

Analyzing the disease module associated with osteosarcoma via a network- and pathway-based approach

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Abstract. Osteosarcoma is the most common type of primary malignant bone tumor observed in children and adolescents. The aim of the present study was to identify an osteosarcoma-related gene module (OSM) by looking for a dense module following the integration of signals from genome-wide association studies (GWAS) into the human protein-protein interaction (PPI) network. A dataset of somatic mutations in osteosarcoma was obtained from the dbGaP database and their testing P-values were incorporated into the PPI network from a recent study using the dmGWAS bioconductor package. An OSM containing 201 genes (OS genes) and 268 interactions, which were closely associated with immune response, intracellular signal transduction and cell activity was identified. Topological analysis of the OSM identified 11 genes, including APP, APPBP2, ATXN1, HSP90B1, IKZF1, KRTAP10-1, PAK1, PDPK1, SMAD4, SUZ12 and TP53 as potential diagnostic biomarkers for osteosarcoma. The overall survival analysis of osteosarcoma for those 11 genes based on a dataset from the Cancer Genome Atlas, identified APP, HSP90B1, SUZ12 and IKZF1 as osteosarcoma survival-related genes. The results of the present study should be helpful in understanding the diagnosis and treatment of osteosarcoma and its underlying mechanisms. In addition, the methodology used in the present study may be suitable for the analysis of other types of disease.

Introduction

Osteosarcoma is the most common histological form of primary bone cancer in children and adolescents (1). The incidence rates of osteosarcoma in Americans under the age of 20 are estimated to be about 5.0 per million per year for

the general population (1). It occurs more frequently in the metaphyseal region of tubular long bones, with 42% occurring in the femur, 19% in the tibia, and 10% in the humerus (1).

Due to complex nuclear and highly unstable genomes, osteosarcoma usually shows both numerical and structural chromosomal changes (2). Osteosarcoma often presents in Paget's disease of the bone, which may be caused by a mutation in the TNFRSF11A gene on chromosome 18q22 (3). Osteosarcoma is a characteristic of Li-Fraumeni syndrome-1 (LFS1), which is caused by a mutation of the TP53 gene, and of Li-Fraumeni syndrome-2 (LFS2), which is caused by a mutation of the CHEK2 gene. Sadikovic *et al* (4) used 10 pediatric osteosarcoma tissue samples for integrative whole-genome analysis of promoter methylation, gene expression, and DNA copy number. Consequently, hypomethylation, overexpression, and copy number gain were identified for the histone cluster 2 genes on chromosomes 1q21.1-q21.3. They also discovered i) the loss of chromosome 8p21.3-p21.2, ii) lower expression of TNFRSF10A, DOCK5, and TNFRSF10D genes, iii) copy number gain of chromosome 6p21.1-p12.3, and iv) amplification-related overexpression of RUNX2.

Currently, multidrug resistance (MDR) is an urgent problem to be solved in osteosarcoma treatment. The human MDR gene 1 (MDR1) reportedly plays an important role in the drug resistance process in osteosarcoma (5). A recent study shows that the expression of trichorhinophalangeal syndrome type 1 (Trps1) is directly related to MDR1/P-gp, and Trps1 can promote MDR1/P-gp gene expression in osteosarcoma cell lines. Therefore, Trps1 should be a promising molecular target for reversing drug resistance in osteosarcoma (6).

Although there has been some improvement in the pathogenesis, diagnosis, and treatment of osteosarcoma in recent years, the mechanism underlying the development of osteosarcoma remains obscure. Furthermore, efforts have rarely been intended at implementing system biology-based analyses to elaborate the underpinning pathological molecular mechanisms of osteosarcoma. Comprehensive analysis of latent causal genes within a pathway and/or a network framework could provide more holistic insights than classical single-gene analyses. In the present study, we first identified an osteosarcoma-related gene module (OSM) by combining the genome-wide association studies (GWAS) dataset of osteosarcoma with whole protein-protein interaction (PPI) network. Functions of genes contained in the OSM were also

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explored through WebGestalt and ToppGene online tools. Potential osteosarcoma diagnosis and treatment targets were further screened through topological and survival analyses of the OSM. This study should help understand the molecular mechanisms of osteosarcoma and provide a valuable pipeline for other types of disease.

Materials and methods

Data sources. Results from MutSigCV (broadinstitute.org/cancer/cga/mutsig) analysis on somatic mutations in osteosarcoma were obtained from dbGaP (ncbi.nlm.nih.gov/gap) (NCBI dbGaP study accession: phs000699.v1.p1 and dbGaP analysis accession: pha003862). The datasets consisted of 58 pairs of osteosarcoma and normal adjacent tissues. Forty-nine percent of the patients were male and 47% had metastases at diagnosis. Five-year overall survival was 49% with 33% for patients with metastatic disease and 64% for patients with localized disease. Illumina HiSeq 2000 was used for the whole genome sequencing of all samples. Genes with a P-value <1 were selected as seeds to identify the disease module underlying osteosarcoma.

The human PPI data containing 16,022 nodes and 228,122 edges were obtained from Hu's study (7), which collected and integrated two PPI datasets, i.e., Protein Interaction Network Analysis (PINA) platform (May 21, 2014) (8) and a human interactome compiled by a recent study (9).

Disease module identification. The OSM was identified using dmGWAS version 3.0 (10), an R package that implements heuristic local search algorithms to recognize candidate subnetworks or genes associated with complex diseases by incorporating the association signal from GWAS datasets into the PPI network, which has been efficiently applied in identifying disease modules. Osteosarcoma-related seed genes with their corresponding tested P-values and PPI networks were used as input, and other parameters were set as per the dmGWAS recommendations. Ultimately, the candidate disease modules were ranked in accordance with their normalized module scores and empirical P-values.

To test the non-randomness of the identified module, we first generated 1,000 random networks with the same number of nodes and edges as the identified OSM by utilizing the 'networkx' module in python (<https://www.python.org/>). Then, we computed the average values of clustering coefficients and the shortest-path distance for each random network. By counting the number of random networks with the average clustering coefficient (N_{cc}) greater than that of the OSM as well as the number of random networks with the average shortest-path distance (N_{sp}) less than that of the OSM, we could evaluate the significance level of non-randomness by calculating the empirical P-value ($N_{cc}/1000$ and $N_{sp}/1000$).

Functional enrichment analysis of the OSM. The functional features of the OSM were examined through WebGestalt (11) and ToppGene (12). WebGestalt incorporates the information from multiple sources to detect the biological themes out of the given gene lists, including identifying the significantly enriched gene ontology (GO) terms. GO terms with a P<0.05

were considered significantly enriched. ToppGene was chosen to analyze the Kyoto Encyclopedia of Genes and Genomes (KEGG) pathways enriched in the OSM. The pathways with false discovery rate (FDR) <0.05 were considered significantly enriched.

Pathway crosstalk analysis of the significantly enriched pathways. Further, we carried out pathway crosstalk analysis to investigate the interactions among significantly enriched pathways (13). To demonstrate the overlap between any pair of pathways, we adopted two measurements, i.e., the Overlap Coefficient

$$(OC) = \frac{|A \cap B|}{\min(|A|, |B|)}$$

and the Jaccard Coefficient

$$(JC) = \frac{|A \cap B|}{|A \cup B|}$$

where *A* and *B* denote the lists of genes contained in the two tested pathways. We carried out the following procedure to establish the pathway crosstalk: i) We chose a set of pathways with FDR <0.05 for crosstalk analysis; ii) we calculated the number of shared OS genes between any pair of pathways. Pathway pairs with <2 overlapped OS genes were discarded; iii) we computed the overlap of all pairs of pathways and ranked them in accordance with their OC and JC values; and iv) we used the Cytoscape (14) software to visualize the chosen pathway crosstalk.

Inferring essential genes in the OSM. Previous studies reported that hub genes (high degree) and bottleneck genes (high betweenness) in gene networks are more important for cell survival (15-17). In addition, another study reported that minimum dominating sets of proteins (MDSets) play a topologically and biologically important role in controllability in protein interaction networks (18). Briefly, MDSet is an optimized subset of nodes from where each remaining node can be immediately reached by a single interaction. To identify the essential genes in the OSM, we ranked all module genes on the basis of their degree and betweenness centrality and obtained the MDSets within the OSM. Overlapping genes among hub genes, bottleneck genes, and genes contained in the MDSets were considered valuable for osteosarcoma progression.

Statistical analysis. All of the statistical analyses were conducted in R 3.4.1 (r-project.org/) and Python 2.7.11 (python.org/downloads/release/python-2711/). Networkx module of Python was used for the non-randomness test of identified gene module. P<0.05 was used as the criteria for the identification of significantly enriched functions.

Results

Identification of disease module associated with osteosarcoma. Fig. 1 illustrates the flow chart of this study. By taking advantage of dmGWAS (10), candidate disease modules related to

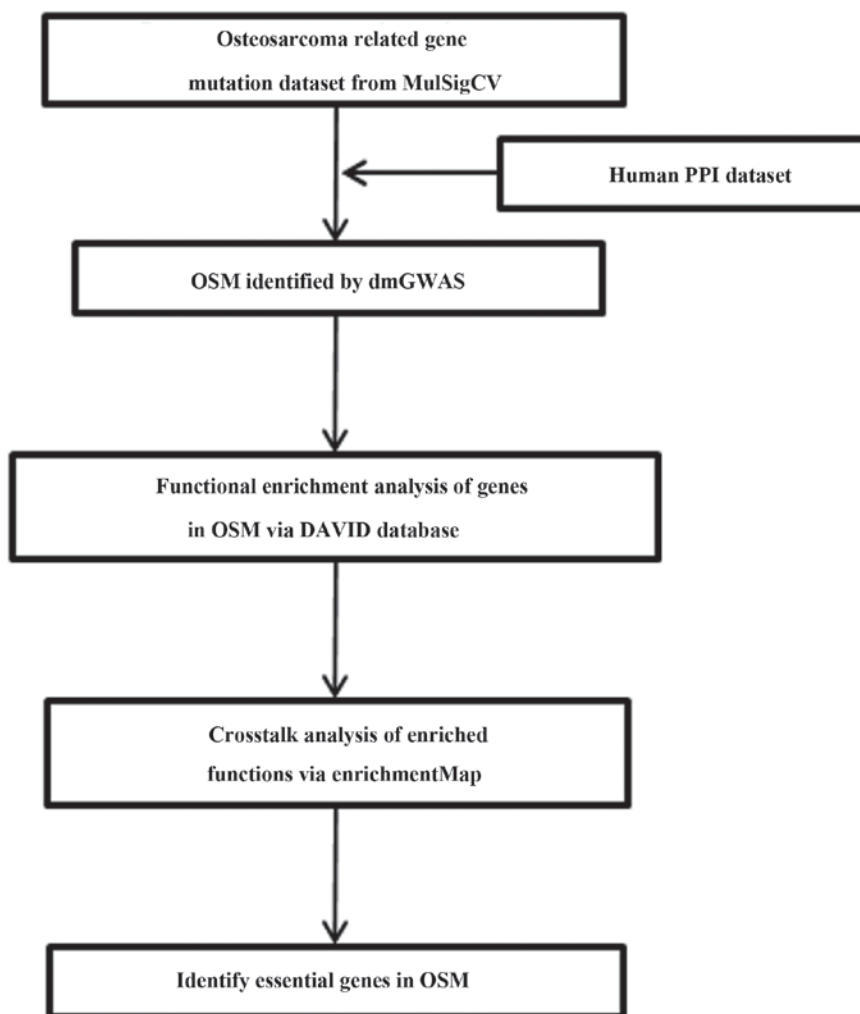


Figure 1. Flow chart of the study. OSM, osteosarcoma-related gene module; PPI, protein-protein interaction; GWAS, genome-wide association studies.

osteosarcoma were deduced by incorporating the association signal from GWAS into the PPI network. The top 150 candidate modules with the highest module scores and empirical $P < 0.001$ were selected. The OSM was obtained by merging these modules and excluding the redundant entries, which resulted in a subnetwork containing 201 nodes and 268 edges (Fig. 2). To test for the non-randomness of the identified disease module, 1,000 random subnetworks were generated, and their corresponding average clustering coefficient and the mean shortest-path distance were compared with the corresponding values of the OSM. For these random subnetworks, the average clustering coefficient was 0.01, which is statistically significantly smaller than that of the OSM (clustering coefficient, 0.07; empirical $P < 0.001$). The average shortest-path distance for the 1000 random subnetwork was 4.75, which was statistically significantly higher than that of the OSM (shortest-path distance, 3.37; empirical $P < 0.001$). This indicated that our identified OSM was a non-random network. Notably, some of the genes within the OSM, such as small nuclear ribonucleoprotein U11/U12 subunit 25 (SNRNP25) (19,20), cyclin B3 (CCNB3) (21), tumor protein p53 (TP53) (22,23), OS9, endoplasmic reticulum lectin (OS9) (24), and phosphatase and tensin homolog (PTEN) (25), have been reportedly associated with osteosarcoma in previous studies.

Significantly enriched functions of the OSM. In this study, significantly enriched GO terms and KEGG pathways of the OSM were identified through WebGestalt and ToppGene online tools, respectively. Consequently, a total of 30 GO terms (Table I) and 32 KEGG pathways (Table II) were significantly associated with the OSM. GO terms related to response to stimulus (e.g., response to estradiol and to epidermal growth factor) (26,27) and intracellular signal transduction (e.g., hippo signaling) (28) were obtained in this study; these were consistent with the previous findings about osteosarcoma. Terms directly related to protein or nucleic acid binding (e.g., RNA polymerase II transcription factor binding, protein N-terminus binding, lipoprotein particle receptor binding, single-stranded RNA binding, and damaged DNA binding) and catalytic activity (e.g., deacetylase activity, phosphotransferase activity, phosphate group as a acceptor, and kinase activity of nucleobase-containing compounds) were also included. GO terms related to translation (e.g., cytoplasmic translation) were also enriched in OS genes. In line with previous studies, several pathways, such as mTOR signaling pathway (ranked 5th) (29,30), Hippo signaling pathway (ranked 9th) (31), PI3K-Akt signaling pathway (ranked 10th) (30,32), MAPK signaling pathway (ranked 11th) (33), Wnt signaling pathway (ranked 22nd) (34,35), p53

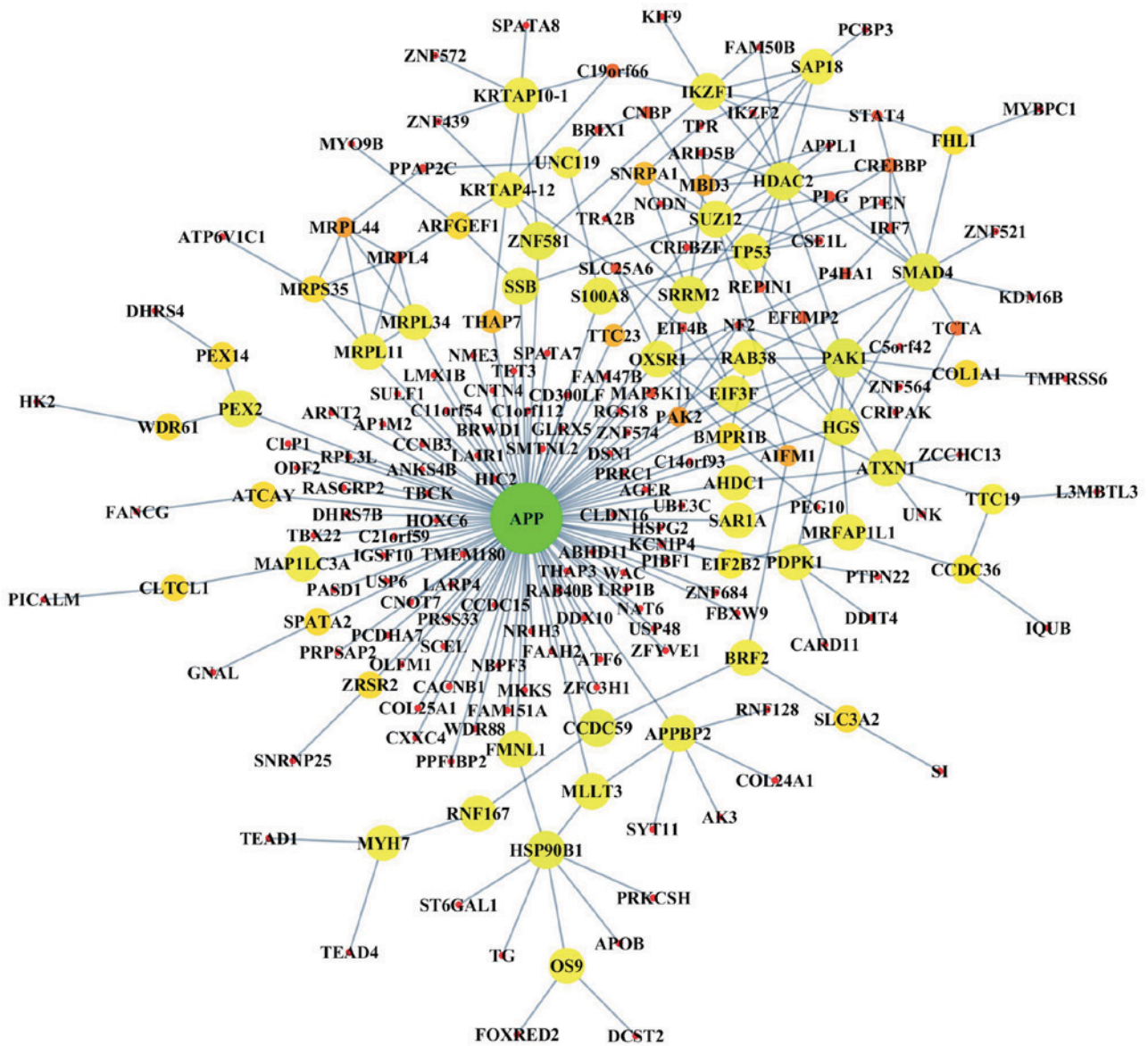


Figure 2. Osteosarcoma-specific network. An osteosarcoma-specific network was constructed by integrating the association signal from GWAS into the protein-protein interaction network with 201 nodes and 268 edges. Node size corresponds to its degree in the OSM. A larger size indicates a higher degree, and the node color corresponds to its betweenness centrality in the OSM. Brighter colors indicate higher betweenness centrality. OSM, osteosarcoma-related gene module; GWAS, genome-wide association studies.

signaling pathway (ranked 24th) (36-38), and TGF- β signaling pathway (ranked 27th) (38,39), were enriched in OS genes. In addition, several cancer-related pathways were identified, such as Pathways in cancer, Proteoglycans in cancer, central carbon metabolism in cancer, and transcriptional misregulation in cancer. Moreover, cell proliferation, survival, and apoptosis-associated biological processes comprising cell cycle, FoxO signaling pathway, protein processing in the endoplasmic reticulum, RNA transport, and focal adhesion were also obtained.

Crosstalk among significantly enriched pathway. To understand how significantly enriched pathways interact with each other, we carried out a pathway crosstalk analysis among the 32 significantly enriched pathways. The approach was based on the assumption that two pathways were considered to interact with each other if they shared a proportion

of the OS genes. With this criterion for pathway crosstalk analysis, 22 pathways were selected. All the pathway pairs were used to build the pathway crosstalk, and the overlapping level between two pathways was measured on the basis of the average scores of the coefficients OC and JC. Based on their crosstalk, these pathways could be roughly divided into two main modules, each of which included pathways that shared more interactions compared with other pathways and might involve the same or similar biological processes (Fig. 3). One module primarily comprised cell growth, death, and cancer-related pathways, such as those associated with the cell cycle, p53 signaling pathway, central carbon metabolism in cancer, transcriptional misregulation in cancer, and chronic myeloid leukemia. Conversely, the second module was mainly dominated by signal transduction-related pathways, including mTOR signaling pathway, FoxO signaling pathway, Hippo signaling pathway, PI3K-Akt signaling

Table I. Gene ontology terms enriched in the osteosarcoma-related gene module.

Category	GO terms	Cell process	P-value	Genes included in the GO term
Biological process	GO:0070482	Response to oxygen levels	1.43x10 ⁻⁴	COL1A1; CREBBP; AGER; HDAC2; SMAD4; PAK1; DDIT4; PTEN; TP53; HSP90B1; AIFM1; ARNT2
Biological process	GO:0048511	Rhythmic process	2.15x10 ⁻³	NR1H3; CREBBP; PASD1; FANCG; HDAC2; SMAD4; PTEN; BMPR1B; TP53; EIF2B2
Biological process	GO:0032355	Response to estradiol	2.19x10 ⁻³	COL1A1; APOB; MBD3; PTEN; AIFM1; ARNT2
Biological process	GO:0002181	Cytoplasmic translation	3.02x10 ⁻³	EIF4B; SSB; UNK; EIF3F
Biological process	GO:0031349	Positive regulation of defense response	4.05x10 ⁻³	NR1H3; CREBBP; PTPN22; SLC25A6; IRF7; PAK1; PAK2; PDPK1; S100A8; HSP90B1; CARD11
Biological process	GO:0071826	Ribonucleoprotein complex subunit organization	6.05x10 ⁻³	CLP1; EIF4B; CNOT7; BRIX1; RPL3L; MRPL11; ZRSR2
Biological process	GO:0035329	Hippo signaling	6.46x10 ⁻³	NF2; TEAD1; TEAD4
Biological process	GO:0055076	Transition metal ion homeostasis	7.64x10 ⁻³	TMPRSS6; APP; SMAD4; S100A8; PICALM
Biological process	GO:0016570	Histone modification	7.68x10 ⁻³	SAP18; CREBBP; KDM6B; SUZ12; HDAC2; SMAD4; WAC; MBD3; TP53; WDR61; ARID5B
Biological process	GO:0070849	Response to epidermal growth factor	8.13x10 ⁻³	COL1A1; PDPK1; TPR
Molecular function	GO:0001085	RNA polymerase II transcription factor binding	1.13x10 ⁻⁴	CREBBP; HDAC2; SMAD4; TEAD1; TEAD4; TP53; MKKS
Molecular function	GO:0019205	Nucleobase-containing compound kinase activity	1.31x10 ⁻³	CLP1; NME3; AK3; CARD11
Molecular function	GO:0005057	Signal transducer activity, downstream of receptor	3.19x10 ⁻³	SMAD4; MAP3K11; PAK1; PAK2; BMPR1B; OXSR1
Molecular function	GO:0003727	Single-stranded RNA binding	5.23x10 ⁻³	EIF4B; ATXN1; TRA2B; CNBP
Molecular function	GO:0016776	Phosphotransferase activity, phosphate group as acceptor	7.33x10 ⁻³	NME3; AK3; CARD11
Molecular function	GO:0047485	Protein N-terminus binding	1.61x10 ⁻²	SRRM2; PEX14; TP53; THAP7
Molecular function	GO:0019213	Deacetylase activity	1.67x10 ⁻²	SAP18; HDAC2; MBD3
Molecular function	GO:0070325	Lipoprotein particle receptor binding	1.84x10 ⁻²	APOB; HSP90B1
Molecular function	GO:0003735	Structural constituent of ribosome	2.10x10 ⁻²	MRPL4; MRPS35; RPL3L; MRPL34; MRPL11
Molecular function	GO:0003684	Damaged DNA binding	2.30x10 ⁻²	CREBBP; FANCG; TP53
Cellular component	GO:0005788	Endoplasmic reticulum lumen	1.07x10 ⁻³	OS9; COL1A1; COL24A1; APOB; P4HA1; PRKCSH; HSP90B1; FOXRED2; COL25A1
Cellular component	GO:0000118	Histone deacetylase complex	7.72x10 ⁻³	SAP18; APPL1; HDAC2; MBD3
Cellular component	GO:0070603	SWI/SNF superfamily-type complex	1.43x10 ⁻²	SUZ12; APPL1; HDAC2; MBD3
Cellular component	GO:0017053	Transcriptional repressor complex	2.46x10 ⁻²	PASD1; APPL1; HDAC2; MBD3
Cellular component	GO:0005840	Ribosome	2.86x10 ⁻²	REPIN1; MRPL4; MRPS35; RPL3L; MRPL34; MRPL11; MRPL44
Cellular component	GO:0008023	Transcription elongation factor complex	2.90x10 ⁻²	MLLT3; PEX2; WDR61
Cellular component	GO:0044454	Nuclear chromosome part	4.17x10 ⁻²	NR1H3; IKZF1; CREBBP; SUZ12; REPIN1; HDAC2; SMAD4; MBD3; SSB; TP53; DSN1
Cellular component	GO:0031983	Vesicle lumen	4.48x10 ⁻²	APOB; APP; PLG; HSP90B1
Cellular component	GO:0030139	Endocytic vesicle	4.52x10 ⁻²	AP1M2; SYT11; RAB38; APOB; HSP90B1; FMNL1; PICALM
Cellular component	GO:0031984	Organelle subcompartment	4.77x10 ⁻²	AP1M2; ARFGEF1; SULF1; RAB38; APP; ZFYVE1; ST6GAL1; CLTCL1

GO, gene ontology.

Table II. Kyoto Encyclopedia of Genes and Genomes pathways enriched in the osteosarcoma-related gene module.

Pathways	P-value	False discovery rate	Genes included in the pathway
Hepatitis B	1.01x10 ⁻⁶	2.47x10 ⁻⁴	STAT4, TP53, SMAD4, HSPG2, PTEN, IRF7, CREBBP
Pathways in cancer	1.67x10 ⁻⁶	2.15x10 ⁻³	RASGRP2, CREBBP, HDAC2, TP53, APPL1, SMAD4, HSP90B1, PTEN, TPR, ARNT2
Prostate cancer	1.80x10 ⁻⁵	1.78x10 ⁻³	PTEN, TP53, CREBBP, HSP90B1, PDPK1
Hepatitis C	1.23x10 ⁻⁴	4.72x10 ⁻³	CLDN16, PDPK1, IRF7, TP53, NR1H3
mTOR signaling pathway	6.68x10 ⁻⁵	4.72x10 ⁻³	PTEN, PDPK1, DDIT4, EIF4B
Cell cycle	8.84x10 ⁻⁵	4.72x10 ⁻³	SMAD4, CCNB3, HDAC2, TP53, CREBBP
Renal cell carcinoma	9.72x10 ⁻⁵	4.72x10 ⁻³	CREBBP, ARNT2, PAK2, PAK1
FoxO signaling pathway	1.28x10 ⁻⁴	4.72x10 ⁻³	SMAD4, PTEN, CCNB3, CREBBP, PDPK1
Hippo signaling pathway	2.44x10 ⁻⁴	7.23x10 ⁻³	SMAD4, BMPR1B, NF2, TEAD1, TEAD4
PI3K-Akt signaling pathway	2.38x10 ⁻⁴	7.23x10 ⁻³	DDIT4, HSP90B1, PTEN, PDPK1, COL1A1, TP53, EIF4B
MAPK signaling pathway	3.29x10 ⁻⁴	8.85x10 ⁻³	RASGRP2, TP53, CACNB1, MAP3K11, PAK1, PAK2
Protein processing in endoplasmic reticulum	3.75x10 ⁻⁴	9.24x10 ⁻³	OS9, SAR1A, PRKCSH, HSP90B1, ATF6
RNA transport	4.06x10 ⁻⁴	9.25x10 ⁻³	EIF3F, EIF2B2, TPR, SAP18, EIF4B
T cell receptor signaling pathway	5.59x10 ⁻⁴	1.18x10 ⁻²	PDPK1, CARD11, PAK1, PAK2
Huntington's disease	6.85x10 ⁻⁴	1.35x10 ⁻²	CLTCL1, HDAC2, TP53, SLC25A6, CREBBP
Thyroid hormone signaling pathway	8.98x10 ⁻⁴	1.40x10 ⁻²	PDPK1, HDAC2, TP53, CREBBP
Endometrial cancer	8.92x10 ⁻⁴	1.40x10 ⁻²	PTEN, TP53, PDPK1
Focal adhesion	8.41x10 ⁻⁴	1.40x10 ⁻²	PTEN, PDPK1, PAK1, PAK2, COL1A1
Proteoglycans in cancer	8.60x10 ⁻⁴	1.40x10 ⁻²	PDPK1, HSPG2, TP53, PAK1, EIF4B
Colorectal cancer	1.49x10 ⁻³	2.20x10 ⁻²	SMAD4, APPL1, TP53
Ribosome	1.56x10 ⁻³	2.20x10 ⁻²	MRPL11, MRPL34, MRPL4, RPL3L
Wnt signaling pathway	1.83x10 ⁻³	2.39x10 ⁻²	SMAD4, TP53, CREBBP, CXXC4
Central carbon metabolism in cancer	1.86x10 ⁻³	2.39x10 ⁻²	HK2, PTEN, TP53
p53 signaling pathway	2.02x10 ⁻³	2.50x10 ⁻²	CCNB3, PTEN, TP53
Chronic myeloid leukemia	2.38x10 ⁻³	2.82x10 ⁻²	SMAD4, HDAC2, TP53
Peroxisome	3.42x10 ⁻³	3.89x10 ⁻²	DHRS4, PEX2, PEX14
TGF- β signaling pathway	3.54x10 ⁻³	3.89x10 ⁻²	SMAD4, BMPR1B, CREBBP
Influenza A	3.78x10 ⁻³	3.99x10 ⁻²	PLG, IRF7, SLC25A6, CREBBP
Protein digestion and absorption	4.30x10 ⁻³	4.24x10 ⁻²	SLC3A2, COL24A1, COL1A1
Transcriptional misregulation in cancer	4.18x10 ⁻³	4.24x10 ⁻²	HDAC2, TP53, ARNT2, MLLT3
Thyroid cancer	4.95x10 ⁻³	4.73x10 ⁻²	TP53, TPR
Galactose metabolism	5.29x10 ⁻³	4.89x10 ⁻²	HK2, SI

pathway, Wnt signaling pathway, and MAPK signaling pathway. Furthermore, these two modules were linked by a couple of pathway interactions.

Essential genes in the OSM. To identify the essential genes within the OSM, we first ranked the OS genes based on their degree as well as betweenness centrality and obtained the MDSEts simultaneously. The genes intersecting among these three gene lists were considered as essential OS genes, which included APP, APPBP2, ATXN1, HSP90B1, IKZF1, KRTAP10-1, PAK1, PDPK1, SMAD4, SUZ12, and TP53. Some of these genes, such as HSP90B1 (30,39), PAK1 (40), SMAD4 (31,41), and TP53 (22,23), have already been reported to be associated with osteosarcoma. Besides, PDPK1 plays an important role in the mTOR signaling pathway and PI3K-Akt

signaling pathway, which are reportedly involved in the pathogenesis of osteosarcoma. Kaplan-Meier analysis for overall survival with osteosarcoma and the expression values of essential genes from the Cancer Genome Atlas (TCGA) identified APP, HSP90B1, SUZ12, and IKZF1 as prognosis-related genes (Fig. 4). High expressions of APP (median survival for low and high APP expression patients is 95 and 64 months), HSP90B1 (median survival for low and high HSP90B1 expression patients is 90 and 60 months), and SUZ12 (median survival for low and high SUZ12 expression patients is 97 and 64 months) were significantly associated with shorter overall survival with osteosarcoma, whereas high expression of IKZF1 (median survival for low and high APP expression patients is 57 and 81 months) was significantly associated with longer overall survival with osteosarcoma.

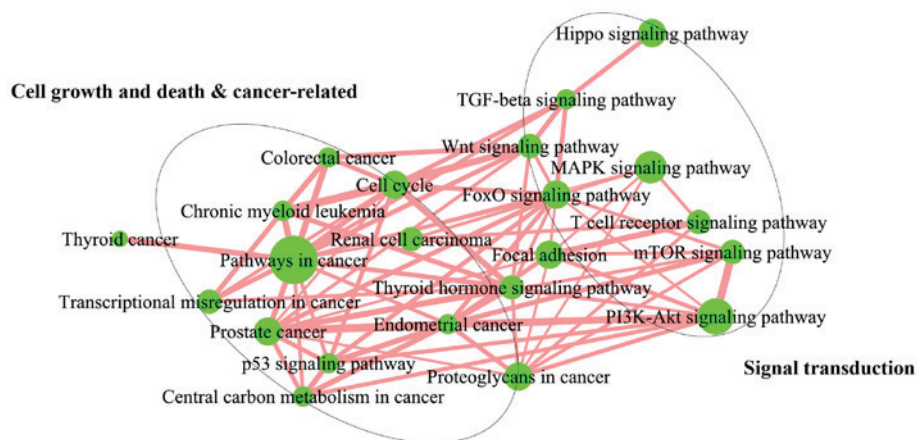


Figure 3. Pathway crosstalk among OS gene-enriched pathways. Nodes represent pathways, and edges represent crosstalk between pathways. Edge-width corresponds to the score of a specific pathway pair. A larger edge-width indicates a higher score, and the node size corresponds to the number of OS genes contained in the corresponding pathway.

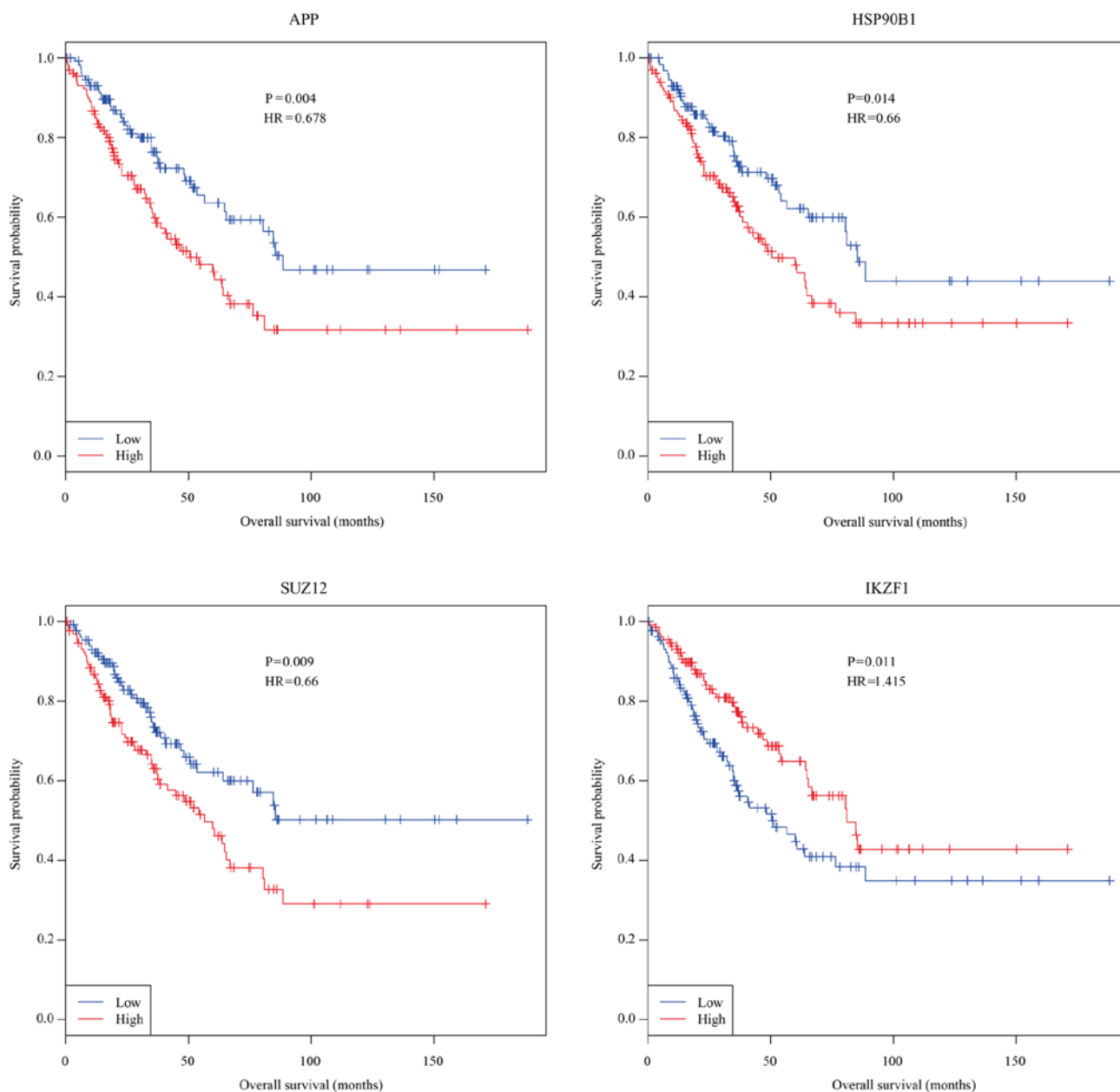


Figure 4. Kaplan-Meier curve analysis of the essential OS genes for overall survival of patients with osteosarcoma. Four essential OS genes were presented, including APP, HSP90B1, SUZ12 and IKZF1. HR, hazard ratio (low vs. high).

Discussion

With the development of high-throughput technology, more and more genes/proteins have been identified as associated with osteosarcoma. Over the past ten years, much has been learnt from studies on animals, human subjects, or cell models about the molecular mechanisms underlying osteosarcoma. However, a comprehensive understanding of the biological process associated with osteosarcoma pathogenesis at the molecular level remains largely unclear. It is imperative to decipher the latent pathogenesis of osteosarcoma at the systems biology level. In this work, we first identified an OSM by combining the GWAS dataset of osteosarcoma with whole PPI network. A relatively comprehensive human physical interactome that integrated PPI data from various sources has been used in this study to reduce the limitations due to incomplete and noisy human interactome. Functions of genes contained in the OSM and potential osteosarcoma diagnosis and treatment targets were further explored.

The OSM we identified was a non-random network and 11 essential OS genes have been identified as essential in the module. Some of the essential in the module, such as HSP90B1 (29,38), PAK1 (39), SMAD4 (30,40), and TP53 (21,22), have already been reported to be related to osteosarcoma, suggesting the reliability of the methods we used in this study. In addition, although several OS genes have been found as not directly involved in the pathogenesis of osteosarcoma, they are a part of biological pathways that play important roles in osteosarcoma development. PDPK1 plays an important role in the mTOR signaling pathway and PI3K-Akt signaling pathway, which are reportedly involved in the pathogenesis of osteosarcoma. DDIT4 and EIF4B were included in the OSM; both of them are involved in mTOR signaling pathway and PI3K-Akt signaling pathway, which are both closely associated with osteosarcoma. Some of the genes, such as STAT4 and LRP1B, have not been demonstrated to be related to osteosarcoma. Some of the members of the same family with those unproved genes, such as STAT3 (42,43) and LRP1 (19), have shown their relevance in osteosarcoma in recent studies.

Kaplan-Meier curve analysis was performed to explore the associations between overall survival and these 11 essential OS genes in patients with osteosarcoma. Consequently, four essential OS genes, namely APP, HSP90B1, SUZ12, and IKZF1, were found to be significantly associated with overall survival with osteosarcoma ($P < 0.05$). Importantly, SUZ12 polycomb repressive complex 2 subunit (SUZ12) has been identified at the breakpoints of a recurrent chromosomal translocation reported in endometrial stromal sarcoma. Thus, the OS genes identified as essential are a list of potential candidates and are reliable for researchers for further exploration.

In conclusion, our study provides a pipeline for systematically analyzing genome-wide datasets of osteosarcoma. Several valuable biomarkers which should be helpful for understanding the underlying mechanisms of osteosarcoma were identified.

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Availability of data and material

The datasets generated and/or analyzed during the current study are available in the dbGaP (ncbi.nlm.nih.gov/gap) (NCBI dbGaP study accession: phs000699.v1.p1 and dbGaP analysis accession: pha003862).

Authors' contributions

YZ and FY made substantial contributions to the conception and design, and interpretation of the data. YZ and FY revised the manuscript critically for important intellectual content and gave final approval of the version to be published. YZ and FY agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the study are appropriately investigated and resolved.

Ethics approval and consent to participate

Not applicable.

Patient consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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