



OPEN The role of hypoxia-senescence co-related molecular subtypes and prognostic characteristics in hepatocellular carcinoma

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Hepatocellular carcinoma (HCC) is known for its high invasiveness, high fatality rate. Both hypoxia and senescence play crucial roles in the initiation and progression of cancer, yet their prognostic implications in HCC are yet to be fully understood. The hypoxia-senescence co-related genes (HSCRGs) were screened from public databases. Transcriptome data and clinical information were obtained from patients with HCC using the Cancer Genome Atlas, GSE76427, and International Cancer Genome Consortium (ICGC). The random forest tree algorithm was used to identify the characteristic genes of the disease, and the genes were verified by related experiments. SVM algorithm was used to classify HCC patients based on HSCRGs. The prediction model based on HSCRGs was established by LASSO, univariate and multivariate COX regression analysis. We used the ICGC for outside validation. The risk score model was analyzed from subgroup analysis, immune infiltration, and functional strength. The expression patterns of key prognostic genes in tumor microenvironment were decoded by single cell analysis. A total of 184 HSCRGs were identified. The expression pattern and functional characteristics of MLH1 gene in HCC were verified. Two HCC subtypes were identified based on HSCRGs. Then, a prediction model based on HSCRGs was established, and risk score was identified as an independent prognostic indicator of HCC. A new nomogram is constructed and shows good prediction ability. We further determined that the level of infiltration of immune cells and the expression of immune checkpoints are significantly affected by the risk score. The immune microenvironment was different between the two risk groups. The high-risk group was dominated by immunosuppressed cells, and the prognosis was poor. Single-cell analysis revealed the expression of seven key prognostic genes in the tumor microenvironment. Finally, qPCR results further verified the expression levels of seven prognostic genes. HSCRGs are of great significance in the prognosis prediction, risk stratification and targeted therapy of patients with HCC.

Keywords Hepatocellular carcinoma, Hypoxia, Senescence, Molecular subtypes, Prognostic risk model, MLH1

Abbreviations

HCC	Hepatocellular carcinoma
HSCRGs	Hypoxia-senescence co-related genes
TCGA	The Cancer Genome Atlas
GEO	Gene Expression Omnibus
ICGC	International Cancer Genome Consortium
CNV	Copy number variation

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DEGs	Differentially expressed genes
GO	Gene Ontology
KEGG	Kyoto Encyclopedia of Genes and Genomes
ssGSEA	Single-sample gene set enrichment analysis
TIMER	Tumor Immune Estimation Resource
PCA	Principal component analysis
RS	Risk score
PFS	Progression-free survival
ROC	Receiver operating characteristic
AUC	Area under the curve
HPA	Human Protein Atlas
qPCR	Quantitative real-time PCR
SDS-PAGE	Sodium dodecyl sulfate–polyacrylamide gel electrophoresis
PVDF	Polyvinylidene difluoride
CCK-8	Cell Counting Kit-8
PFA	Paraformaldehyde
CVSS	Crystal violet staining solution
DMEM	Dulbecco's Modified Eagle Medium
FBS	Fetal bovine serum
ANOVA	Analysis of variance
K-M	Kaplan–Meier
MDSCs	Myeloid-derived suppressor cells
Tregs	Regulatory T cells
NK cells	Natural killer cells
RNAss	RNA stemness score
SPP1	Secreted phosphoprotein 1
MK	Midkine

Hepatocellular carcinoma (HCC) accounts for nearly 80% of primary liver cancers and is the third most common cause of cancer-related deaths globally^{1,2}. Owing to the early symptoms are not obvious, most patients with HCC are already in the advanced stage when diagnosed³. This makes the chance of surgical eradication small⁴. In recent years, with the development of immunotherapy, it plays a very important role in the treatment of tumors⁵, especially in the treatment of advanced HCC⁶, there is a consensus of the latest guidelines that atezolizumab plus bevacizumab has become the first-line preferred regimen for advanced HCC⁷. Despite advancements in therapeutic approaches for HCC, the overall 5-year survival rate for HCC patients still remains below 20%⁸. Therefore, the identification of molecular biomarkers is critically significant for the early diagnosis, survival prognosis, and recurrence monitoring of HCC⁹.

Hypoxia represents an inherent characteristic of solid tumors, arising from the imbalance between the proliferation rate of tumor cells and the vascular nutrient supply¹⁰. Existing research has recognized the crucial role of hypoxia in tumor angiogenesis, cell proliferation, cellular differentiation, and apoptosis^{11,12}. However, the underlying regulatory mechanisms still remain unclear. Hypoxia-inducible factor (HIF), a key transcription factor expressed across nuclear cells, becomes upregulated under hypoxic conditions and serves a pivotal role in regulating cellular senescence¹³. Study also suggests that intermittent hypoxia is linked to oxidative stress and chronic inflammation, thus accelerating the cellular senescence process¹⁴.

Cellular senescence is defined as the gradual decline in the normal physiological functions and proliferative capacity of cells over time or in response to external stress, resulting in an irreversible or persistent cell cycle arrest process^{15,16}. Notably, Carlos et al.¹⁷ identified 12 features of senescence, such as genomic instability and mitochondrial dysfunction, that are significantly associated with hypoxia, serving as either causes or consequences. The hypoxic microenvironment may protect tumors from natural antitumor immune responses by promoting immune evasion, thus modulating cellular senescence¹⁶. Furthermore, the incidence of cancer increases in the elderly population¹⁸. This indicates a potential connection between hypoxia, senescence, and cancer, where hypoxia contributes to both senescence and cancer. However, the prognostic role of hypoxia-induced senescence in HCC remains to be elucidated.

MutL homolog 1 (MLH1), the protein encoded by this gene can heterodimerize with mismatch repair endonuclease PMS2 to form MutL alpha, part of the DNA mismatch repair (MMR) system¹⁹. The encoded protein is also involved in DNA damage signaling and can heterodimerize with DNA mismatch repair protein MLH3 to form MutL gamma, which is involved in meiosis²⁰. This gene was identified as a locus frequently mutated in hereditary nonpolyposis colon cancer (HNPCC)¹⁹. Studies have shown that defects in the MMR genes, especially MLH1, can lead to genome-wide mutations and the development of cancer^{21–23}. Most of the studies on MMR and MLH1 gene focus on intestinal tumors, but their studies in HCC are still very limited and need to be further elucidated.

The aim of this study was to explore the molecular subtypes and prognostic characteristics of hypoxia-senescence co-related genes (HSCRGs) in HCC through the development of molecular subtyping and prognostic risk models. The findings could potentially contribute to clinical risk stratification and personalized treatment for HCC patients, thereby improving the prognosis of HCC patients.

Materials and methods

Data collection and identification of HSCRGs

In this study, a total of 478 HCC samples from two high-throughput platforms were included: 363 samples from TCGA (<https://tcga-data.nci.nih.gov/tcga/>) and 115 samples from GEO (GSE76427) (<http://www.ncbi.nlm.nih.gov/geo/>). The mRNA expression data and clinical information from the Japan-HCC cohort were downloaded at International Cancer Genome Consortium (ICGC, <https://dcc.icgc.org/projects/LIRI-JP>). Additional information, including somatic mutation data, copy number variations (CNV), clinical details, and survival data, was collected. All patients were required to have complete follow-up information and RNA-seq data. Patients with incomplete survival information were excluded from subsequent analyses. Subsequently, 308 senescence-related genes (SRGs) were obtained from the CellAge database (<http://genomics.senescence.info/cells/>, accessed on February 2, 2024). Additionally, a search with the keyword “hypoxia” in the GeneCards database (<http://www.genecards.org/>, accessed on February 2, 2024) under the filter condition of Relevance Scores > 1.5 yielded a total of 1603 hypoxia-related genes (HRGs). Intersection of these sets using Venn diagram resulted in 184 HSCRGs (Table S1). The single-cell RNA seq (scRNA-seq) data of 4 HCC patients were obtained from GSE146115 in the GEO database, with a total of 3200 cells obtained. Table S2 presents baseline characteristics of these cohorts.

Unsupervised clustering based on HSCRGs

The R package “ConsensusClusterPlus”²⁴ was utilized for hierarchical agglomerative clustering of samples. Unsupervised analysis incorporated stability evidence to ascertain cluster count and membership. This iterative process was repeated 1,000 times to ensure clustering stability.

Gene enrichment analysis

The Gene Ontology (GO) and Kyoto Encyclopedia of Genes and Genomes (KEGG) gene enrichment analysis was used to explore the relevant cytological functions and pathways of DEGs^{25–27}. q -value < 0.05 was the cutoff criterion for determining whether a gene is significantly enriched.

Immune cell infiltration and immune function analysis

We employed the “GSVA” R package to perform single-sample gene set enrichment analysis (ssGSEA) for the quantitative assessment of immune cell infiltration and immune functionality in each sample. Additionally, 48 immune checkpoints from prior studies were incorporated²⁸. The stromal/immune/estimate scores were computed using the “estimate” R package. Further analysis of the correlation between the expression of HLA-DPA1/CD4 in different immune cell types and marker genes was conducted using the Tumor Immune Estimation Resource (TIMER) database (timer.comp-genomics.org), accessed on February 22, 2024. The TIMER offers 6 main analysis modules that allow users to interactively explore the association between immune infiltration and a variety of factors, including gene expression, clinical outcomes, somatic mutations, and somatic copy number alterations²⁹. Stemness Score (RNAss) was downloaded from the Pan-Cancer Atlas Center at <https://pancanatlas.xenahubs.net>.

Identification of differentially expressed genes between hypoxia and senescence co-related Subtypes

The “Limma” R package³⁰ was employed to detect differentially expressed genes (DEGs) among distinct HSCRGs subtypes, considering an adjusted p -value threshold of < 0.01 (adjusted for multiple testing using the Benjamini–Hochberg correction method). The overlapping set of DEGs between the two groups was then identified, and their expressions across all samples were extracted for further analysis.

Screening of disease characteristic genes using the random forest algorithm

In this study, we employed the random forest model for gene selection³¹. To ensure the stability and convergence of the model, the number of trees (ntree) was set to 500. Additionally, other hyperparameters were configured as follows: the maximum number of features (max_features) was set to “sqrt”, meaning that the number of features considered at each split is the square root of the total number of features; the minimum number of samples required to split an internal node (min_samples_split) was set to 2; and the minimum number of samples required in a leaf node (min_samples_leaf) was set to 1. The importance score, measured by Mean Decrease Gini, was utilized to identify genes critical for disease classification. The parameter settings were determined based on default configurations and preliminary experimental results, ensuring optimal model performance while mitigating the risk of overfitting.

Construction of the HSCRGs-based prognostic risk model

A training dataset ($n = 239$) and a test dataset ($n = 239$) were randomly selected from a pool of 478 patients in a 1:1 ratio, so as to prevent overfitting, select the optimal model and parameters, and provide a reliable assessment of the generalization ability of the model. In the training cohort, we utilized the “survival,” “glmnet,” “survminer,” and “timeROC” R packages to perform univariate and multivariate Cox regression analyses, and employed LASSO regression to construct the risk score. In the LASSO regression model, we utilized the R package “glmnet” for feature selection and model construction³². Specifically, we determined the optimal lambda value via tenfold cross-validation to ensure that the model avoided overfitting while retaining the most predictive genes. During the cross-validation process, the lambda value corresponding to the minimum cross-validation error was selected. Additionally, the alpha parameter was set to 1 to enforce the L1 regularization property of LASSO regression, enabling sparse feature selection. Initially, univariate Cox regression analysis was conducted to identify genes significantly associated with prognosis ($P < 0.05$, adjusted for multiple testing using the Benjamini–Hochberg correction method). Subsequently, these genes were subjected to LASSO regression analysis, with the optimal

model parameters selected through tenfold cross-validation. Following this, multivariate Cox regression analysis was performed to establish the risk score, which was determined based on the minimum Akaike Information Criterion (AIC) value. A lower AIC value indicates a more accurate model³³. The risk score was formulated as a predictive factor, represented by the sum of coefficients and associated genes: Risk score^{20,23,24} = $\sum_{i=1}^n \text{Coef}_i \times X_i$. Where Coef_i is the correlation coefficient of the prognostic key genes, and X_i signifies the expression of the prognostic key genes. Lastly, multivariate Cox proportional hazards regression analysis was executed to identify crucial clinical phenotypes.

Validation of the HSCRGs-based risk score

To evaluate the generalizability of our model, we employed both a test set and an external validation dataset. Specifically, we validated the model's generalizability by applying the risk score to the LIRI-JP dataset from the ICGC database, which comprises survival status and survival time data from 231 HCC patients. We reviewed prognostic signatures developed by various researchers in recent years, including anoikis-related gene signatures³⁴, methylation-related gene signatures³⁵, immune-related gene signatures³⁶, and ferroptosis-related gene signatures³⁷. Additionally, we conducted a C-index comparison, where the C-index ranges from 0.5 to 1, with values closer to 1 indicating higher predictive accuracy.

Quality control and single-cell RNA-seq analysis

To investigate tumor cell heterogeneity in HCC cells, we incorporated single-cell RNA sequencing data from GSE146115. Quality control (QC) procedures were conducted using the R package “Seurat”. Single cells were deemed low-quality and subsequently removed if they exhibited fewer than 50 unique molecular identifiers (UMIs) or if mitochondrial-derived UMI counts exceeded 5%. Patient batch effects were normalized using the integration function within “Seurat”. The top 1500 variable genes were selected for further analysis. Subsequently, principal component analysis (PCA) and t-distributed stochastic neighbor embedding (t-SNE) were employed to process the data, with major cell clusters visualized in two-dimensional t-SNE plots³⁸. We employed the FindAllMarkers function to identify the markers of each cell cluster. The R package “SingleR” is used for the annotation of different cell types³⁹. Finally, the R packages “CellChat”⁴⁰ and “patchwork” were used for intercellular communication analysis and network visualization.

Human protein atlas (HPA)

Cancer tissue microarray sections were obtained from HPA (<https://www.proteinatlas.org/>) for immunohistochemical staining, and the corresponding slides were digitally scanned to generate images. All relevant immunohistochemistry results in this study are from the HPA database.

Cells culture and establishment of stably transfected cells

One strain of normal human liver cells (LO2) and three strains of human liver cancer cell lines (Hep 3B, HepG2, and Huh-7) were provided by the State Key Laboratory of Cellular Stress Biology at the School of Life Sciences, Xiamen University. Each cell line was cultured in its specific culture medium. MLH1 was knocked down with pPLK-CMV-MLH1-sh1-GFP-Puro plasmid (MLH1). pPLK-CMV-GFP-Puro plasmid was used as control (NC). The plasmids were purchased from GenePharma (Shanghai, China), and the whole constructs were verified by sequencing. Briefly, Hep 3B cells were placed in 6-well plates overnight and then transfected with pcDNA3.1/MLH1-sh1 and pcDNA3.1/MLH1-sh2 plasmids and pcDNA3.1/NC plasmid using LipoMax reagent (SUDGEN, China) according to the supplier's instructions. Twenty-four hours after transfection, cells were selected with 1 µg/ml puromycin (Invitrogen, USA) for 14 days. Stable colonies were screened and stored in 1 µg/ml puromycin.

Quantitative real-time PCR

Total RNA extracts were prepared from cells and tissues using TRIzol reagent, followed by reverse transcription into cDNA for qRT-PCR. After obtaining the CT values for the target samples, the relative expression levels of the target genes were calculated using $2^{-\Delta\Delta Ct}$, with normal liver cells and adjacent tissues serving as controls. Human ACTB or GAPDH was utilized as the reference gene. The primer sequences were synthesized by QIAGEN Biotech Co., Ltd. (Xiamen Synthesis Department), as detailed in Table S3.

Western blot

The protein was transferred onto a polyvinylidene difluoride (PVDF) membrane (Millipore, Billerica, MA, USA) following 10% SDS-PAGE electrophoresis. After blocking with 5% skim milk for 1 h, the membrane was incubated overnight at 4 °C with MLH1 antibody (diluted to 1:1000; #ab131924, Abcam, USA) and β-actin antibody (diluted to 1:1000; #ab115777, Abcam, USA). Subsequently, the membrane was incubated at room temperature for 1 h with secondary antibodies conjugated to enzymes. The blot signal was detected using an enhanced chemiluminescence reagent (Advansta, USA).

Cell counting Kit-8 assay

The growth of Hep 3B cells was assessed using the CCK-8 assay kit (APExBIO, USA). A total of 2000 cells were seeded per well in a 96-well plate with 100 µL of culture medium and incubated for a duration of 4 days.

Colony formation assay

Transfected Hep 3B cells are grown in 6-well plates (500 cells per well) and cultured for approximately 14 days. The medium was changed every 3 days. The cells were then fixed with 4% PFA and stained with 0.1% CVSS for 20 min. After rinsing with PBS, colony formation was photographed and counted.

Flow cytometry analysis of the cell apoptosis

Following a 48-h period of Hep 3B cells transfection and incubation, the cells were carefully washed and subsequently collected in flow cytometry tubes. Staining was performed in strict accordance with the instructions provided by the reagent manufacturer (YEASEN, #40305ES20, China), followed by detection using an advanced analytical flow cytometer (BD LSRFortessa™ X-20, USA).

Wound-healing assay

Hep 3B cells were seeded in a six-well plate and cultured overnight until confluence was achieved. Subsequently, the cells were gently scratched using a 200 µl pipette tip to create a wound, and the process of wound healing was monitored at both 0 and 48 h.

Cell migration and invasion assays

The stably transfected cells (Hep 3B) were seeded in transwell chambers (8 mm pore size, Corning, USA) containing 100 µl of serum-free DMEM medium. The lower chamber was filled with 600 µl of medium supplemented with 20% FBS. To evaluate cellular invasion capability, the transwell chambers were pre-coated with matrigel and after a further incubation period of 48 h, the invaded cells that traversed the membrane were stained using a solution of 0.1% crystal violet and subsequently quantified.

Statistical analysis

Biological information analyses were conducted using R version 4.3.2. Data are expressed as mean ± SD of three independent tests. Differences between experimental and control groups were compared by Student's t-test and one-way or two-way ANOVA. Survival rates were calculated by the K-M method. Results were analysed using GraphPad Prism 8.0. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$, ns, not significant.

Results

Study workflow

In this study, we integrated bioinformatics, machine learning, and experimental validation methodologies, as outlined in the accompanying flowchart (Fig. 1).

Genetic variation of HSCRGs in HCC

Using the “Venn” R package, 1603 hypoxia-related genes and 307 senescence -related genes were analyzed to identify 184 HSCRGs (Fig. 2a). Initially, widespread copy number variations (CNV) were observed on the chromosomes of HSCRGs (Fig. 2b). The analysis indicated that CNV is prevalent in HSCRGs associated with HCC. Over half of the HSCRGs exhibited copy number gains (Fig. S1), with SHC1 and TP73 being the most common genes associated with copy number gains and losses, respectively. Subsequently, we investigated the differential expression of these genes and identified 20 genes significantly upregulated in cancer tissues (Fig. 2c). Univariate COX and correlation analysis were employed to study the interaction, association, and impact of these DEGs on disease prognosis. 16 genes were identified as risk factors ($HR > 1$), 3 genes as a protective factor ($HR < 1$), and they exhibited a positive correlation, significantly influencing HCC prognosis (all $P < 0.05$) (Fig. 2d), suggesting that they may contribute to the occurrence and development of HCC.

MLH1 was identified as a disease characteristic gene

In order to further screen disease characteristic genes, we used the random forest algorithm to analyze the above 20 differential genes, and the results showed that MLH1 was the most important for disease (Fig. 3a). Survival analysis showed that HCC patients with high MLH1 expression had significantly lower survival rates (Fig. 3b). qPCR results further verified that MLH1 was highly expressed in liver cancer cell lines, while it was low expressed in normal liver cells (Fig. 3c). Western blot results showed that the expression of MLH1 in malignant tumor cells was higher than that in normal cells (Fig. 3d). It can be seen that MLH1 is highly expressed in Hep 3B cells, therefore, we will use Hep 3B cells for our subsequent experiments. In addition, we searched the immunohistochemical staining results of MLH1 from the Human Protein Atlas (HPA) database, and also found that MLH1 protein was highly expressed in tumor tissues compared to normal tissues (Fig. 3e,f). Similarly, single-cell sequencing also showed that MLH1 was highly expressed mainly in liver malignant cells (Fig. 3g). These results indicate that MLH1 gene, as a co-related gene of hypoxia and senescence, is highly expressed in HCC and also predicts poor survival prognosis.

To elucidate the effect of MLH1 on HCC cells, we constructed two MLH1-targeting shRNA and transfected them into Hep 3B HCC cell lines. The efficiency of MLH1 knockdown was detected by qPCR and western blot (Fig. 4a,b). We found that MLH1 knockdown significantly inhibited the proliferation and clone formation capacity of Hep 3B cells in the CCK-8 and plate cloning experiments, respectively (Fig. 4c,d). The suppression of MLH1 expression, meanwhile, can effectively trigger apoptosis in Hep 3B cells (Fig. 4e). The results of wound healing assay showed that the migration ability of Hep 3B cells was significantly inhibited after knockdown of MLH1 (Fig. 4f). At the same time, the transwell assay also showed that MLH1 knockdown significantly inhibited the migration and invasion ability of Hep 3B cells (Fig. 4g). These results suggest that MLH1 may be an oncogene, as inhibiting the expression of MLH1 can suppress the proliferation, migration and invasion of HCC cells and induce apoptosis.

The initial clustering: unique immune infiltration characteristics and biological behaviors of hypoxia and senescence co-related subtypes

We utilized the R package “ConsensusClusterPlus” to conduct a cluster analysis of the patients, based on the varied expression patterns of HSCRGs. The analysis delineated two hypoxia and senescence correlated phenotypes,

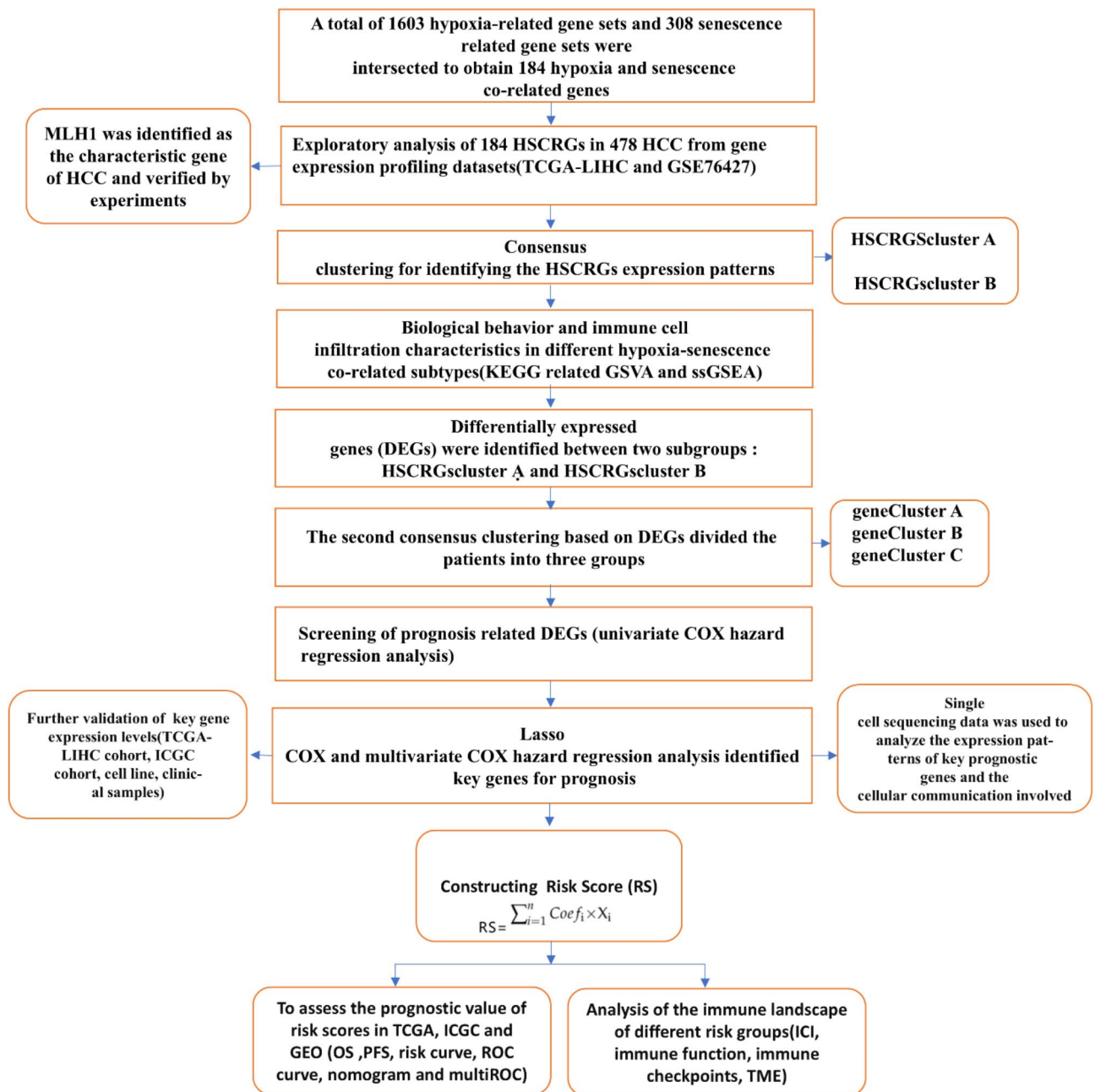


Fig. 1. The flowchart of the entire study.

designated as HSCRGs-clusters A and B (Fig. 5a). Furthermore, the principal component analysis (PCA) plot successfully differentiated the distribution patterns of HCC samples within clusters A and B of HSCRGs, demonstrating the efficacy of this clustering pattern (Fig. 5b). Among the two clusters, patients in HSCRGs-cluster A had a better survival prognosis, while patients in HSCRGs-cluster B had a relatively poor survival prognosis ($P < 0.001$) (Fig. 5c). A heatmap revealed elevated expression levels of HSCRGs in HSCRGs-cluster B, corresponding with advanced clinical stages (Fig. 5d). Additionally, we utilized the single-sample gene set enrichment analysis (ssGSEA) algorithm to assess the degree of immune infiltration between the two subgroups (Fig. 5e). The results revealed that HSCRGs-cluster B exhibited a markedly higher abundance of immune cells, including activated dendritic cells, MDSC and regulatory T cells. In contrast, HSCRGs-cluster A is enriched with only two types of cells, eosinophilia and neutrophils. To explore the biological distinctions between the two HSCRGs-clusters, we conducted GO and KEGG-related GSVA (Fig. 5f,g). The results indicated that biological processes related to amino acid metabolism and signaling pathways associated with the metabolism of various bioactive substances were significantly enriched in cluster A. In contrast, the positive regulation of organelle tissue and the pathogenic *Escherichia coli* infection signaling pathway were significantly enriched in cluster B. These results showed that the two subgroups exhibited distinct characteristics in terms of survival prognosis, gene expression, and immune infiltration levels.

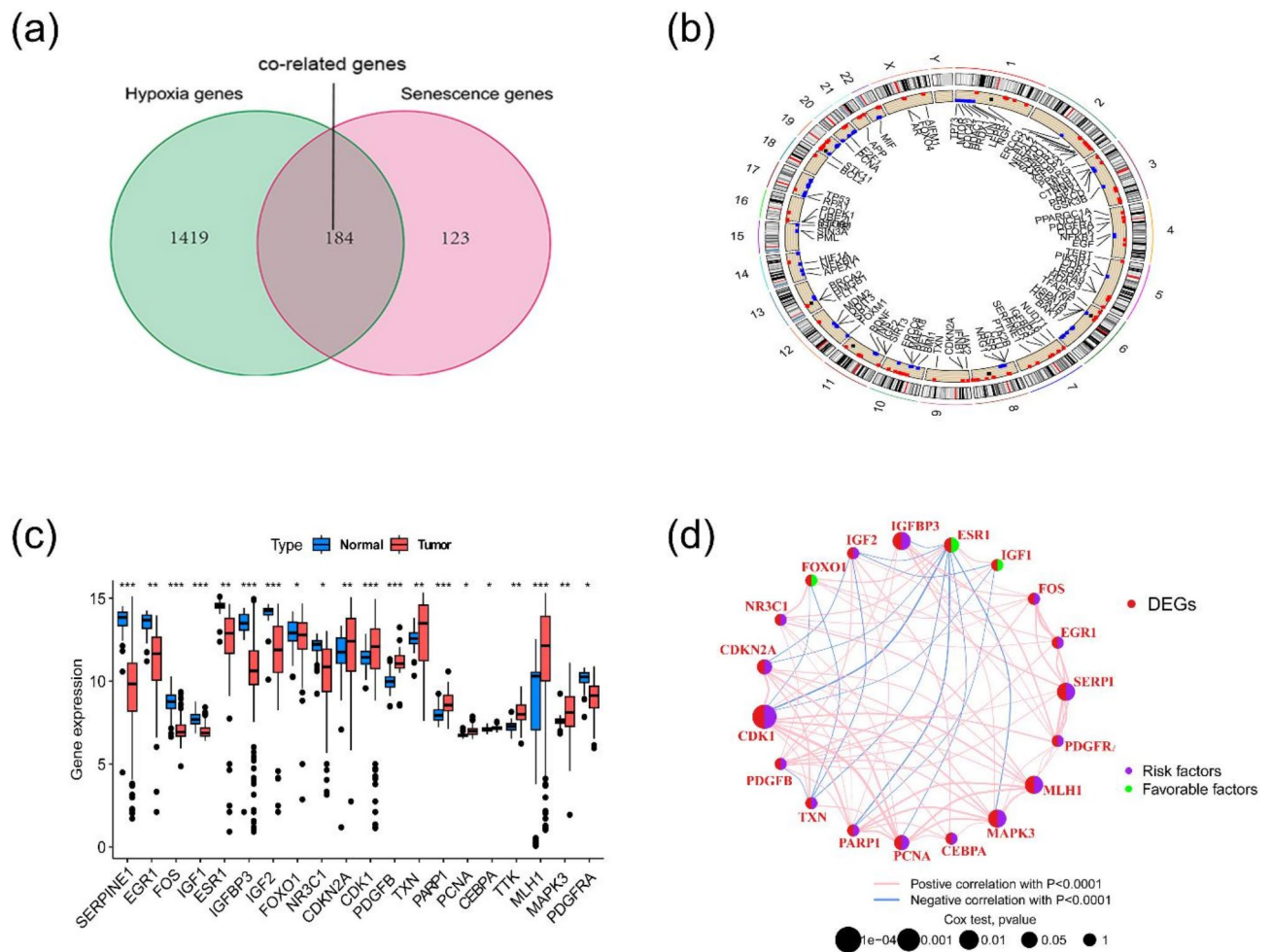


Fig. 2. (a) A total of 184 HSCRGs. (b) The location of CNV alterations of HSCRGs on different chromosomes. (c) The expression of different HSCRGs between normal and tumor tissues. (d) Prognostic network diagram of DEGs in HCC. The circle size represents the range of significance values of each DEG on the prognosis. The p-values were calculated by log-rank test. Green dots represent favorable factors for prognosis, and purple dots represent risk factors for prognosis. The lines linking DEGs represent their correlation. The thickness of the lines represents the strength of correlation between DEGs. Negative and positive correlations were marked with blue and red, respectively. HSCRGs, hypoxia-senescence co-related genes; CNV, copy number variation; HCC, hepatocellular carcinoma; DEGs, differentially expressed genes. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

The secondary clustering: comprehensive analysis of differentially expressed genes based on hypoxia and senescence co-related subtypes in HCC

To further investigate the biological functions of HSCRGs subtypes in HCC, a differential analysis was conducted to identify the differentially expressed genes (DEGs) within HSCRGs clusters using the “limma” script. The consensus clustering analysis identified 831 DEGs, revealing three distinct gene cluster subtypes: 216 samples in gene cluster A, 186 samples in gene cluster B, and 76 samples in gene cluster C (Fig. 6a). Survival analysis showed that patients with gene cluster C had the worst prognosis, gene cluster A patients had the best prognosis, and patients with gene cluster B had a median prognosis ($P < 0.001$) (Fig. 6b). A heatmap illustrates that the majority of patients in gene clusters A and C are aligned with HSCRG clusters A and B, respectively (Fig. 6c). Expressions of all 184 HSCRGs varied significantly across the different gene clusters (Fig. 6d). Thus, the gene clusters corresponded well with HSCRGs-clusters. GO enrichment analysis revealed that the DEGs were involved in organic acid catabolic and carboxylic acid catabolic processes. Additionally, KEGG pathway enrichment analysis indicated that these DEGs were predominantly enriched in the cell cycle, ECM receptor interaction, and other signaling pathways (Fig. 6e,f).

Construction of a prognostic signature based on differentially expressed genes

An analysis was conducted to assess the prognostic value of differentially expressed genes (DEGs) based on HSCRGs in HCC patients. Specifically, univariate Cox analysis was executed, identifying 443 prognostic factors with $p < 0.05$, including 103 favorable factors and 340 risk factors. The figure displays the top 10 genes with the most significant prognostic impact (Fig. 7a). Using the “glmnet” package, LASSO analysis was performed,

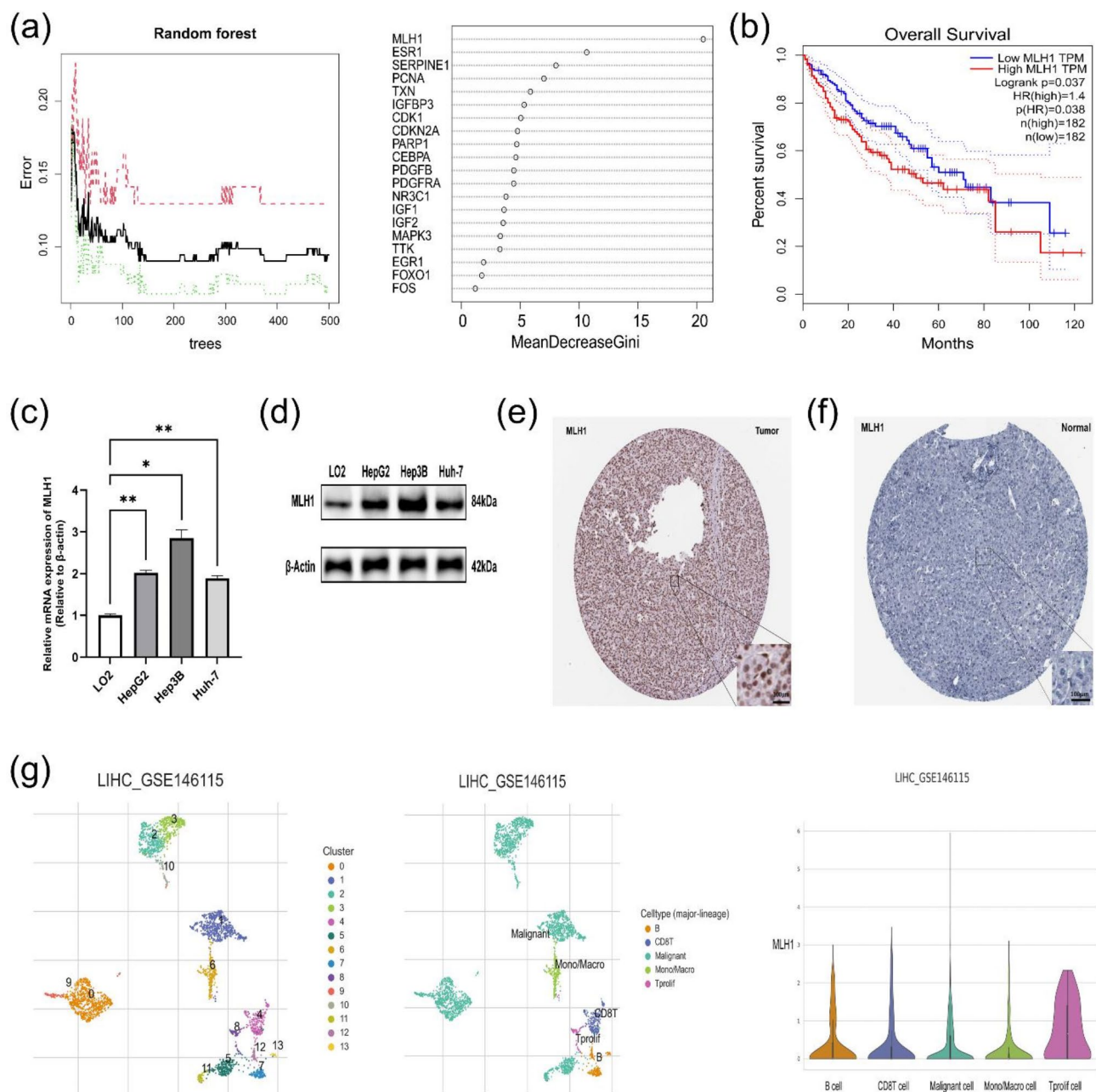


Fig. 3. (a) Random forests identifying key genes for disease. (b) Kaplan–Meier curves showed overall survival difference between high and low MLH1 expression groups in the TCGA-LIHC cohort ($p=0.037$). (c, d) Real time-PCR and Western blot revealed that the expression of MLH1 was notably increased in HCC cell lines. (e, f) Immunohistochemical staining of MLH1 in tumor tissues and normal tissues of HCC patients in the HPA database (100 \times). (g) Expression pattern of MLH1 in the tumor microenvironment by single cell analysis. HCC, hepatocellular carcinoma; HPA, Human Protein Atlas. * $p<0.05$, ** $p<0.01$.

selecting 11 essential variables from the pool of 443 prognostic factors (Fig. 7b,c). Multivariate Cox analysis was employed to establish a prognostic risk model consisting of seven key prognostic genes and to calculate the risk score (RS) for HCC patients (Fig. 7d). The computation of the RS utilized the following formula: Risk score = $(0.369) \times \text{KPNA2} + (0.271) \times \text{TRIB3} + (0.232) \times \text{ATP1B3} + (0.147) \times \text{EPO} + (-0.157) \times \text{CXCL9} + (-0.139) \times \text{LINC01554} + (-0.132) \times \text{ANXA10}$. To validate the impact of these seven key prognostic genes on the survival and prognosis of HCC patients, the relationship between the expression levels of these genes and patients' survival rates was analyzed. Findings revealed a significant association between the expression levels of these genes and patients' survival prognosis. Specifically, patients exhibiting high expression of KPNA2, ATP1B3, TRIB3, and EPO demonstrated a significantly reduced survival rate, whereas those with elevated levels of CXCL9, LINC01554, and ANXA10 showed a significantly enhanced survival rate (Figs. 7e–k; S2a–g). These results emphasize the critical role of these seven genes.

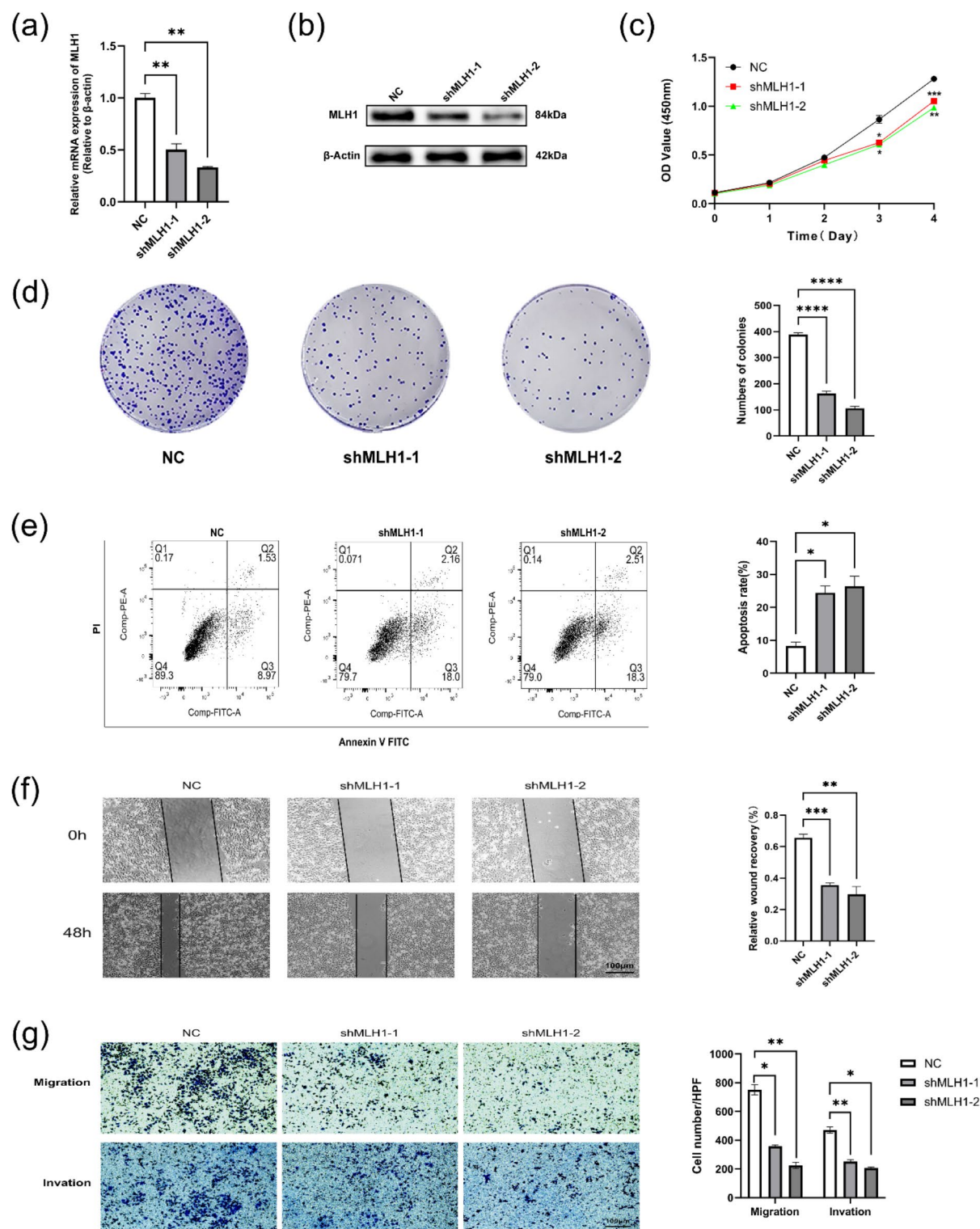


Fig. 4. (a, b) The knockdown levels of MLH1 in Hep 3B cell line were detected by qPCR and western blot. β-actin was used as internal parameter. (c) Cell proliferation capacity was determined by CCK-8 analysis after knockdown of MLH1 in Hep 3B cells. (d) Effect of inhibition of MLH1 expression on colony formation of Hep 3B cells. (e) Effect of inhibition of MLH1 gene expression on apoptosis of Hep 3B cells (f) Wound healing assays revealed that knockdown MLH1 notably inhibited migration ability of Hep 3B cells (100×). (g) Transwell assays revealed that knockdown MLH1 notably inhibited migration and invasion of Hep 3B cells (100×). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$.

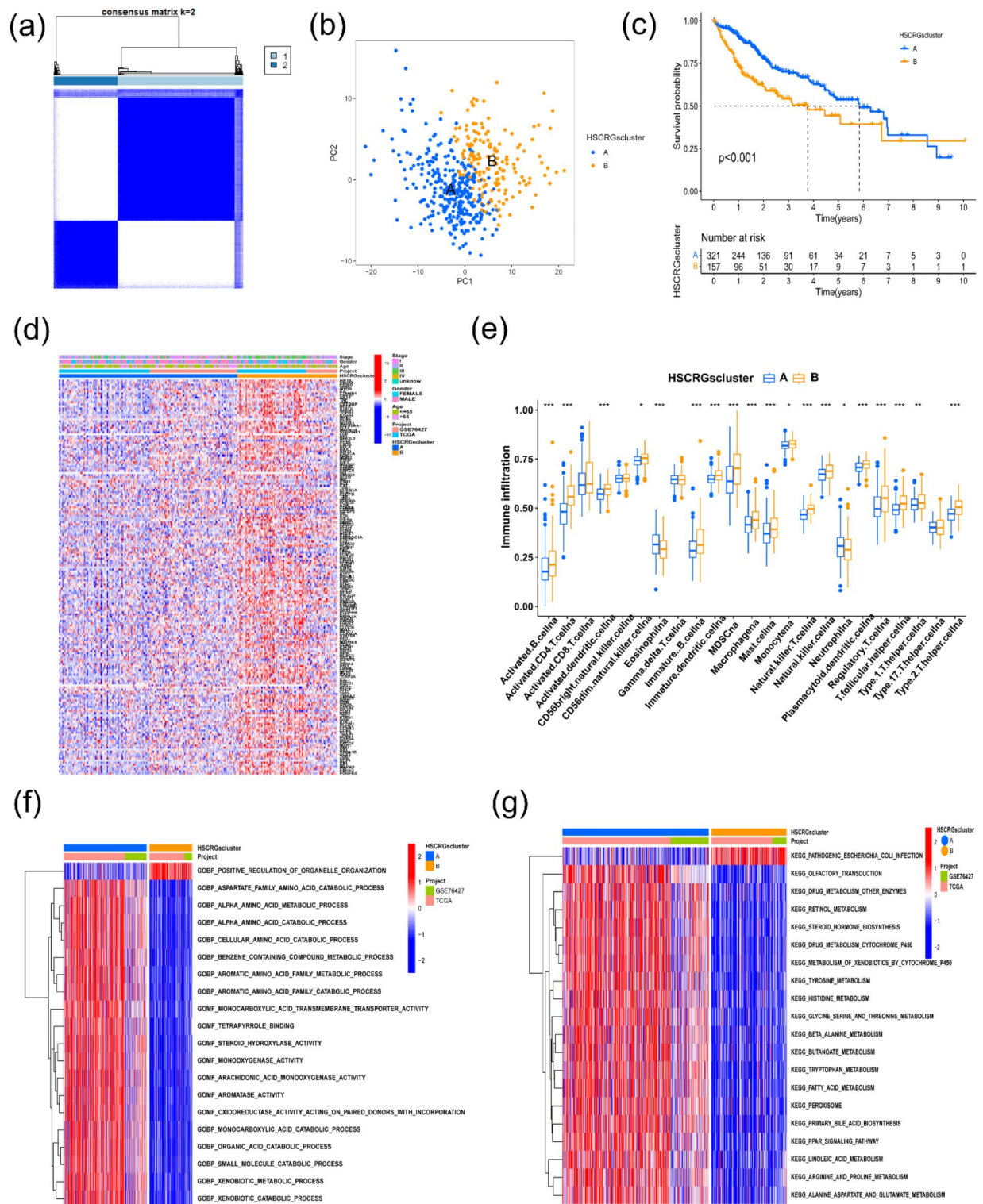


Fig. 5. (a) The consensus matrixes for all HCC samples displayed the clustering stability with 1000 iterations. All samples were clustered into an appropriate number of subtypes ($k=2$). (b) Principal component analysis of the two subgroups. (c) Kaplan–Meier curves showed the overall survival difference between HSCRGscluster A and B ($p < 0.001$). (d) The heatmap demonstrates the expression of HSCRGs in different HSCRGsclusters. Heatmap colors indicate relative HSCRGs expression levels. (e) The abundance of each immune cell infiltration in HSCRGscluster A and B. (f, g) GO and KEGG related GSVA showing the activation status of biological behaviors in HSCRGscluster A and B. HCC, hepatocellular carcinoma; HSCRGs, hypoxia-senescence co-related genes; GO, Gene Ontology; KEGG, Kyoto Encyclopedia of Genes and Genomes (www.kegg.jp/kegg/kegg1.html); GSVA, gene set variation analysis. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

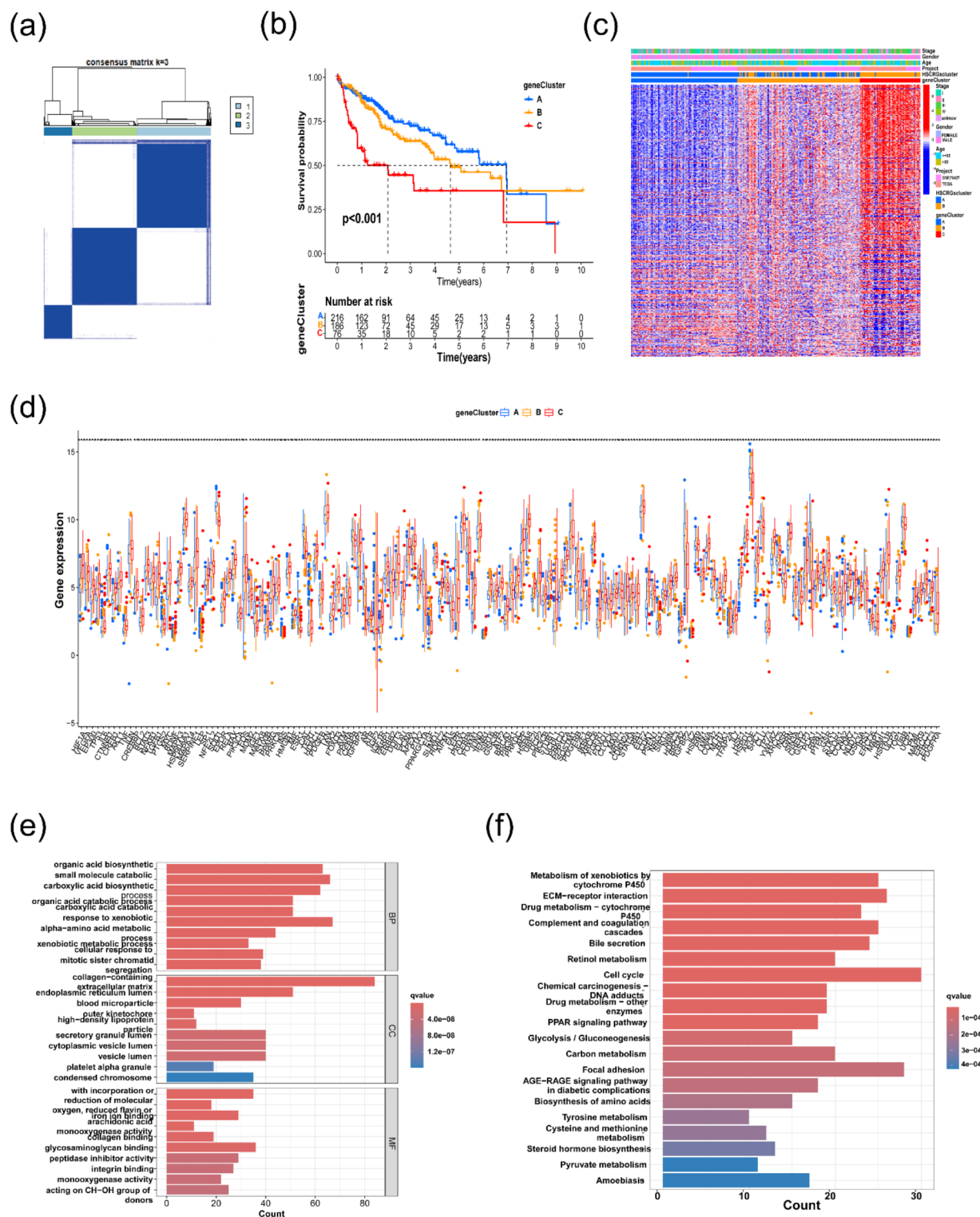


Fig. 6. (a) The consensus matrixes for TCGA-LIHC cohorts based on the DEGs among the 2 HSCRGs clusters. TCGA samples were clustered into an appropriate number of subtypes ($k=3$). (b) Kaplan–Meier curves showed an overall survival difference between gene clusters ($p < 0.001$). (c) The heatmap shows the expression of the hypoxia and senescence co-related DEGs in different HSCRGs clusters and gene clusters. (d) The difference of HSCRGs expression in different gene clusters. (e, f) GO and KEGG enrichment analysis of hypoxia and senescence co-related DEGs. DEGs, differentially expressed genes; HSCRGs, hypoxia-senescence co-related genes; GO, Gene Ontology; KEGG, Kyoto Encyclopedia of Genes and Genomes (www.kegg.jp/kegg/kegg1.html). * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

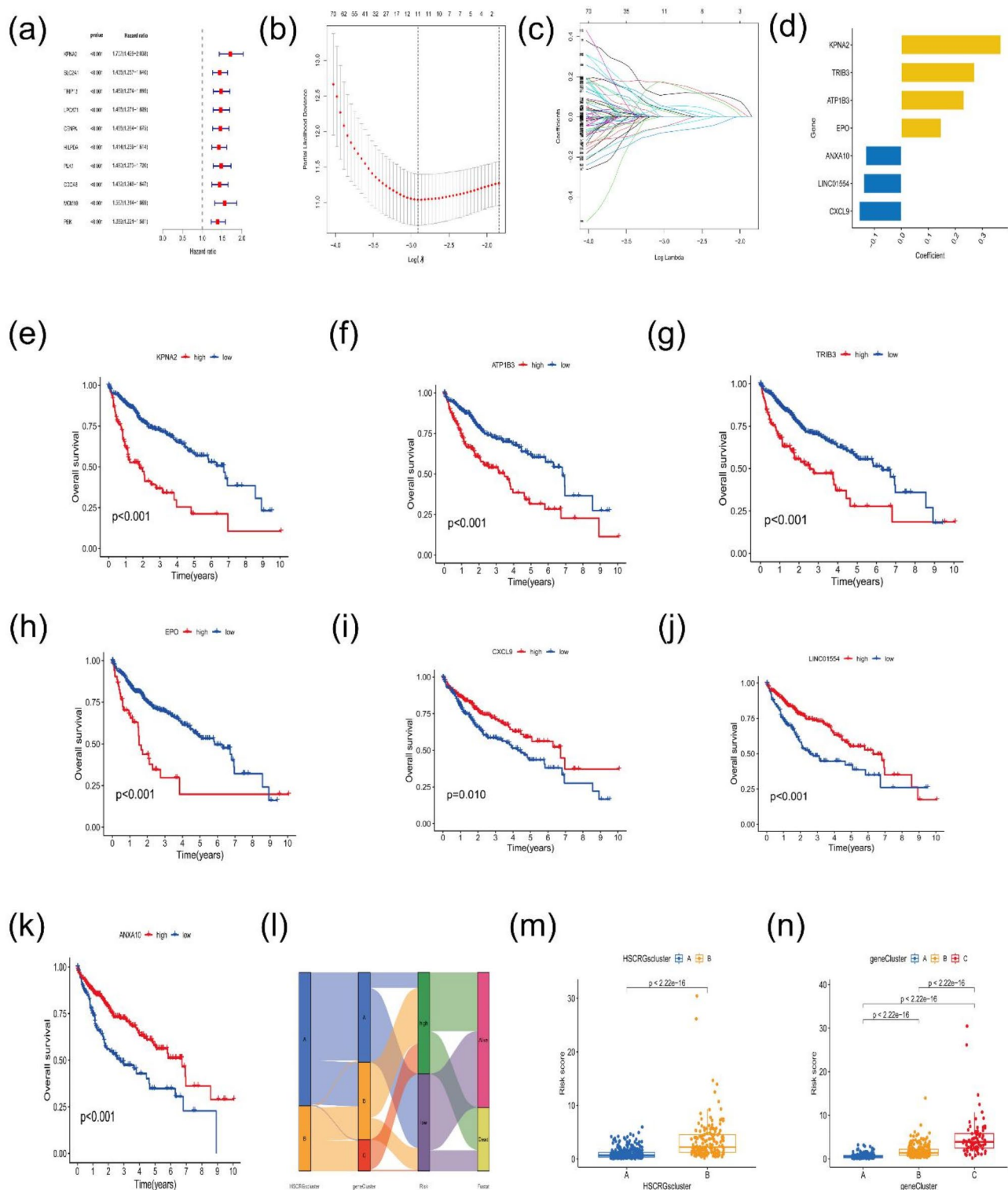


Fig. 7. (a) The univariate Cox analysis of hypoxia-senescence co-related DEGs. (b, c) Identification of feature prognostic variables via LASSO analysis. (d) The prognosis key genes coefficient via multivariate Cox regression analysis. (e–k) Survival curves of 7 key prognostic genes ($p < 0.001$ and 0.05). (l) The Sankey diagram shows the potential relationship of risk score and clinical survival outcome in HSCRGs-clusters and gene clusters. (m, n) Difference analysis of risk score in HSCRGs-clusters and gene clusters. DEGs, differentially expressed genes; HSCRGs, hypoxia-senescence co-related genes ($p < 0.001$).

The Sankey plot delineates the potential correlation between the risk score and clinical prognosis within HSCRGs clusters and gene clusters (Fig. 7l). HCC patients were initially classified into two HSCRGs clusters and then divided into three gene clusters. Contrary to gene cluster A, which is associated with more favorable prognoses, patients in gene cluster C, characterized by poorer prognoses, were grouped with the high-risk score group. Similarly, the majority of patients in gene cluster B, characterized by unfavorable prognoses, also were part of the high-risk score group. Further investigation into the relationship between the RS and the two clustering modes revealed significant differences in the RS across the diverse clustering modes. Notably, the median RS in HSCRGs-cluster B was significantly higher than in HSCRGs-cluster A ($p < 0.001$) (Fig. 7m). Moreover, the median RS of gene cluster C exceeded that of gene clusters A and B ($p < 0.001$) (Fig. 7n). Patients in HSCRGs cluster B and gene cluster C demonstrated a relatively worse prognosis, validating the consistency of the predictive efficacy. These results showed that the risk score functions as an independent indicator for prognostic prediction.

Development and validation of a risk model based on risk score

To explore the potential association between the risk score and clinical outcome prognosis for HCC samples, the samples were divided into a training cohort and a test cohort at a 1:1 ratio using the “caret” script. In addition, the ICGC-LIRI-JP cohort was utilized as our independent external validation cohort. Significant differences in survival rates between the low-risk and high-risk groups were observed across the entire cohort, training cohort, testing cohort, and ICGC cohort, with the poorest prognosis noted in the high-risk group across all four cohorts ($p < 0.05$) (Figs. 8a–c; S3a). Concurrently, Kaplan–Meier survival analysis indicated that the high-risk group experienced worse progression-free survival (PFS) compared to the low-risk group across all three cohorts (Fig. 8d–f). The area under the curve (AUC) from the ROC curve served to evaluate the model’s predictive efficacy. At one, three, and five years, the AUC of the ROC curve was 0.753, 0.728, and 0.706 for the entire cohort; 0.829, 0.833, and 0.786 for the training cohort; 0.690, 0.646, and 0.639 for the test cohort; 0.829, 0.760, and 0.503 for the ICGC cohort (Figs. 8g–i; S3b). This suggests that the risk score is more effectively utilized to predict patient prognosis. The nomogram illustrated that the risk score played a pivotal role in forecasting overall survival at 1, 3, and 5 years (Fig. 8j). Calibration curves indicated that the predictive lines closely approximated the ideal line at 1, 3, and 5 years (Fig. 8k). The nomogram also showed good predictive performance in the ICGC cohort (Fig. S3c,d). The areas under the ROC curves (AUCs) for the nomogram in the entire cohort, training cohort, test cohort, and ICGC cohort were 0.765, 0.780, 0.751, and 0.866, respectively. These AUC values were superior to other clinical features, thereby demonstrating the robust performance of this nomogram in predicting the survival of HCC patients (Figs. 8l; S3e–g). The expression patterns of the seven key prognostic genes across different risk groups, as well as the distribution of survival time in relation to the risk score within the training cohort, test cohort, and ICGC cohort were respectively displayed (Fig. S4a–c). These results showed that risk score has robust predictive effect.

Finally, we performed a comprehensive and systematic comparison of the prognostic signatures associated with HCC that have been developed in recent years. The results demonstrated that the C-index of our model was significantly higher than those of the other four models, thereby providing stronger evidence for the superior predictive accuracy and overall performance of our model (Fig. S5).

Analyzing tumor immune microenvironment, functional strength and mutation characteristics in the two risk groups

Results from CIBERSORT showed higher infiltration levels of resting CD4+ memory T cells and Macrophages M1 in the low-risk group, while activated CD4+ memory T cells, Monocytes, and Neutrophils demonstrated elevated levels in the high-risk group (Fig. 9a,b). Findings from ssGSEA revealed that several immune functions, including cytolytic activity and type I IFN response, were heightened in the low-risk group (Fig. 9c). Furthermore, it was observed that expression levels of immune checkpoints, including CD44, CTLA4, and PDCD1, were significantly higher in the low-risk group than in the high-risk group (Fig. 9d). The immune cell bubble plot, generated by seven different software tools, predicted the correlation between various immune cells and risk scores (Fig. 9e). Correlations between the seven prognostic key genes and 22 immune infiltrating cells were also unfolded (Fig. 9f). Diverse immune infiltrating cells were significantly correlated with the seven prognostic key genes, such as CD8 T cells, Macrophages M1, and activated CD4 memory T cells, etc., indicating potential functional associations. The ESTIMATE algorithm analysis revealed that the stromal score and composite score were significantly higher in the low-risk group, suggesting that the tumor microenvironment in the low-risk group possessed elevated levels of stromal and immune cells, leading to reduced tumor cell infiltration (Fig. 9g). Accumulating evidence indicates that the elevated expression of stemness-related biomarkers in tumor cells correlates strongly with drug resistance and cancer recurrence. Therefore, the correlation between RNA stemness score (RNAss) and risk score was assessed, revealing a significantly positive correlation between the risk score and RNAss (Fig. 9h). These findings demonstrated that the low-risk group exhibited an immune-active profile, while the high-risk group was characterized by a relatively immune-cold status. Patients within the low-risk group could potentially derive greater benefits from immunotherapy, given their active tumor microenvironment.

We presented the top ten significantly enriched functional annotations for the two risk groups using GSEA (Fig. S6a–d). The results indicate that in the high-risk group, there is a strengthening of functional annotations related to the chromosome centromeric region, condensed chromosome centromeric region, and cell cycle, etc. Conversely, in the low-risk group, functional annotations related to cellular amino acid catabolic process, fatty acid catabolic process, and fatty acid metabolism, etc. were strengthened. Next, we presented the top 20 most frequently altered genes in both the low-risk and high-risk groups. CTNNB1 (25%) and TP53 (39%) were

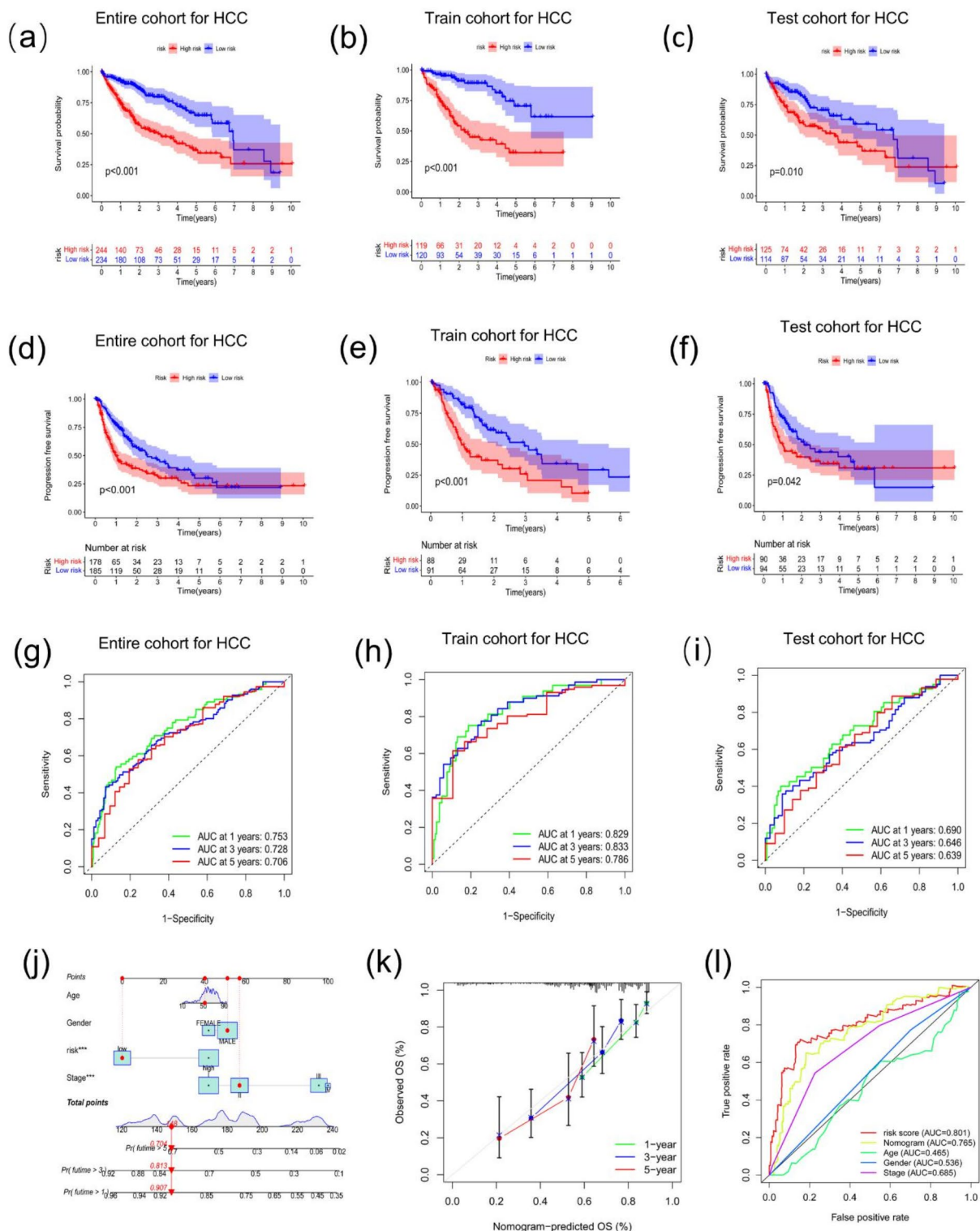


Fig. 8. (a–c) Survival differences between the low-risk group and the high-risk group in the entire cohort, training cohort, and test cohort ($p < 0.001$ and 0.05). (d–f) PFS between low-risk group and high-risk group in the entire, training and test cohorts ($p < 0.001$ and 0.05). (g–i) ROC curves at 1, 3, and 5 years in the entire cohort, training cohort, and test cohort. (j) Predictive nomogram based on the risk score and other clinical features. (k) Calibration curves at 1, 3, and 5 years. (l) ROC curves for clinical parameters, risk score and nomogram in the entire cohort. PFS, Progression-free survival; ROC, receiver operating characteristic curve.

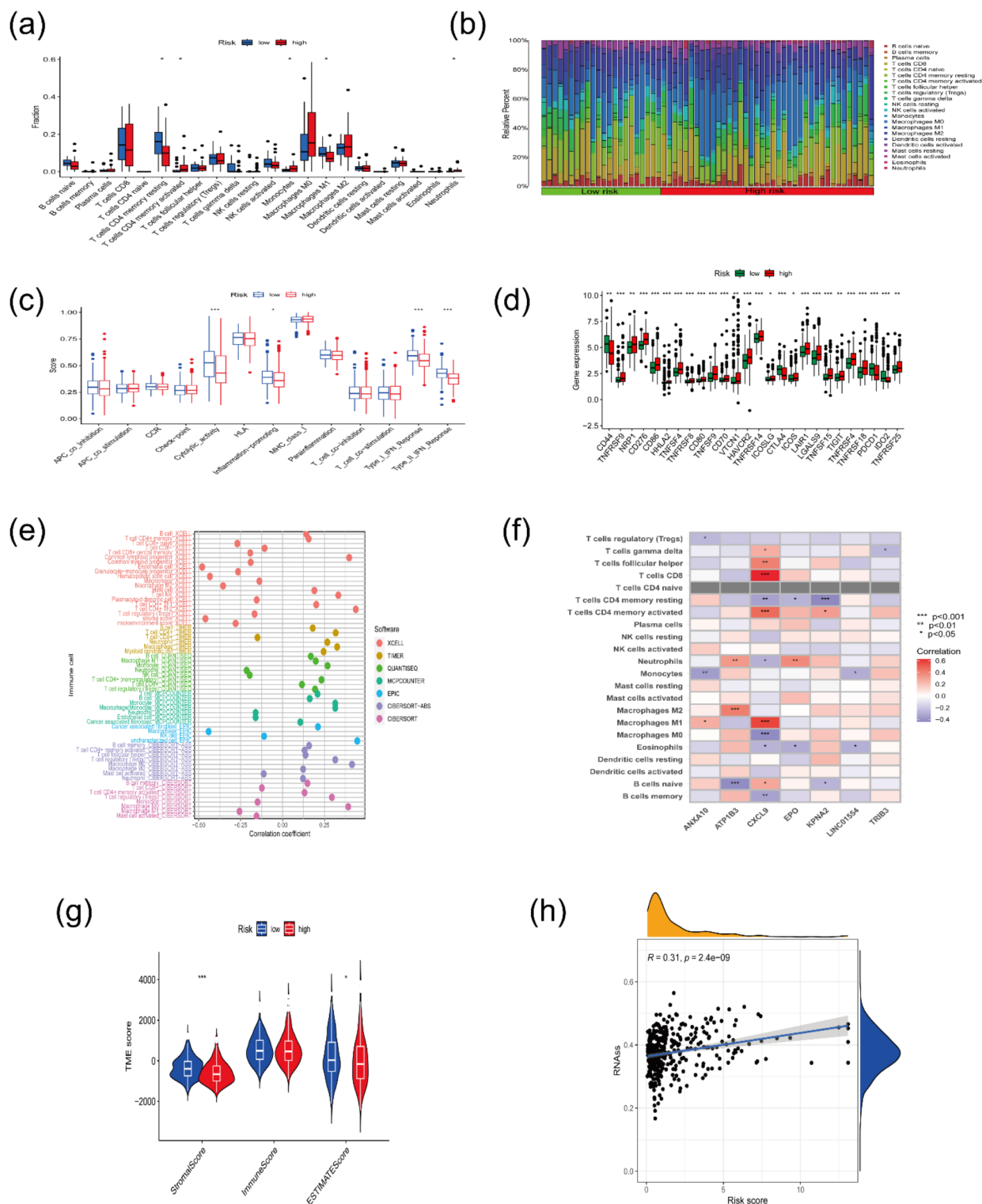


Fig. 9. (a) Estimation of 22 immune infiltrating cells between the low-risk group and the high-risk group by CIBERSOR. (b) Proportion of 22 immune infiltrating cells for each HCC sample by CIBERSOR. (c) Estimation of immune activities between the low-risk group and the high-risk group by ssGSEA. (d) The expression pattern of immune checkpoints between the low-risk group and the high-risk group. (e) Different software analyzed the correlation of immune cells with risk scores. (f) Correlations between 7 key genes and 22 immune infiltrating cells. (g) Differences in stromal, immune, and ESTIMATE scores in the two different risk groups. (h) The relationship between risk score and RNAss. HCC, hepatocellular carcinoma; ssGSEA, Single sample gene set enrichment analysis; RNAss, RNA stemness score.

identified as the most frequently altered genes in the low-risk and high-risk groups, respectively. The most common mutation type observed in both groups was missense mutation (Fig. S6e,f).

Single-cell analysis

Single-cell analysis was conducted based on GSE146115. In this study, a total of 3200 single cells from 4 HCC patients were included. The quality control criteria are presented in the Materials and Methods section. Among them, 3198 single cells met the quality control standards (Fig. S7a–c). The heatmap was used to display the most significantly expressed genes in 11 clusters (Fig. S7d). We used tSNE to perform dimensionality reduction and clustering on the preprocessed scRNA-seq data, and finally obtained 11 clusters (Fig. 10a). Cell types were automatically annotated by the SingleR package, and these 11 clusters were clustered into 4 cell types, including Tumor cells, T cells, Macrophage, and NK cells (Fig. 10b). Subsequently, we assessed the expression patterns of the seven key prognostic genes. KPNA2 was expressed in both tumor cells and T cells; ATP1B3 was found in T cells and macrophages; and TRIB3, CXCL9, LINC01554, and ANXA10 were predominantly expressed in tumor cells (Fig. 10c,d). Cellchat, a computational tool, is designed to identify communication patterns and predict functions within less explored pathways⁴⁰. Our analysis revealed that tumor cells function as the primary signal transducers within the cellular communication network, evidenced by both the number and strength of interactions (Fig. 10e,f). We then explored whether the seven key prognostic genes played roles in cell signaling pathways. Our findings demonstrate the enrichment of key genes in the SPP1 and MK signaling pathways. Further examination of these pathways revealed that tumor cells predominantly function as senders in the SPP1 signaling pathway, with major recipient cell subsets being NK cells, macrophages, and T cells. Additionally, tumor cells serve as senders, receivers, and influencers in the MK signaling pathway, indicating the potential for feedback loops (Fig. 10g–j).

Validation of the expression levels of the seven key prognostic genes

In further validation of the expression of the seven key genes, the immunohistochemical staining results for five genes (KPNA2, ATP1B3, TRIB3, EPO, and ANXA10) were obtained from the HPA database, revealing significant differences in the expression of related proteins between cancerous and normal liver tissues (Fig. S8). Furthermore, the mRNA expression levels of these genes were evaluated in normal hepatocytes and various HCC cell lines. Results indicated significant upregulation of KPNA2, ATP1B3, TRIB3, and CXCL9 in HCC cell lines, whereas EPO, LINC01554, and ANXA10 were markedly upregulated in normal hepatocytes ($P < 0.05$) (Fig. 11a–g). These results showed that the seven key prognostic genes could serve as a crucial foundation for evaluating the prognosis of HCC patients.

Discussion

In this study, the identification of 184 HSCRGs was followed by the revelation of two distinct co-expression clusters within these genes. Significant differences in immune infiltration are exhibited by these two clusters. Analysis of immunoinfiltration reveals that cluster B of HSCRGs is characterized by active immune activity and significant immune cell infiltration within the tumor microenvironment. Within cluster B, MDSCs, activated dendritic cells, and Tregs are identified as playing crucial roles among the main immune cells. MDSCs exhibit strong immunosuppressive activity, inhibiting T cell and NK cell functions, thus facilitating immune escape⁴¹. It has been demonstrated that Tregs are recruited by tumor cells within the tumor microenvironment, undermining anti-tumor immunity⁴². Furthermore, systematic disruption of dendritic cell differentiation and development within the tumor microenvironment is regarded as a significant contributor to tumor immune escape⁴³. These immunosuppressive characteristics might account for the adverse prognosis observed in cluster B of HSCRGs.

In recent years, significant progress has been made in molecular classification and precision oncology research for HCC. For example, studies based on genes related to anoikis, methylation, and immune subtypes have successfully divided HCC patients into different molecular subtypes and identified prognostic genes, providing valuable insights into the molecular mechanisms and treatment of HCC^{34–36}. However, these studies primarily focused on individual factors such as anoikis, methylation, or immune subtypes, and did not comprehensively explore the interplay between hypoxia and senescence in HCC. Our study uniquely integrates HSCRGs to delineate molecular subtypes and construct a prognostic risk model. This approach not only captures the complex interactions between hypoxia and senescence but also provides a novel perspective on the tumor microenvironment and immune landscape in HCC⁴⁴. By identifying two distinct HSCRGs clusters and developing a risk score model, we offer a more comprehensive understanding of HCC heterogeneity and potential therapeutic targets⁴⁵. This distinguishes our work from previous studies and underscores the importance of considering multiple biological processes in HCC classification and prognosis prediction.

The external validation of our prognostic model using the ICGC cohort significantly strengthens the reliability and generalizability of our findings. The consistent performance of the nomogram across both our internal datasets and the independent ICGC cohort underscores the robustness of our risk stratification approach. This external validation is crucial as it demonstrates that our model can be effectively applied to diverse patient populations, enhancing its potential clinical utility^{46,47}. The successful validation in the ICGC cohort⁴⁸, which comprises patients from different geographical regions and treatment backgrounds⁴⁹, further supports the notion that our HSCRGs signature captures fundamental biological processes in HCC progression that transcend specific patient cohorts.

MLH1 is a tumor suppressor gene located in the region of human chromosome 1p36.1, and the protein encoded by MLH1 gene is one of the key proteins involved in DNA mismatch repair pathway⁵⁰. Studies have shown that the mutation of MLH1 gene is closely related to the incidence of various cancers, such as colorectal cancer, gastric cancer, and endometrial cancer^{51–53}. Statistics show that MLH1 gene mutations occur in 8–21% of colorectal cancer patients^{54–56}, 14.5% of gastric cancer patients, and 24–37% of endometrial cancers^{53,57,58}.

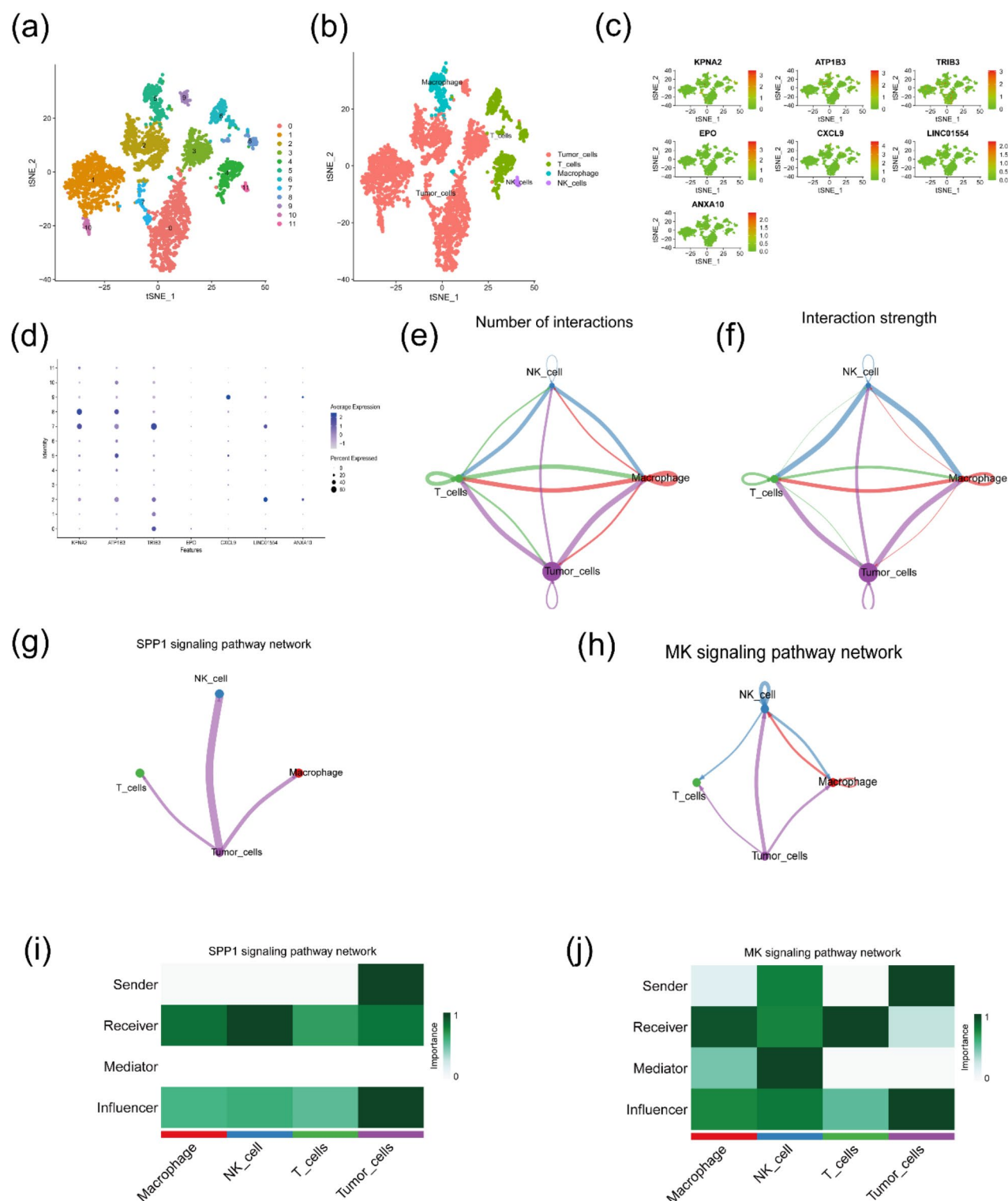


Fig. 10. (a, b) Identification of cell subgroups in the tumor microenvironment of hepatocellular carcinoma. (c, d) Expression pattern of the seven key genes in the tumor microenvironment. (e, f) Diagrams displaying the interaction number and strength in cell clusters. (g, h) associated with malignant cell subpopulation and their cell communication networks. The thicker the line represented, the more the number of interactions, and the stronger the interaction strength between the two cell types. (i, j) Primary originators and influencers of key signaling pathways.

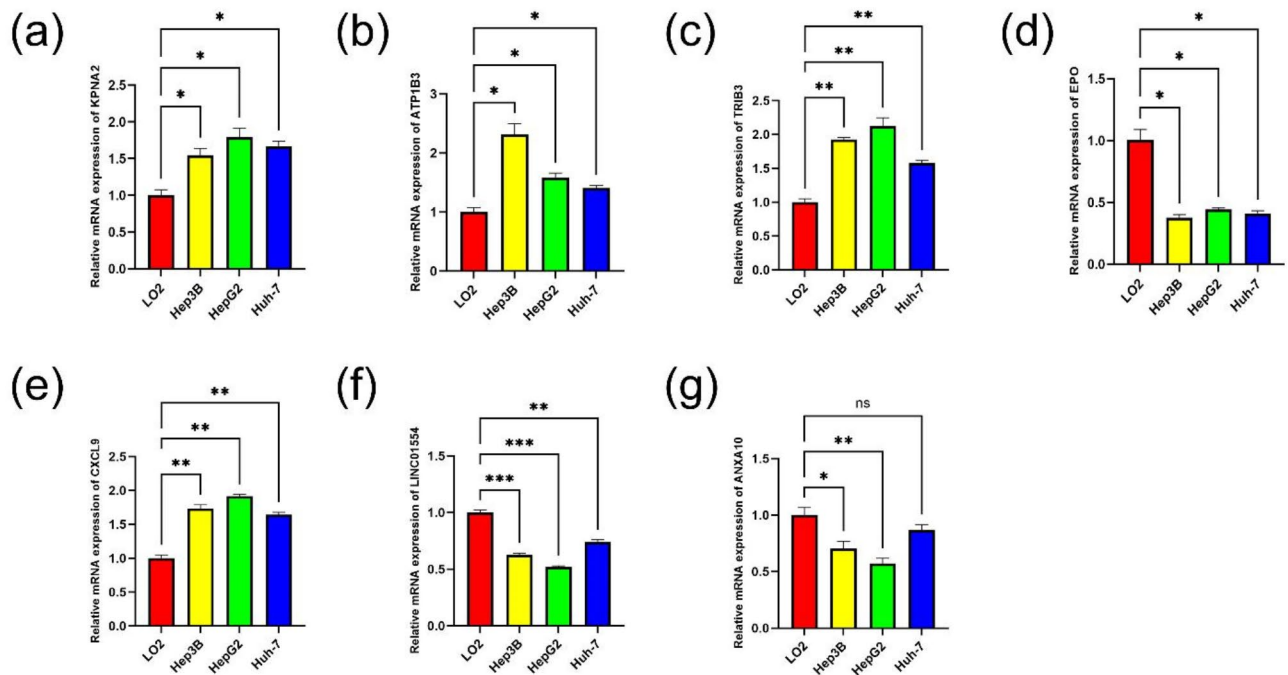


Fig. 11. (a–g) The mRNA levels of the seven prognostic key genes in normal hepatocellular cell line and hepatocellular carcinoma cell lines (benign cell: LO2; malignant cells: Hep3B, HepG2, and Huh-7). * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, ns, non-significant.

Loss, low expression of MLH1 gene, or mutations are important factors in the pathogenesis of these cancers^{59–61}. However, the function of MLH1 in liver cancer, especially HCC, is unclear. In this study, we found that MLH1 is highly expressed in HCC, and the prognosis of HCC patients with high expression of MLH1 is significantly worse. In addition, we have verified the function of MLH1 at the cellular level for the first time, and knocking down MLH1 can significantly inhibit the proliferation, migration and invasion of cancer cells. This suggests that MLH1 may be an oncogene in HCC, and targeting MLH1 may be a new target for HCC treatment.

Subsequently, three clusters of DEGs related to hypoxia and senescence were identified, and these clusters exhibited significant associations with immune activity. We reiterated the significance of alterations in hypoxia and senescence in shaping distinct tumor immune microenvironment (TIME) landscapes. Additionally, we developed a scoring system, denoted as the RS (Risk Score), to quantify the hypoxia and senescence patterns in each HCC patient. This scoring system aims to facilitate individualized prognostic analysis and precise treatment planning for HCC. Previous studies have demonstrated that a prognostic nomogram based on RS can enhance the accuracy of survival rate estimation for patients with breast cancer⁶². Likewise, the risk score may be valuable in predicting prognosis and indicating immune infiltration in colon cancer⁶³. In addition, the risk score can also be used to risk stratify patients with HCC and help individualize treatment for patients⁶⁴. These analyses further suggest that the RS could serve as a potential and reliable prognostic marker in HCC.

Single-cell transcriptome data is sequenced from high-quality annotated cells, which makes it more accurate than ordinary bulk RNA sequencing data⁶⁵. Therefore, it is widely used to dissect the tumor microenvironment to further understand tumor heterogeneity⁶⁶. In this study, we dissected the expression patterns of seven key prognostic genes in the tumor microenvironment of HCC based on single-cell analysis. We found that tumor cells, T cells, and macrophages were the main cell subtypes, and TRIB3 was the most expressed in the tumor microenvironment among the 7 key genes, mainly expressed in tumor cells. TRIB3 has been found to reduce CD8(+) T cell infiltration and induce immune evasion by inhibiting the STAT1-CXCL10 axis in colorectal cancer⁶⁷, which is consistent with our findings suggesting that TRIB3 may be a target for the treatment of cancer. Next, we identified that the ligand receptor CXCL9/SPP1 mediates cellular crosstalk between tumor cells and macrophages. It has been shown that changes in macrophage polarity, determined by the expression of two genes, CXCL9 and SPP1, are a simple but critical feature of the tumor microenvironment⁶⁸. The CXCL9:SPP1 ratio can characterize the abundance of anti-tumor immune cells in tumors, the regulation of communication networks that indicate tumor control or progression, and the response to immunotherapy.

The present study had certain limitations. Primarily, in the experimental part, we did not combine clinical samples for further validation, and our findings have not been fully elucidated, and the biological function of the prognostic core gene has not been fully elucidated. Secondly, our findings suggest that these HSCRGs play different roles in HCC, such as IME landscape, drug sensitivity, and immunotherapy efficacy. However, the underlying molecular mechanisms have not been evaluated, and further studies are needed to elucidate the detailed mechanisms of HSCRGs in HCC. Thirdly, HSCRGs clustering and risk models can effectively distinguish the risk stratification, sensitivity of immunotherapy, and prognosis assessment of HCC patients. Therefore, further research is needed on whether these HSCRGs can be used as diagnostic markers or therapeutic targets.

for HCC to guide more effective immunotherapy strategies. Finally, in our study, we confirmed that MLH1 gene is a pro-cancer gene in HCC, but its potential molecular mechanism of action and whether it has clinical application value need to be further studied.

In addition, future research should explore the potential of drug repurposing and the use of various vitamins, such as vitamin D, as preventive measures. These interventions have been shown to have regulatory effects and could positively impact HCC outcomes. For instance, vitamin D has been reported to modulate immune responses and exert anti-tumor effects, which could be beneficial in the management of HCC⁶⁹.

Conclusions

In summary, this study delineated subgroups correlated with hypoxia and senescence, constructing a prognostic risk model for HCC. The expression and specific function of MLH1 gene in HCC were identified. The results highlighted the identification of seven prognostic genes significantly associated with tumor occurrence and immune cell infiltration. The prognostic risk model exhibited robust and effective performance in predicting overall survival in HCC, as demonstrated by successful external validation in the ICGC cohort. This validation underscores the potential clinical utility of our model in improving risk stratification and guiding personalized treatment strategies for HCC patients. Overall, these findings have significant implications for exploring the molecular pathways and mechanisms in HCC and advancing treatments and prognostic approaches.

Data availability

All data generated or analyzed during this study are included in this published article and are available from the corresponding author on reasonable request.

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Author contributions

FC: Methodology, Formal Analysis, Software, Visualization, Validation, Writing—original draft, Writing—review and editing. YC, XC, and CC: Data curation, Formal Analysis, Visualization, Writing—original draft, Writing—review and editing. QF, JL, and YZ: Software, Validation, Writing—review and editing. JZ: Funding acquisition, Project administration, Writing—review and editing.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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