into high-risk and low-risk groups according to the median risk score (-0.0320772653171833, -0.00532802039832265, 0.0019647229505629 for TCGA training, TCGA testing, and GEO1 validating and GEO2 validating, respectively) and analyzed using Kaplan-Meier curves. OS was significantly lower in the high-risk group

than in the low-risk group in both the training and testing sets (Figure 3D). The ROC curve showed that the area under the curve (AUC) values obtained in the training and testing sets for periods of 1, 3, and 5 years were greater than 0.70, indicating that the model had high training/testing accuracy (Figure 3E). Therefore, the model had strong predictive efficacy for the prognosis in BRCA patient.

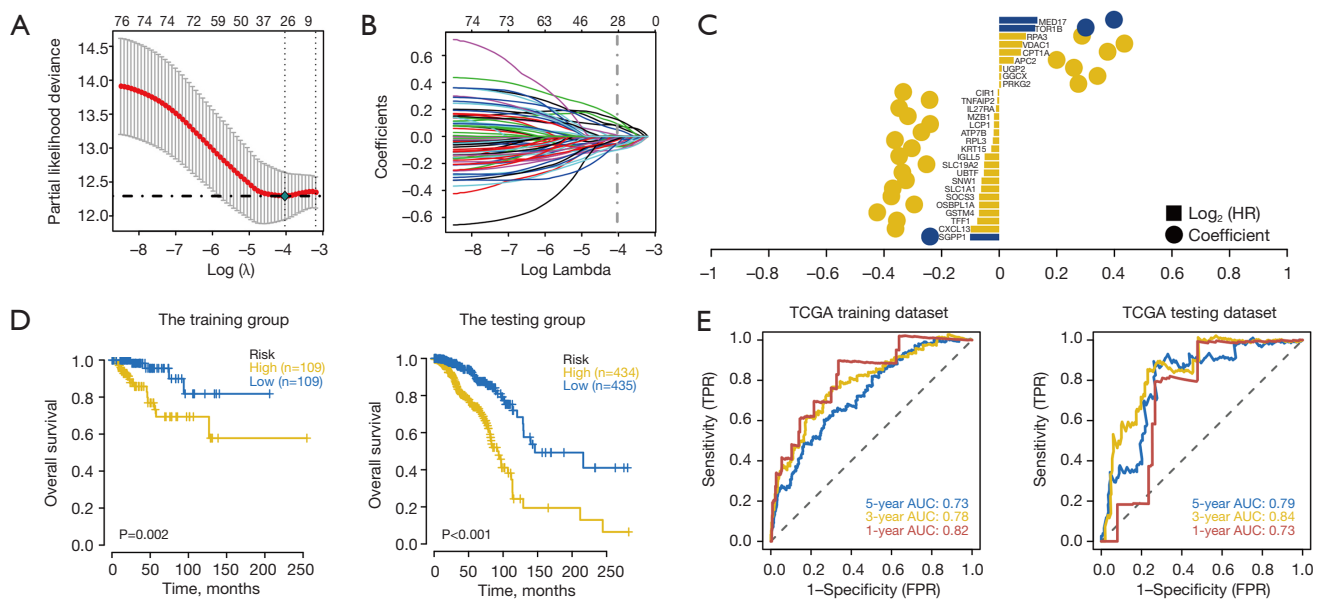
#### *Multi-omics analysis exploring clinical predictive value of the prognostic model for BRCA*

The tumor microenvironment (TME), mainly composed of tumor-associated fibroblasts, immune cells, extracellular matrix, various growth factors, inflammatory factors, specific physicochemical characteristics, and cancer cells, significantly affects the diagnosis, survival outcome and clinical treatment sensitivity of tumors (19). We analyzed the relationship between risk score and tumor-infiltrating immune to further explore the molecular mechanisms of risk score affecting BRCA progression. Our result showed that risk score was significantly positively correlated with macrophages (M0, M1 and M2) and neutrophils; while was negatively correlated with dendritic cells, T cells, B cells, plasm cells, and monocytes (Figure 4A).

In clinical practice, for early-stage BRCA, surgery combined with chemotherapy is effective. Based on drug sensitivity data from the GDSC database and the comparison of the IC50 values to get a better comprehensive analysis of chemotherapy response, we predicted chemotherapy sensitivity for each tumor sample and explored the correlation with risk score and sensitivity of common chemotherapy drugs for BRCA patients. Pearson correlation between the risk score and IC50 of different chemical compounds was conducted, and six chemical compounds (bleomycin, camptothecin, cisplatin, docetaxel, doxorubicin, gemcitabine) were identified as



**Figure 2** GO enrichment and interactome analysis of DEGs in BRCA with bone metastasis. (A) Top non-redundant enrichment clusters were displayed in a Metascape bar graph, one per cluster. Network of enriched terms were colored by cluster ID. (B) PPI network. GO, Gene Ontology; DEGs, differentially expressed genes; BRCA, breast cancer; PPI, protein-protein interaction.



**Figure 3** DEGs in BRCA with bone metastasis in univariate Cox regression with P value of  $<0.01$  were included in the LASSO-Cox regression model to establish an optimal prognostic model. (A) The LASSO regression model revealed partial likelihood deviance of various numbers of variables. The partial likelihood deviance values are represented by red dots, the SE is represented by grey lines, and the two vertical dotted lines on the left and right, respectively, represent optimal values by minimum and 1-SE criteria. “Lambda” is the tuning parameter. (B) LASSO-Cox regression coefficient selection and variable screening. The lambda value is represented on the lower horizontal axis, and the number of variables in the LASSO-Cox regression model with a non-zero regression coefficient is represented on the upper horizontal axis scale. The value of the regression coefficient is represented on the left vertical axis. (C) Risk score was created for each patient after incorporating the expression values of each specific gene and weighted with its estimated regression coefficients. The blue dots indicate genes with the absolute value of LASSO coefficient  $>0.1$ , and the yellow dots indicate genes with the absolute value of LASSO coefficients  $<0.1$ . (D) Kaplan-Meier curves indicated that the high-risk group had a significantly worse OS compared to low-risk group in training and testing groups, respectively. (E) ROC curves demonstrated that prognostic risk score was able to predict the 1-, 3-, and 5-year survival of patients in training and testing groups, respectively. HR, hazard ratio; TCGA, The Cancer Genome Atlas; AUC, area under the curve; TPR, true positive rate; FPR, false positive rate; DEGs, differentially expressed genes; BRCA, breast cancer; LASSO, least absolute shrinkage and selection operator; SE, standard error; OS, overall survival; ROC, receiver operating characteristic.

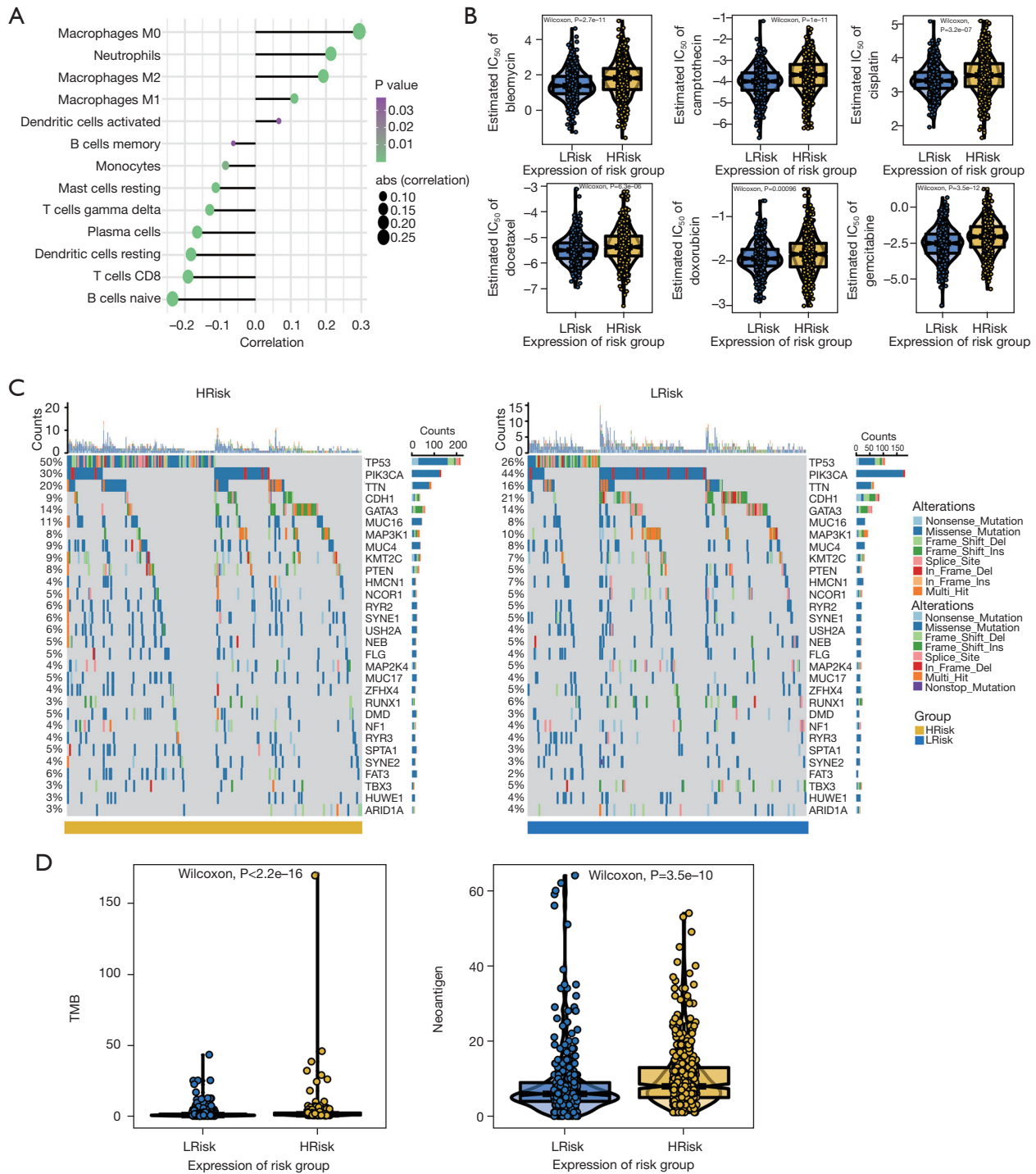
having a negative correlation with the risk score, indicating that BRCA patients in high-risk group had a lower drug sensitivity (Figure 4B).

We further explored the mutation profiles of patients in the high- and low-risk groups, and the results showed that the proportion of mutations in genes such as TP53 was significantly higher in the high-risk group than in the low-risk group (Figure 4C). Further, the tumor mutational burden (TMB) and neoantigen in high-risk group were significantly higher than low risk groups (Figure 4D). Taken together, this model had a good clinical predictive value.

### Robust analysis of the prognostic model for BRCA

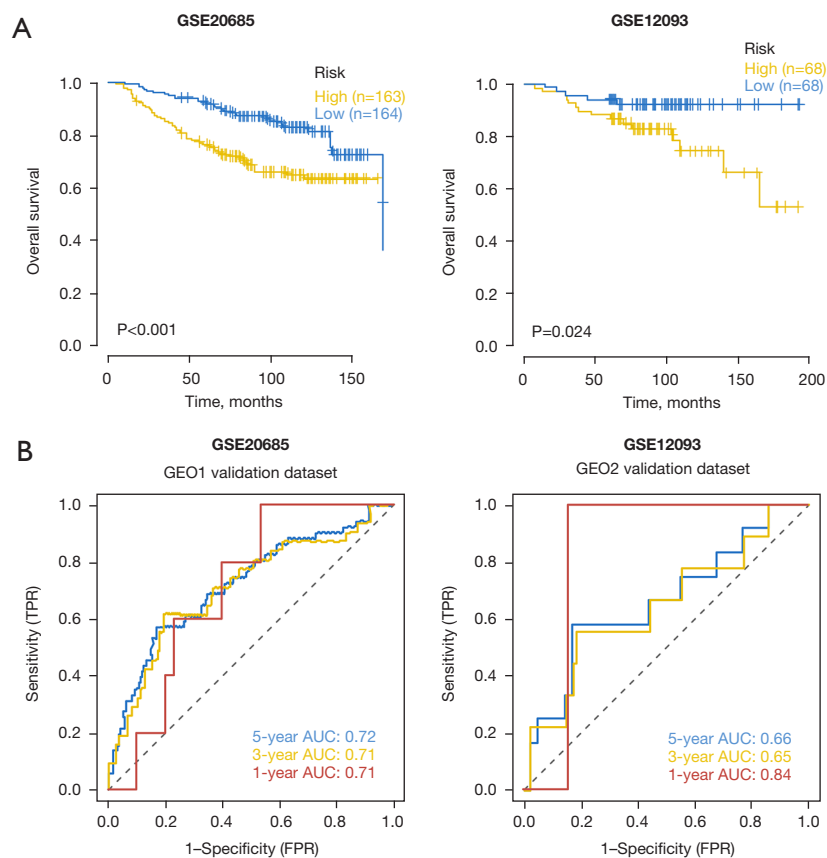
The data used for validating the prognostic model were

processed data of BRCA patients with survival data in the GEO database (GSE20685 and GSE12093). Based on the model, clinical staging of BRCA patients in the GEO database was predicted and survival differences between the high- and low-risk groups were assessed using Kaplan-Meier analysis. The OS of the high-risk group in two data sets was significantly lower than that of the low-risk group (Figure 5A). ROC curve analysis was performed to verify the predictive accuracy of the model. The results showed the AUC values of 1-, 3-, and 5-year in GSE20685 data set were not less than 0.70, and the AUC values of 1-, 3-, and 5-year in GSE12093 data set were not less than 0.65, indicating that the model had strong predictive efficacy for patient prognosis (Figure 5B).



**Figure 4** Multi-omics analysis of clinical predictive value. (A) Correlation between risk score and infiltrating immune cells in BRCA were analyzed. (B) Chemotherapy IC<sub>50</sub> of bleomycin, camptothecin, cisplatin, docetaxel, doxorubicin, gemcitabine in high-risk and low-risk groups was estimated. (C) Waterfall plot (oncplot) showed the distribution of mutations in high-risk and low-risk groups. (D) TMB and neoantigen in high-risk group were significantly higher than low risk groups. TMB, tumor mutational burden; BRCA, breast cancer; IC<sub>50</sub>, half maximal inhibitory concentration.





**Figure 5** ROC curves and Kaplan-Meier curves of the high- and low-risk groups classified by the prognostic risk score. (A) Kaplan-Meier curves indicated that the high-risk group had a significantly worse OS compared to low-risk group in GSE20685 and GSE12093 databases, respectively. (B) ROC curves demonstrated that prognostic risk score was able to predict the 1-, 3-, and 5-year survival of patients in GSE20685 and GSE12093 databases, respectively. AUC, area under the curve; ROC, receiver operating characteristic; OS, overall survival.

### Analysis of independent prognostic factor

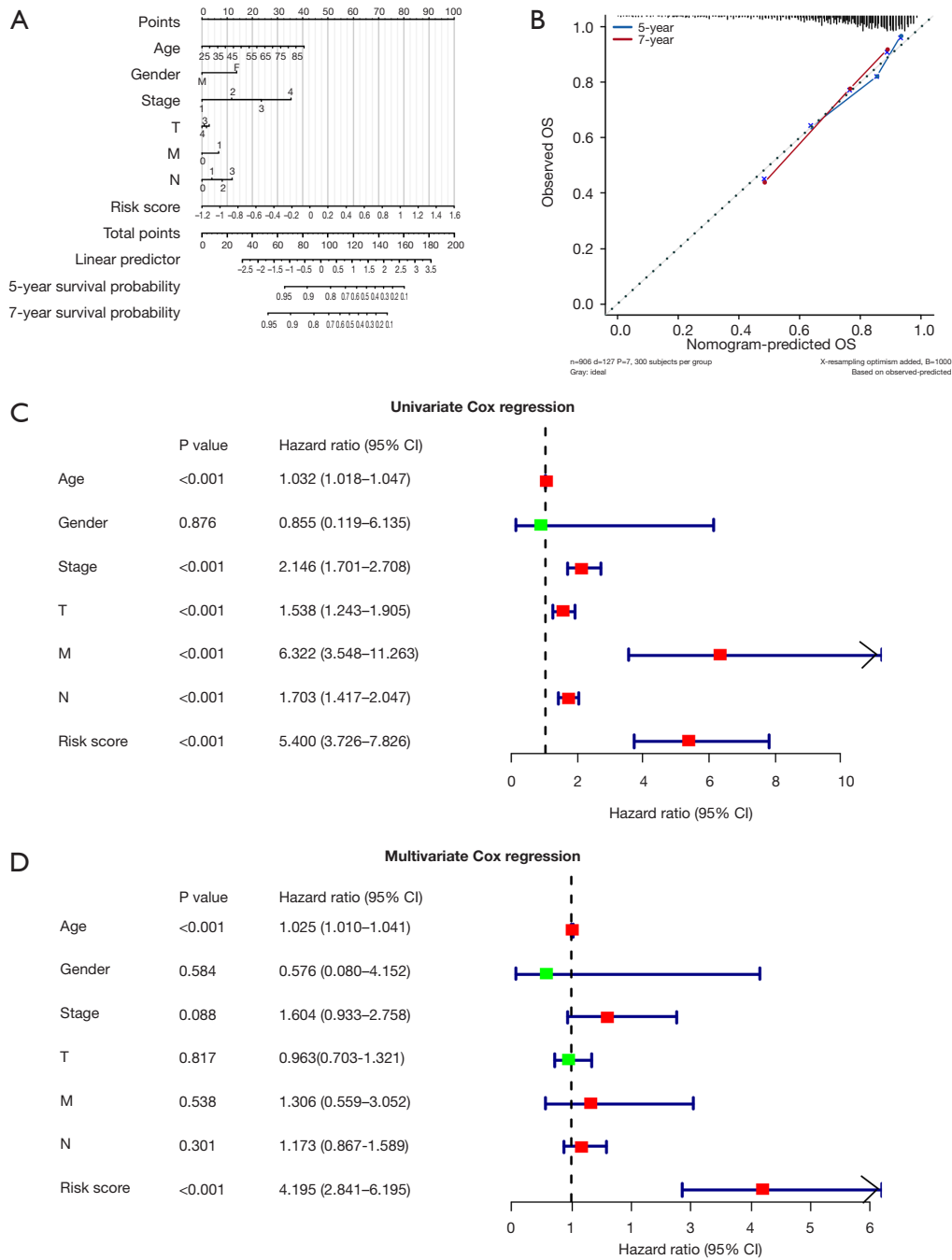
To analyze the independent prognostic factor for BRCA patients, we built the multivariable logistic regression prediction model based on integrating clinical information and the risk scores of patients in the high and low-risk groups and used the nomogram to visualize the model (Figure 6A). The total points were summated by adding each point of age, gender, stage, TMN classification, and risk score, respectively, and we found that the clinical indicators and risk score values all contributed to the total point. The calibration curves of 5- and 7-year survival demonstrated favorable prediction performance of nomogram (Figure 6B). Univariate Cox regression analysis and multivariate Cox regression analysis results demonstrated that age and risk score were the independent prognostic factors for BRCA patients (Figure 6C,6D).

### Relationship between risk score and clinical parameters

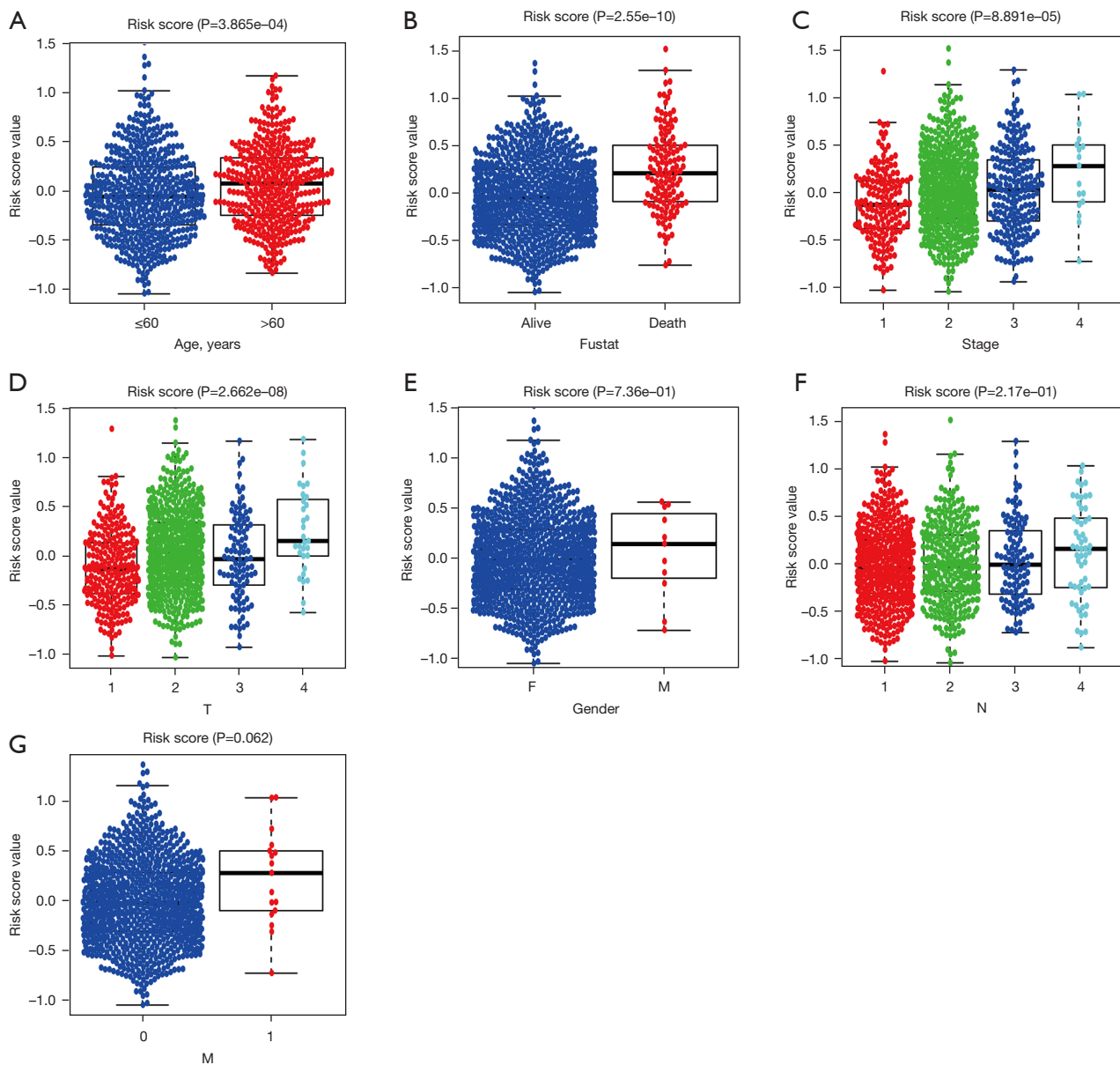
To further understand the relationship between the risk score and other clinical data, we grouped the risk score values of all samples by different clinical parameters, and found that the risk score was significantly associated with age (Figure 7A), fustat (Figure 7B), clinical-stage (Figure 7C) and the extent of the tumor (T, Figure 7D) (all  $P < 0.001$ ), but not with gender (Figure 7E), the extent of spread to the lymph nodes (N, Figure 7F) classification and the presence of metastasis (M, Figure 7G) classification.

### Identifying potential biological pathways associated with BRCA

We then used GSVA to reveal the pathways associated with the progression of BRCA based on the TGCA database.



**Figure 6** Nomogram predicting OS in BRCA patients based on risk score. (A) Nomogram model was used to predict the probability of 5- and 7-year OS of BRCA. Points were assigned for seven features. The sum of these points was located on the total point axis. The total points axis contained the sum of these points. The bottom scales' total points corresponded to BRCA's predicted 5- and 7-year OS. (B) Calibration curve of 5- and 7-year survival was showed in the nomogram model. X-axis indicated nomogram predicted survival, and Y-axis indicated actual survival. (C,D) The univariate and multivariate Cox regression analyses verified the independent value of prognostic model for BRCA. Point estimates and associated P-values for covariates are shown. CI, confidence interval; OS, overall survival; BRCA, breast cancer.

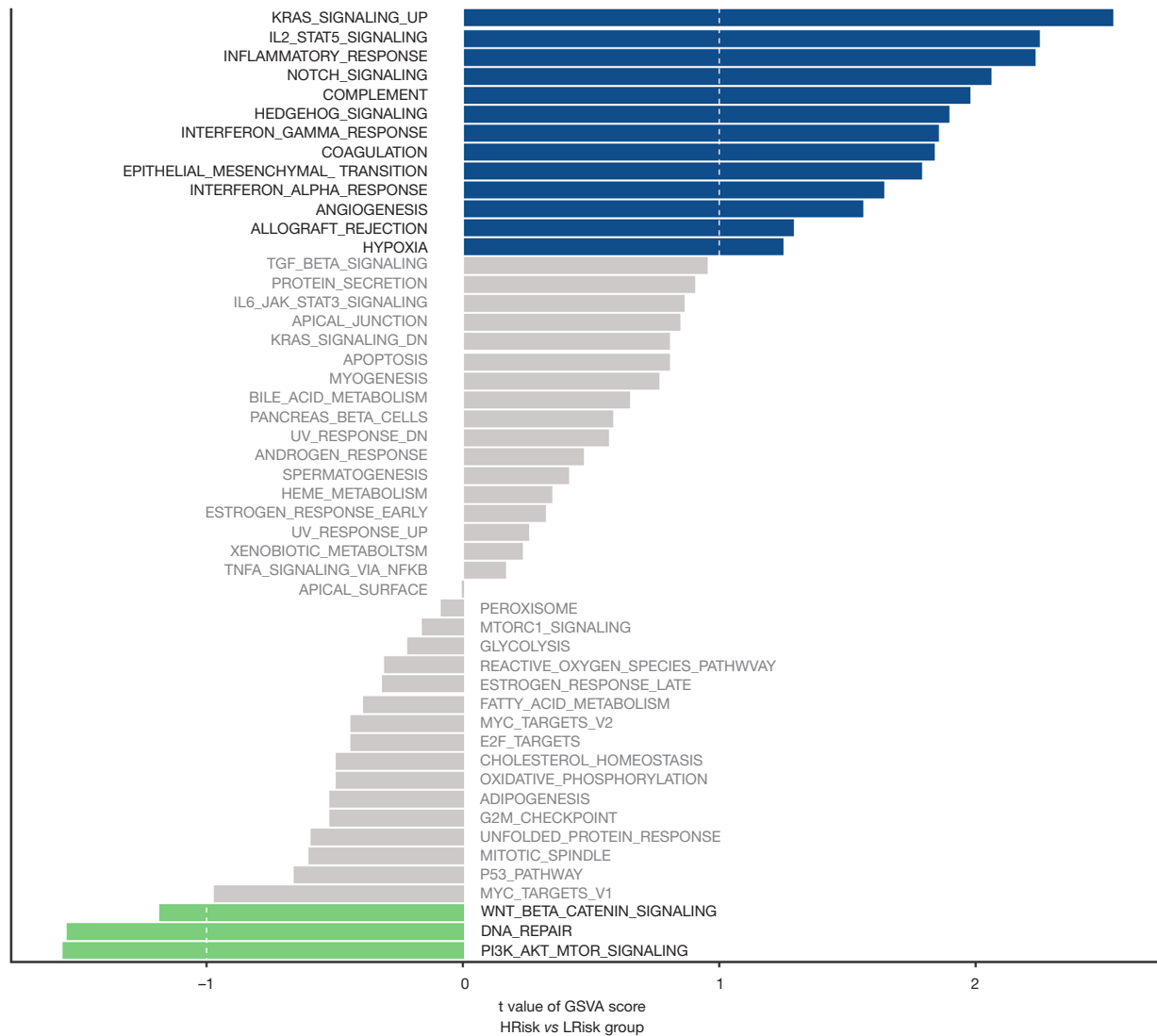


**Figure 7** The correlation analyses between clinical parameters and the risk score. (A-G) The Wilcoxon rank-sum test showed that the risk scores of BRCA patients were significantly related to age (A), fustat (B), clinical stage (C), and T classification (D), but not gender (E), N classification (F), and M classification (G). F, female; M, male; BRCA, breast cancer.

The data showed that signaling pathways converging at various biological processes were significantly different between low-risk and high-risk groups (Figure 8). The high-risk group was more likely to be related to KRAS signaling, IL2-STAT5 signaling, inflammatory response, Notch signaling, complement, hedgehog signaling, interferon- $\gamma$  (IFN- $\gamma$ ) response, coagulation, EMT, interferon- $\alpha$  (IFN- $\alpha$ ) response, angiogenesis, allograft rejection, hypoxia;

while the low-risk was preferentially related to P13K-AKT-mTOR signaling, DNA repair, and Wnt signaling, indicating that disruption of these signaling pathways in BRCA patients would affect their prognosis.

GSEA analysis was conducted to identify significant enrichment patterns using the TGCA database. GO pathway enrichment analysis revealed that the 677 DEGs were enriched in female meiotic nuclei division, meiotic I



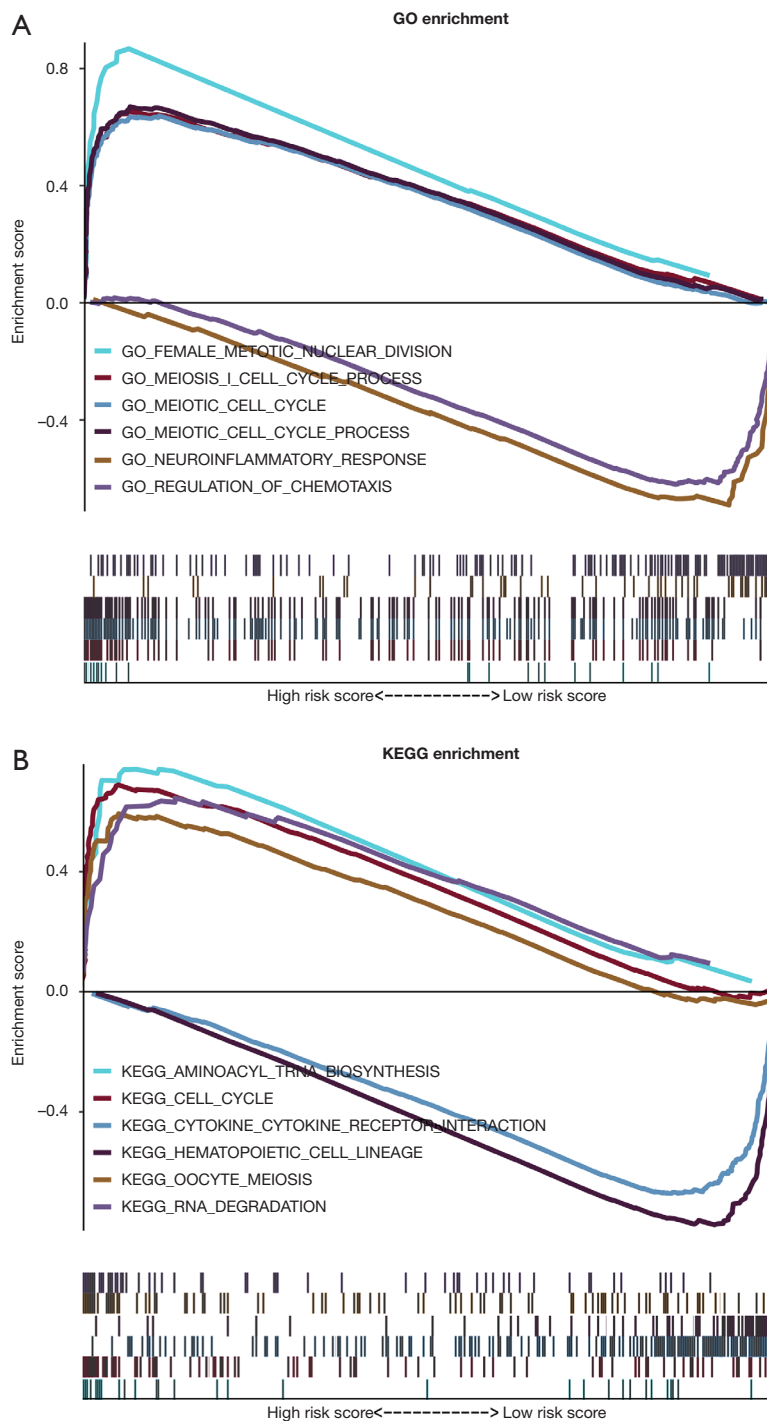
**Figure 8** GSVA analysis revealing potential biomarker pathway. Differences in pathway activities was scored by GSVA between high-risk and low-risk groups. T values were shown from a linear model. We set  $|t| > 1$  as a cutoff value. The blue column indicated activated pathways in high-risk, the green column indicated activated pathways in low-risk, and the gray column indicated pathways with  $|t| < 1$ . GSVA, gene set variation analysis.

cell cycle, meiotic cell cycle, neuroinflammatory response, and regulation of chemotaxis (Figure 9A). KEGG pathway enrichment results revealed these genes were enriched in aminoacyl tRNA biosynthesis (ARS), cell cycle, cytokine-cytokine receptor interactions, hematopoietic cell lineage, and RNA degradation (Figure 9B).

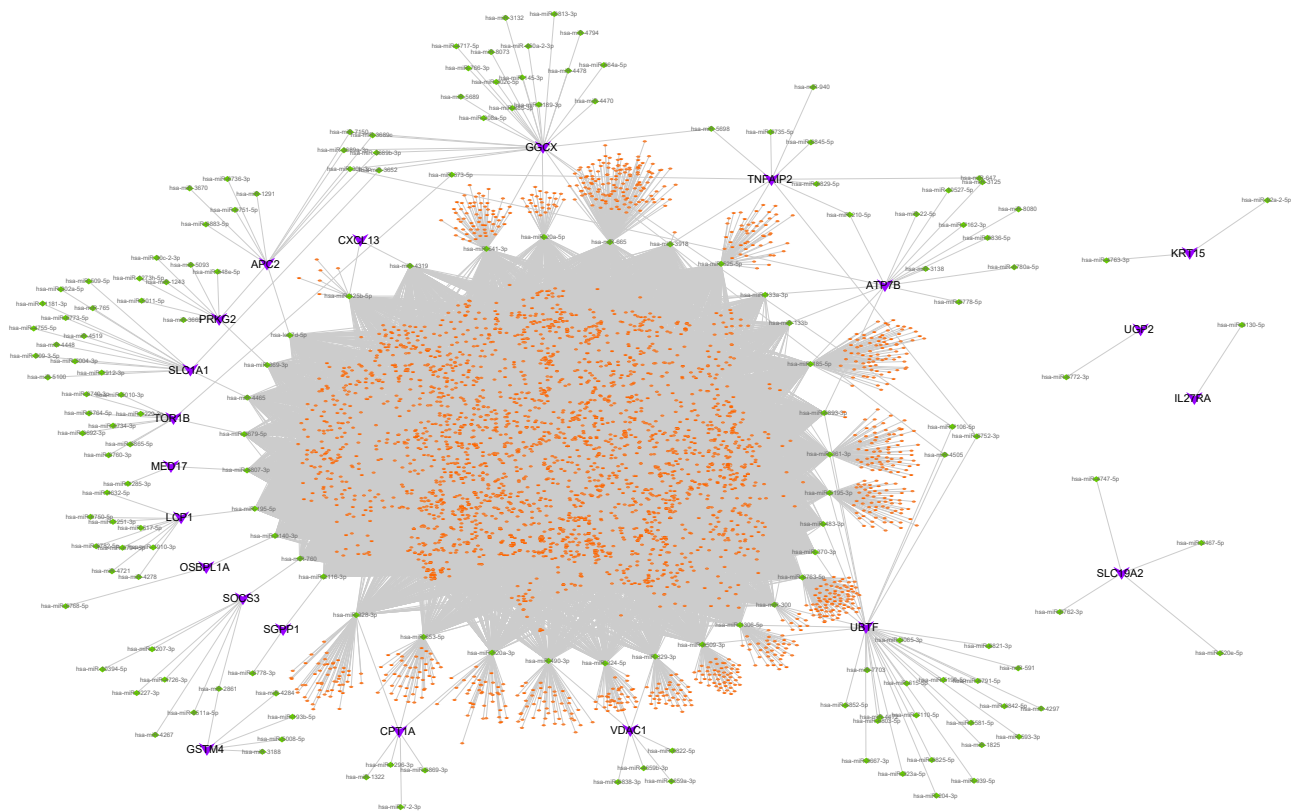
### Predicting mRNA-miRNA-lncRNA interaction

miRNAs and lncRNAs play critical roles in the progression

of BRCA (20-22). Therefore, we conducted a competitive endogenous RNA (ceRNA) network to visualize the mRNA-miRNA-lncRNA interaction. The miRWalk database and the ENCORI database were used to predict miRNA-binding sites and lncRNA-binding sites of these 28 genes. With the miRWalk database, 347 mRNA-miRNA pairs (accessibility  $< 0.001$  and TargetScan of 1 or miRDB of 1) were identified, including 21 mRNAs and 168 miRNAs. Next, these miRNAs were used to predict reciprocal lncRNAs using ENCORI database, and a total of



**Figure 9** GSEA enrichment plots (GO-base and KEGG-base). (A) Enriched pathway was analyzed by the GSEA based on GO. (B) Enriched pathway was analyzed by the GSEA based on KEGG. ES >0 represented that the distribution of the gene set was biased upstream of the ranking list, and ES <0 indicated the gene set distribution was biased downstream of the ranking list. GSEA, gene set enrichment analysis; GO, Gene Ontology; KEGG, Kyoto Encyclopedia of Genes and Genomes; ES, enrichment score.



**Figure 10** CeRNA regulation network of mRNA-miRNA-lncRNA interaction. A total of 347 mRNA-miRNA pairs (including 21 mRNAs and 168 miRNAs) and 13,766 mRNA-miRNA-lncRNA pairs (including 34 miRNAs and 4,040 lncRNAs) were predicted. The red diamonds indicated lncRNAs, green diamonds indicate miRNAs, and the purple diamonds indicated mRNAs. CeRNA, competitive endogenous RNA; lncRNA, long noncoding RNA; miRNA, microRNA; mRNA, messenger RNA.

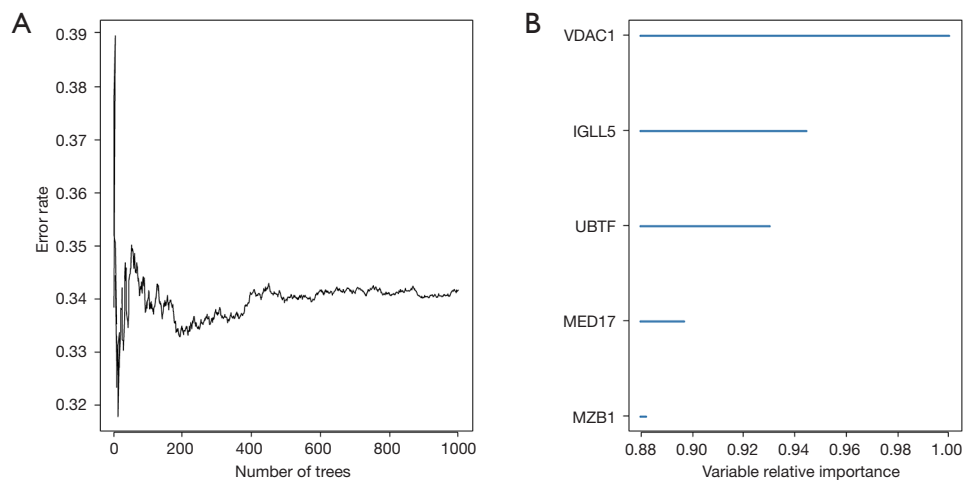
13,766 miRNA-lncRNA pairs were predicted (including 34 miRNAs and 4,040 lncRNAs). The CeRNA network was constructed by Cytoscape (v3.7) (Figure 10).

### Identification of key genes via RSF analysis

Sensitivity analyses were conducted by the tree number in the RSF model and the derived variable importance ranking (Figure 11A). In our study, genes with relative importance greater than 0.8 were considered as the ultimate marker genes (Figure 11B). The key genes that were associated with prognosis of BRCA included voltage-dependent anion-selective channel 1 (*VDAC-1*), immunoglobulin lambda like polypeptide 5 (*IgLL5*), upstream binding transcription factor (*UBTF*), mediator complex subunit 17 (*MED17*), and marginal zone B and B1 cell specific protein (*MZB1*).

### Discussion

BRCA is the most commonly occurring cancer in women and the second most common cancer overall (2). Even though women with non-metastatic invasive BRCA have a 5-year survival rate of up to 90%, women with distant metastatic invasive BRCA have a 5-year survival rate of only 30–40% (5,6). Most of the patients still have poor prognoses after metastasis. Bone is the most common site of metastasis for BRCA (7–9). A prognostic model based on multiple predictors can be used to predict the risks of a specific endpoint for individual patients. Many prognostic models for BRCA have been developed, but only a few have been extensively validated in various settings (23). Furthermore, their performance is suboptimal in independent populations, particularly in patients with high risk and in young and elderly patients (23). Therefore, we developed a prognostic score model for prognostic prediction in BRCA based on



**Figure 11** Identifying important gene by RSF. (A) Optimal tree number selection and (B) variable importance ranking for RSF model was used to predict important gene in BRCA. RSF, random survival forest; BRCA, breast cancer.

the genes associated with bone metastasis of BRCA and externally validated the reproducibility and generalizability of this prognostic model.

Based on the analysis of expression profile data of 326 patients from GSE2034, GSE124647, and GSE39494 BRCA-related databases, a total of 677 DEGs (379 upregulated genes and 298 downregulated genes) were preliminarily screened by Combat-seq correction, and 77 DEGs were identified by univariate Cox regression, with P value of  $<0.01$  between BRCA with metastasis and without metastasis. A total of 28 of these genes (such as *SGPPI*, *CXCL13*, and *TFF1*) ultimately performed better in the LASSO Cox regression model for variable compression and were used to establish an optimal prognostic score model. A recent study showed a potential role of sphingosine-1-phosphate phosphatase 1 (*SGPPI*) in driving the metastasis of BRCA into the bone microenvironment through the IL22R1-S1PR1 axis (24). Chemokine C-X-C motif ligand 13 (*CXCL13*) can target BRCA cells to promote proliferation, migration, and invasion (25,26). Furthermore, upregulation of trefoil factor-1 (*TFF1*) in estrogen-receptor (ER) positive BRCA is associated with a higher risk of bone metastasis (27). The risk score value for each sample by LASSO regression analysis based on these genes was obtained, and we divided these BRCA patients into two groups based on a median risk score. The high-risk group showed a significantly worse OS compared to the low-risk group. ROC curve analysis revealed that the model had high training/testing accuracy.

The clinical predictive value of the prognostic model for

BRCA was further evaluated using multi-omics analysis. Although BRCA has been viewed as a relatively non-immunogenic cancer, the BRCA TME is rich in immune infiltrates with distinct functions and varies according to tumor subtypes (28,29). Recent advances in immunoncology have revealed prognostic and predictive values for tumor-infiltrating lymphocytes (TILs) in BRCA, especially in patients with hormone receptor negative subtype. Higher tumor-infiltrating B cells, tumor-infiltrating T cells, and dendritic cells represent a favorable prognosis, while high tumor-associated macrophages (TAM) and *neutrophil* infiltration promote progression in BRCA (30-34). Similar to the above studies, after analysis of the relationship between risk score and tumor-infiltrating immune cells, we found that risk score was significantly positively correlated with TAM and neutrophils, and negatively correlated with B cells, T cells, and dendritic cells. Meanwhile, TME is of prime importance in clinical settings due to the development of drug resistance and recurrence of BRCA by inducing genes involved in self-renewal. Based on drug sensitivity data from the GDSC database, we found that high-risk group had a higher IC<sub>50</sub> of Bleomycin, Camptothecin, Cisplatin, Docetaxel, Doxorubicin, and Gemcitabine, indicating that BRCA patients in high-risk group presented low sensitivity to these drugs. Moreover, TMB is associated with high neoantigen burden and helps predict responses to certain cancer immunotherapies. In addition, high TMB is associated with better response rates to immunotherapies in melanoma, non-small cell lung cancer (NSCLC) and urothelial cancer (35-38). In

this study, we found that TMB and neoantigen in the high-risk group were significantly higher than in low-risk group, this may be because high TMB is more common in metastatic BRCA (39). All these data suggested that based on the predicting model, BRCA patients with high-risk score exhibited features of poor prognosis, indicating that this model had a good clinical predictive value. To validate the robustness of the prognostic model, we downloaded the processed data of BRCA patients with survival information. Based on this model, high-risk patients had a worse OS. Further, the ROC curve analysis revealed that this model had strong predictive efficacy for patient prognosis. Through multivariate Cox regression analysis, we were able to conclude that our prognostic model was efficient and independent of other clinical factors, such as age, gender, clinical stage, and TNM classification. The nomogram model incorporating these factors exhibited better discrimination ability for predicting prognosis in BRCA patients. Therefore, the model may provide a promising method for distinguishing the high-risk BRCA patients and help guide the stratified treatment of BRCA patients.

The prognostic biomarker pathways of BRCA were screened. The results of GSVA showed that different signal pathways were activated in different risk groups of BRCA. Being consistent with existing reports, our study indicates that KRAS signaling, IL2-STAT5 signaling, Notch signaling, and hedgehog signaling play important roles in BRCA metastasis (40-44). GSEA analysis showed significantly increased expression of genes in the high-risk group, mainly involving the meiotic nuclear division, meiosis I cell cycle, and meiotic cell cycle. The miRNAs and lncRNAs also play critical roles in the progression of BRCA through a variety of biological effects and mechanisms (20-22). Aco-expression network of the 28 genes-related mRNAs and lncRNAs was constructed in this study, and most nodes in the network were reported for the first time. Then, RSF revealed that the key genes that were associated with the prognosis of BRCA included *VDAC-1*, *IGLL5*, *UBTF*, *MED17*, and *MZB1*, with a relative importance >0.8. Among them, *VDAC1*, *MED17*, and *MZB1* are unfavorable and associated with poor prognosis in BRCA, while *IGLL5* was identified as the best predictor of relapse-free survival with >85% accuracy (45-49). Although experimental validation has not been conducted, the above results provide potential targets for future treatment of BCRA patients with bone metastasis.

## Conclusions

In conclusion, 677 genes related to BRCA bone metastasis were screened by DEGs analysis based on public databases. Based on the univariate Cox regression and LASSO-Cox regression model analysis, we developed a prognostic model consisting of 28 prognostic DEGs, which can help distinguish the high-risk BRCA patients. The predictive efficacy of our prognostic model was further tested by external validation cohorts. Furthermore, the 28 signature genes-based predictive model and nomogram might be useful for prognostic prediction for BRCA patients. The prognostic prediction model of BRCA in this study can provide a promising method for clinical helping on clinical decision making and prognosis prediction for BRCA patients. Meanwhile, screening for prognostic biomarker genes and pathways in BRCA may provide potential therapeutic targets for future treatment.

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## Footnote

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