

Alternative splicing of leptin receptor overlapping transcript in osteosarcoma

Emel Rothzerg^{1,2} , Xuan D Ho³, Jiake Xu¹, David Wood¹, Aare Märtson⁴, Katre Maasalu⁴ and Sulev Kõks^{2,5} 

¹School of Biomedical Sciences, The University of Western Australia, Perth, WA 6009, Australia; ²Perron Institute for Neurological and Translational Science, QEII Medical Centre, Nedlands, WA 6009, Australia; ³Department of Oncology, College of Medicine and Pharmacy, Hue University, Hue 53000, Vietnam; ⁴Department of Traumatology and Orthopaedics, University of Tartu, Tartu University Hospital, Tartu 50411, Estonia; ⁵Centre for Molecular Medicine and Innovative Therapeutics, Murdoch University, Murdoch, WA 6150, Australia

Corresponding author: Emel Rothzerg. Email: emel.rothzerg@research.uwa.edu.au

Impact statement

Osteosarcoma (OS, also known as osteogenic sarcoma) is the most common primary malignancy of bone in children and adolescents. The molecular mechanisms of OS are extremely complicated and its molecular mediators remain to be elucidated. We sequenced total RNA from 18 OS bone samples (paired normal–tumor biopsies). We found statistically significant (FDR <0.05) 26 differentially expressed transcript variants of *LEPROT* gene with different expressions in normal and tumor samples. These findings contribute to the understanding of molecular mechanisms of OS development and provide encouragement to pursue further research.

Abstract

Alternative splicing of RNA is an essential mechanism that increases proteomic diversity in eukaryotic cells. Aberrant alternative splicing is often associated with various human diseases, including cancer. We conducted whole-transcriptome analysis of 18 osteosarcoma bone samples (paired normal–tumor biopsies). Using RNA-seq, we identified statistically significant (FDR <0.05) 26 differentially expressed transcript variants of leptin receptor overlapping transcript (*LEPROT*) gene. Some of the transcripts were overexpressed in normal cells, whereas others were overexpressed in tumor cells. The function of *LEPROT* is not completely understood. Herein, we highlight a possible association between OS and aberrant alternative splicing events and its interaction with the expression of *LEPROT*. We also discuss the role of *LEPROT* in regulating growth hormone and its receptor, and the relationship with initiation and progression of OS. This research study may help to understand the association of

alternative splicing mechanism in OS and in tumorigenesis more generally. Further, *LEPROT* gene can also be considered as a potential biomarker of osteosarcoma.

Keywords: Osteosarcoma, transcriptome, LEPROT, RNA sequencing, alternative splicing, osteogenic sarcoma

Experimental Biology and Medicine 2020; 245: 1437–1443. DOI: 10.1177/1535370220949139

Introduction

Osteosarcoma (OS) is the most common primary tumor of bone in children and adolescents, with a second peak in incidence in people over the age of 50.^{1,2} OS is characterized by the presence of malignant mesenchymal stem cells (MSCs) producing immature bone matrix or osteoid.³ OS commonly develops in long bones such as the distal femur, proximal tibia, or proximal humerus.⁴ Patients usually present with pain and swelling. The diagnosis is confirmed by histology and staging studies such as MRI and systemic radionuclide scans.^{5–7} Current treatment of OS, a combination of surgery and chemotherapy (doxorubicin,

methotrexate, and cisplatin), has improved outcomes significantly, although this regime is still only successful in 90% of patients.⁸ The precise underlying mechanism of OS remains obscure in most individuals; however, the risk of developing OS is influenced by bone turnover, age, environment (drug or radiation therapy), other bone diseases (such as Paget's disease), genetic alterations and hormonal regulation of puberty (such as growth hormone).^{9–13}

RNA sequencing (RNA-Seq) technology is a powerful tool to analyze the transcriptome of a cell.¹⁴ Gene expression studies have been traditionally carried out by northern blot and quantitative polymerase chain reaction (qPCR),

which are limited to single transcript expressions.^{15,16} The RNA-seq technique provides higher resolution of the dynamic nature of the transcriptome.^{15,17} Beyond measuring gene expression, this technique facilitates the discovery of novel transcripts, identification of alternative (differential) splicing (AS) events in genes, and detection of allele-specific expression on a genome-wide scale.^{15–18} Consequently, RNA-seq is a useful method for interpreting the functional elements of the genome and also understanding the underlying mechanisms of complex diseases in a species.^{19,20} AS is a crucial mechanism that generates proteomic diversity in eukaryotes.¹⁹ It is mainly regulated by cis-acting elements and trans-acting factors.²¹ Growing evidence suggests that more than 90% of multi-exon genes undergo AS in humans.^{22,23} Deregulation of AS programming can produce a variety of transcript isoforms with unique protein-coding and possibly different or antagonistic biological functions from the same gene.^{24,25} Predictably, abnormal splicing can disturb normal cellular physiology and eventually lead to diseases, including cancer.^{23–26} The involvement of AS in each of the widely recognized and accepted hallmarks of cancer has been investigated.²⁷ In particular, apoptosis and metastasis are directly affected by AS.²⁸ Moreover, it can also play an essential role in invasiveness, angiogenesis, and chemo/radio-resistance to therapy.^{28,29}

Little is known about the underlying molecular mechanism of AS in various cancer types, especially in OS. To improve our understanding of the genetic mechanisms involved in developing OS, we performed RNA-Seq transcriptome analysis from 18 normal–tumor pairs of bone biopsies by computational bioinformatics. Differential exon usage was studied to highlight AS and transcription events present between normal and tumor samples using the DEXSeq package. Another aim of this study was to identify potential molecular biomarkers and novel therapeutic target candidates for the early detection and treatment of OS.

Materials and methods

Samples collection

The study was investigated and approved by the Ethics Review Committee on Biomedical Research of Hue University of Medicine and Pharmacy. The participants and patient representatives signed and dated the informed consent forms before surgery.

Normal and cancerous bone samples were collected directly after surgery (limb sparing or amputation) from 18 Vietnamese patients who, previously, had histological confirmation of OS. The collected biopsies were replaced on dry ice and stored at -80°C until processed for RNA extraction.

Total RNA isolation from bone biopsies

Approximately 50 mg of bone sample was ground with liquid nitrogen in a pestle and mortar and pre-TRIzol treatment was performed (Invitrogen Corp., Carlsbad, CA, USA). RNeasy Fibrous Tissue Mini Kit (Qiagen Inc., Valencia CA, USA) was used to isolate total RNA from bone tissue following the manufacturer's protocol.

Isolated RNA was completely dissolved in RNase-free water and stored at -80°C . The quality of total RNA was determined by Agilent 2100 Bioanalyzer system and the RNA 6000 Nano Kit (Agilent Technologies Inc., CA, USA).

Fifty nanograms of total RNA was amplified using Ovation RNA-Seq System V2 (NuGen, Emeryville, CA, USA) and the resulting cDNAs were pooled in equal amounts. The pooled cDNA was used to prepare the DNA fragment library using SOLiD System chemistry (Life Technologies Corp, Carlsbad, CA, USA). Sequencing was done by SOLiD 5500 W platform and DNA sequencing chemistry (Life Technologies Corp., Carlsbad, CA, USA). Raw data (75 bp) were color-space mapped to the human genome hg38 (GRCH38) reference through the mapping algorithm implemented in the LifescapeTM Genomic Analysis software (Life Technologies Corp.). The mapping confidence had been noted as higher than 90 due to the quality threshold was set to 10. The reads scores below 10 were filtered out. Mapping quality was at average of 30. Annotation of the reads based on the gencode v22 files.³⁰

Statistical data analyses were performed through the DEXseq package for R.³¹ DEXseq is a Bioconductor package specifically designed to find differential exon usage (DEU) based on RNA-seq data. DEU describes the relative usage of exons induced by the experimental conditions.³²

More details on data pre-processing can be found here (<https://bioconductor.org/packages/release/bioc/vignettes/DEXSeq/inst/doc/DEXSeq.html>). The DEXseq package also performs sample comparison and adjusts the *P*-value to overcome multiple testing problems.^{33–35} Through DEXseq package, the Benjamini-Hochberg procedure used to control the false discovery rate (FDR).³⁶

Results

Patient characteristics

Paired samples (normal–tumor) of surgical biopsies of bone were collected from 18 Vietnamese OS patients. Diagnosis was confirmed by a pathologist by examination of the biopsies. Tumor sites were located in the femur (55.56%), tibia (33.33%), and humerus (11.11%). Patient age ranged from 7 to 52 years (mean = 18 years) and there were 7 females and 11 males. Patients' demographic and clinical characteristics are listed in Table 1.

Validation of differential exon usage of LEPROT in patient samples

A mean-average (MA)-plot of the log₂ fold change of all transcripts (over 4075 transcripts) expressed in normal and tumor samples is presented in Figure 1. Red points indicate the log fold change versus average normalized count per exon (FDR < 0.05), whereas red triangles represent exons expressed with log₂-fold change greater than 2 or less than -2 .

The purpose of the study was to investigate AS events between 18 paired normal-tumor OS samples by RNA-seq. As shown in Figure 2(a), statistically significant (FDR < 0.05) changes in expression levels of leptin receptor overlapping

Table 1. Characteristics of osteosarcoma patients in the present study ($n=18$).

Patient code	Gender	Age	Site of tumor	Stage	Metastasis	Chemotherapy
OSVN001	Female	16	Femur	I	No	Yes
OSDN001	Male	23	Tibia	III	Yes	Yes
OSVN003	Male	13	Femur	I	No	Yes
OSVN004	Female	16	Femur	I	No	Yes
OSVN005	Male	18	Femur	I	No	Yes
OSVN006	Male	18	Femur	I	No	Yes
OSVN008	Male	52	Femur	I	Yes	No
OSHN008	Female	24	Tibia	I	No	Yes
OSHN009	Male	16	Femur	I	No	Yes
OSHN010	Female	20	Femur	I	No	Yes
OSHN011	Male	7	Tibia	I	No	No
OSHN012	Male	11	Humerus	I	No	No
OSHN013	Male	17	Femur	I	No	Yes
OSHN014	Female	16	Tibia	III	No	Yes
OSVN015	Male	15	Tibia	I	No	Yes
OSHN015	Female	8	Tibia	I	No	Yes
OSHN016	Male	20	Femur	I	No	Yes
OSHN017	Female	23	Humerus	I	No	Yes

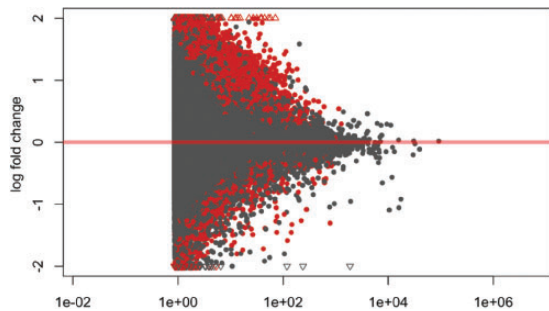


Figure 1. Mean-average (MA)-plot of normalized mean expression versus log₂-fold change. The red marks represent the log of fold change versus average normalized count per exon that are significant (FDR < 0.05). The red triangles represent exons with log₂-fold change greater than 2 or less than -2. The grey marks and triangles represent non-significant results. (A color version of this figure is available in the online journal.)

transcript (*LEPROT*) exons were observed between normal and tumor samples. Most of the exons are expressed in normal tissue, while expression in the tumor sample remained low. However, DEXseq removes the exon level changes in expression to highlight differential exon usage of the gene. The exons shown in purple presented with significant differential exon usage (bottom panel, bin E014, E040, and E042), suggesting potential AS events (Figure 2 (b)). The comparisons of each exon expression between tumor and normal samples were performed by normalization counts, as shown in Figure 2(c).

We identified 27 novel transcript variants of the *LEPROT* gene (Table 2), 26 of those transcripts have statistically significant (FDR < 0.05) different exon usage. This suggests that different isoforms use the exons differently. One transcript (E037) identified as having different exon usage was subsequently shown to be non-significant (FDR > 0.05, highlighted in red in Table 2).

As visualized in Figure 2(a) and listed in Table 2, 5 transcripts of *LEPROT* demonstrated overexpression in the tumor samples, while 22 transcripts (21 significant/1 non-

significant) presented with overexpression in the normal samples. Decrease expression of *LEPROT* transcripts in tumor samples eventually downregulates general *LEPROT* expression in tumor samples.

Discussion

The limiting factor in improving treatment for OS is a lack of understanding of the molecular mechanism of the disease, which leads to an inability to diagnose and treat OS at an earlier stage, or to develop more effective therapies. RNA-seq can be a potentially powerful method to identify differential exon usage in OS and allow identification of potential biomarkers of the disease.²⁷ Differential usage of exons produces different transcripts from the same gene.¹⁸ Cancerous cells can have alternate patterns of exon usage within individual genes compared to normal cells, suggesting that AS may play a key role in shaping the phenotype of the tumor.²³

In this study, we have investigated AS events in 18 paired normal - tumor OS samples. Interestingly, our results showed that the *LEPROT* gene underwent AS and identified 26 statistically significant (FDR < 0.05) novel transcripts. These transcripts showed different expression levels between tumor and normal tissues, suggesting there is a potential functional association between AS of *LEPROT* and cancer progression.

A genome-wide expression analysis has suggested an association between *LEPROT* regulation and apoptosis pathway.³⁷ Unfortunately, the study did not explain the association further. However, the manifestations of *LEPROT* gene mutations have not been extensively studied, resulting in an incomplete understanding of the function or dysfunction of this gene in cancer metabolism.³⁸

LEPROT is expressed widely in many human tissues, but does not appear to be expressed in tumors.³⁹ Therefore, loss or frequent downregulation of *LEPROT* expression could be associated with tumor formation. The

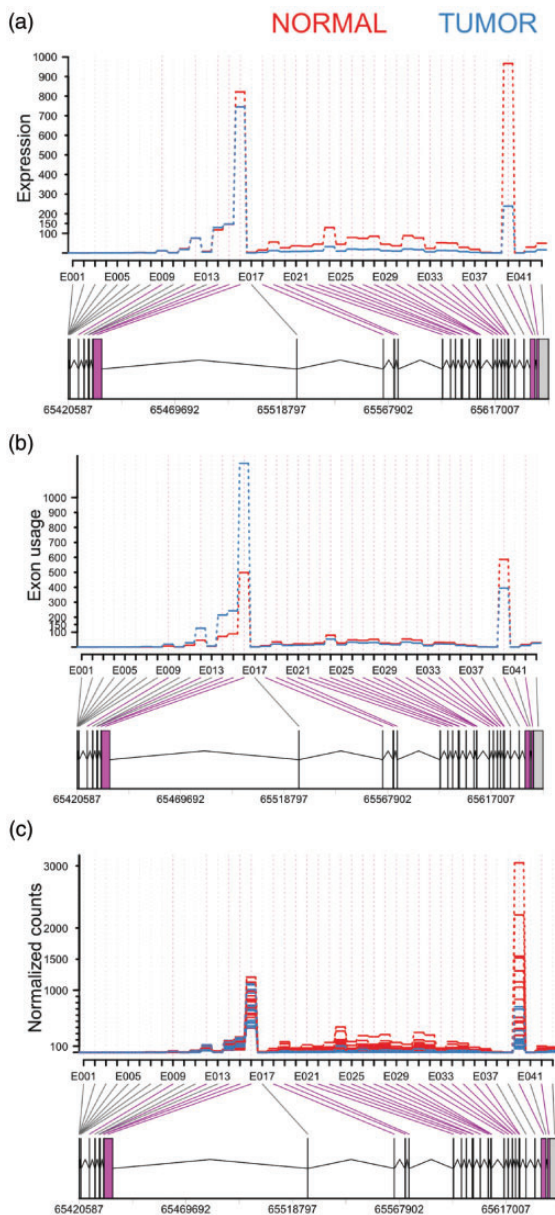


Figure 2. DEXseq analysis on RNA-Seq data. The x-axis shows individual exons within *LEPROT* gene, whereas the y-axis represents exon expression (a), exon usage (b), and normalization counts (c). The bars below the x-axis represent exons. The lines between the exons are introns. The numbers at the bottom are genomic locations of *LEPROT*. A highlights the fitted expression values of each of the exons of *LEPROT* gene for normal (red) and tumor (blue) samples. B visualizes exon usage in the gene. The exon in purple (E014, E040 and E042) and 26 purple lines between the bars and exon names indicate a significant differential exon usage ($FDR < 0.05$), whereas E037 revealed insignificant splicing ($FDR > 0.05$). C shows the comparison of exon expression between the samples. (A color version of this figure is available in the online journal.)

cause of downregulation of the *LEPROT* gene in cancer cells remains unknown. One study has suggested that AS can downregulate overall gene expression by tagging specific transcripts for degradation through the nonsense-mediated mRNA decay (NMD) surveillance pathway.⁴⁰ NMD frequently controls the translation stage and degrades the transcripts if they contain a premature termination codon (PTC), which can arise from genetic mutations or AS.^{41,42} Truncated proteins cannot function

properly or could even be toxic to the body; therefore, the synthesis of truncated proteins can contribute to various cancer types.⁴³ We therefore encourage further investigation of the regulation of *LEPROT* gene expression in normal and tumor cells. Our analysis highlighted *LEPROT* transcripts as being significantly under-expressed in 21 out of 26 tumor samples. Decrease expression of *LEPROT* transcripts in tumor samples, eventually can lead to reduction of total *LEPROT* expression level. The five overexpressed transcripts (absolute value of \log_2 fold-change > 1) can be considered as the noise from overall downregulation of *LEPROT* gene in OS. Therefore, it can be argued that they are not specific to OS initiation and progression. *LEPROT* is encoded by *LEP* receptor (*LEPR*) gene and they share the first two 5'-UTR exons.⁴⁴ Unsurprisingly, we previously identified significant downregulation of *LEPR* in OS.³⁰

Several studies have discussed the association between *LEPROT* expression level and growth hormone (GH) activity.⁴⁴ GH stimulates the development of bone and cartilage in children and adolescents.⁴⁵ It also has been associated with induction of insulin-like growth factor 1 (*IGF-1*) and *IGF-1* receptor (*IGF-1R*) gene expression, alterations in glucose metabolism, and modulation of cell proliferation genes.^{46–48} *IGF-1* is produced in the liver, stimulated by GH, and plays a main role in tissue growth and development.^{49–52} Higher circulating levels of *IGF-1* have a profound impact on cell proliferation, differentiation, promotion of cellular longevity, and inhibition of apoptosis.^{53,54} Consequently, overexpression of *IGF-1/IGF-1R* has been implicated in tumor formation, angiogenesis, and metastasis in various human cancer types, including OS.^{46–48,53} According to one study, *LEPROT* is directly involved in a receptor-mediated cell signaling pathway by regulating cell surface expression of growth hormone receptor (GHR) at the molecular level. The same study also suggested that silencing of *LEPROT* increases cell-surface expression of GHR in a mouse model.⁵⁵ Thus, increasing GHR expression level will lead to higher circulating levels of *IGF-1* and may eventually result in tumorigenesis.^{47–49,53,55}

Dysregulation of *LEPROT* is associated with various bone inflammation diseases in humans through the key inflammatory cytokines such as tumor necrosis factor alpha (*TNF- α*) and interleukin 6 (*IL-6*). Several studies have highlighted that bone inflammation is a frequent precursor to initiation and progression of OS.⁵⁶ Further, OS cells promote local inflammation and this leads to activation of local immune responses.⁵⁷ Not surprisingly, upregulation of *IL-6* and *TNF- α* has been observed in human OS cells.^{58,59} In addition, *IL-6* mediates tumor-host interactions that facilitate lung colonization of metastasis-initiating by OS cells.^{60,61} Consequently, *LEPROT* may be implicated in OS initiation and metastasis through upregulating expression of *IL-6* and *TNF- α* .

In conclusion, our data provide strong evidence that AS events of the *LEPROT* gene may be a risk factor for OS, and downregulation of *LEPROT* can be associated with tumorigenesis in bone. These results may facilitate a better understanding of the underlying molecular mechanism related to

Table 2. Differently spliced transcript variants of *LEPROT*.

Group ID: Exon ID	Normal ^a	Tumor ^a	log2(fold-change) normal/tumor	P value	padj	Genomic data start	Genomic data end	Genomic data width
ENSG00000213625.7+ENSG00000116678.17: E014	71.55	214.78	-1.59	3.03E-13	4.07E-08	65431803	65431920	118
ENSG00000213625.7+ENSG00000116678.17: E015	88.50	242.77	-1.49	2.74E-10	9.22E-06	65431921	65432064	144
ENSG00000213625.7+ENSG00000116678.17: E027	45.21	28.69	0.66	3.32E-09	4.25E-05	65608753	65608901	149
ENSG00000213625.7+ENSG00000116678.17: E032	46.70	27.21	0.78	4.39E-09	4.73E-05	65617964	65618146	183
ENSG00000213625.7+ENSG00000116678.17: E016	498.02	1229.84	-1.30	1.01E-08	7.57E-05	65432065	65436007	3943
ENSG00000213625.7+ENSG00000116678.17: E022	21.01	13.80	0.61	8.97E-09	7.57E-05	65596448	65596593	146
ENSG00000213625.7+ENSG00000116678.17: E036	17.21	10.89	0.66	1.10E-08	7.57E-05	65622906	65622981	76
ENSG00000213625.7+ENSG00000116678.17: E021	21.80	12.71	0.78	9.81E-09	7.57E-05	65592657	65592865	209
ENSG00000213625.7+ENSG00000116678.17: E019	33.89	20.33	0.74	1.29E-08	8.44E-05	65570473	65570802	330
ENSG00000213625.7+ENSG00000116678.17: E040	586.05	394.12	0.57	1.75E-08	0.00010921	65633152	65635409	2258
ENSG00000213625.7+ENSG00000116678.17: E009	6.97	19.68	-1.50	2.13E-08	0.00011916	65425303	65425378	76
ENSG00000213625.7+ENSG00000116678.17: E028	51.71	31.11	0.73	3.28E-08	0.00013701	65609947	65610106	160
ENSG00000213625.7+ENSG00000116678.17: E023	27.34	17.71	0.63	1.37E-07	0.00037999	65598660	65598804	145
ENSG00000213625.7+ENSG00000116678.17: E024	78.79	53.17	0.57	3.83E-07	0.00072278	65601392	65601682	291
ENSG00000213625.7+ENSG00000116678.17: E031	53.74	33.47	0.68	3.83E-07	0.00072278	65616008	65616224	217
ENSG00000213625.7+ENSG00000116678.17: E012	45.95	125.95	-1.45	4.18E-07	0.000759	65429931	65430048	118
ENSG00000213625.7+ENSG00000116678.17: E034	31.50	20.95	0.59	3.14E-06	0.00236337	65619940	65620023	84
ENSG00000213625.7+ENSG00000116678.17: E035	30.34	19.92	0.61	3.24E-06	0.00240758	65621353	65621458	106
ENSG00000213625.7+ENSG00000116678.17: E042	17.90	10.30	0.80	5.92E-06	0.00325498	65636191	65637102	912
ENSG00000213625.7+ENSG00000116678.17: E029	27.13	19.09	0.51	6.46E-06	0.00347045	65610214	65610268	55
ENSG00000213625.7+ENSG00000116678.17: E033	14.09	9.19	0.62	6.61E-06	0.00352845	65619928	65619939	12
ENSG00000213625.7+ENSG00000116678.17: E020	15.80	10.90	0.54	9.26E-06	0.00429905	65572326	65572449	124
ENSG00000213625.7+ENSG00000116678.17: E025	26.93	15.93	0.76	1.14E-05	0.00479061	65601843	65601960	118
ENSG00000213625.7+ENSG00000116678.17: E026	47.90	32.81	0.55	1.19E-05	0.00490364	65605038	65605237	200
ENSG00000213625.7+ENSG00000116678.17: E018	8.83	4.67	0.92	1.83E-05	0.00607585	65565546	65565605	60
ENSG00000213625.7+ENSG00000116678.17: E030	21.85	15.65	0.48	4.28E-05	0.00984627	65610269	65610296	28
ENSG00000213625.7+ENSG00000116678.17: E037	11.05	5.21	1.08	0.000784	0.05035195	65622982	65623384	403

^aNormalized counts.

the initiation and progression of OS, thereby allowing identification of effective novel molecular target candidates for the treatment of the disease.

Authors' contributions: ER wrote the manuscript. XDH contributed in samples collection and laboratory works. JX provided valuable opinions related to the study. AM and KM

participated in design of the experiments. DW and SK supervised the experiments. All authors revised the manuscript.

DECLARATION OF CONFLICTING INTERESTS

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.



ETHICAL APPROVAL

The Ethics Review Committee on Biomedical Research of Hue University of Medicine and Pharmacy approved the protocols and informed consent form elaborated in the study. The informed consent forms signed and dated by the participants and representatives of patients.

FUNDING

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The study has been supported by institutional research funding (IUT20-46) from the Estonian Research Agency and by the European Union's Seventh Framework Programme (FP7/2007-2013) under a grant agreement [grant number 602398] (HypOrth).

ORCID IDS

Emel Rothzerg  <https://orcid.org/0000-0003-1957-930X>
Sulev Kõks  <https://orcid.org/0000-0001-6087-6643>

REFERENCES

- Mirabello L, Troisi RJ, Savage SA. Osteosarcoma incidence and survival rates from 1973 to 2004: data from the surveillance, epidemiology, and end results program. *Cancer* 2009;**115**:1531-43
- Durfee RA, Mohammed M, Luu HH. Review of osteosarcoma and current management. *Rheumatol Ther* 2016;**3**:221-43
- Brown HK, Schiavone K, Gouin F, Heymann MF, Heymann D. Biology of bone sarcomas and new therapeutic developments. *Calcif Tissue Int* 2018;**102**:174-95
- Xu Q, Gao T, Zhang B, Zeng J, Dai M. Primary osteosarcoma in elderly patients: a report of three cases. *Oncol Lett* 2019;**18**:990-6
- Zhang X, Guan Z. PET/CT in the diagnosis and prognosis of osteosarcoma. *Front Biosci* 2018;**23**:2157-65
- Wagh A, Kokane G, Jendi S, Khatib S, Mistry J, Vaidya K. Early diagnosis: a seeking misfortune for osteosarcoma of mandible-rare case report. *Indian J Otolaryngol Head Neck Surg* 2019;**71**:748-51
- Yang P, Gilg M, Evans S, Totti F, Stevenson J, Jeys L, Parry M. Survival of osteosarcoma patients following diagnosis of synchronous skip metastases. *J Orthop* 2020;**18**:121-5
- Igarashi K, Yamamoto N, Shirai T, Nishida H, Hayashi K, Tanzawa Y, Kimura H, Takeuchi A, Miwa S, Inatani H, Shimozaki S, Kato T, Tsuchiya H. Late recurrence of osteosarcoma: a report of two cases. *J Orthop Surg* 2014;**22**:415-9
- Pritchard-Jones K, Kaatsch P, Steliarova-Foucher E, Stiller CA, Coebergh JW. Cancer in children and adolescents in Europe: developments over 20 years and future challenges. *Eur J Cancer* 2006;**42**:2183-90
- Logue JP, Cairnduff F. Radiation induced extraskeletal osteosarcoma. *Br J Radiol* 1991;**64**:171-2
- Seton M. Paget disease of bone: diagnosis and drug therapy. *Cleve Clin J Med* 2013;**80**:452-62
- Srivastava S, Wang S, Tong YA, Pirollo K, Chang EH. Several mutant p53 proteins detected in cancer-prone families with Li-Fraumeni syndrome exhibit transdominant effects on the biochemical properties of the wild-type p53. *Oncogene* 1993;**8**:2449-56
- Hansen MF, Koufos A, Gallie BL, Phillips RA, Fodstad O, Brogger A, Gedde-Dahl T, Cavenee WK. Osteosarcoma and retinoblastoma: a shared chromosomal mechanism revealing recessive predisposition. *Proc Natl Acad Sci U S A* 1985;**82**:6216-20
- Wang Z, Gerstein M, Snyder M. RNA-Seq: a revolutionary tool for transcriptomics. *Nat Rev Genet* 2009;**10**:57-63
- Kukurba KR, Montgomery SB. RNA sequencing and analysis. *Cold Spring Harb Protoc* 2015;**2015**:951-69
- Butz H, Patocs A. Brief summary of the most important molecular genetic methods (PCR, qPCR, microarray, Next-Generation sequencing, etc.). *Exp Suppl* 2019;**111**:33-52
- Levin JZ, Yassour M, Adiconis X, Nusbaum C, Thompson DA, Friedman N, Gnirke A, Regev A. Comprehensive comparative analysis of strand-specific RNA sequencing methods. *Nat Methods* 2010;**7**:709-15
- Li Y, Rao X, Mattox WW, Amos CI, Liu B. RNA-Seq analysis of differential splice junction usage and intron retentions by DEXSeq. *PLoS One* 2015;**10**:e0136653
- El Marabti E, Younis I. The cancer spliceome: reprogramming of alternative splicing in cancer. *Front Mol Biosci* 2018;**5**:80
- Frost FG, Cherukuri PF, Milanovich S, Boerkoel CF. Pan-cancer RNA-seq data stratifies tumours by some hallmarks of cancer. *J Cell Mol Med* 2020;**24**:418-30
- Srebrow A, Kornbliht AR. The connection between splicing and cancer. *J Cell Sci* 2006;**119**:2635-41
- Eksi R, Li HD, Menon R, Wen Y, Omenn GS, Kretzler M, Guan Y. Systematically differentiating functions for alternatively spliced isoforms through integrating RNA-seq data. *PLoS Comput Biol* 2013;**9**:e1003314
- Ghigna C, Valacca C, Biamonti G. Alternative splicing and tumor progression. *Curr Genomics* 2008;**9**:556-70
- Yang Q, Zhao J, Zhang W, Chen D, Wang Y. Aberrant alternative splicing in breast cancer. *J Mol Cell Biol* 2019;**11**:920-9
- Venables JP. Aberrant and alternative splicing in cancer. *Cancer Res* 2004;**64**:7647-54
- Wang Y, Liu J, Huang BO, Xu YM, Li J, Huang LF, Lin J, Zhang J, Min QH, Yang WM, Wang XZ. Mechanism of alternative splicing and its regulation. *Biomed Rep* 2015;**3**:152-8
- Sveen A, Kilpinen S, Ruusulehto A, Lothe RA, Skotheim RI. Aberrant RNA splicing in cancer; expression changes and driver mutations of splicing factor genes. *Oncogene* 2016;**35**:2413-27
- Qi F, Li Y, Yang X, Wu YP, Lin LJ, Liu XM. Significance of alternative splicing in cancer cells. *Chin Med J* 2020;**133**:221-8
- Dvinge H, Guenthoer J, Porter PL, Bradley RK. RNA components of the spliceosome regulate tissue- and cancer-specific alternative splicing. *Genome Res* 2019;**29**:1591-604
- Ho XD, Phung P, V QL, V HN, Reimann E, Prans E, Koks G, Maasalu K, Le NT, L HT, H GN, Martson A, Koks S. Whole transcriptome analysis identifies differentially regulated networks between osteosarcoma and normal bone samples. *Exp Biol Med* 2017;**242**:1802-11
- Anders S, Reyes A, Huber W. Detecting differential usage of exons from RNA-seq data. *Genome Res* 2012;**22**:2008-17
- Ho XD, Nguyen HG, Trinh LH, Reimann E, Prans E, Koks G, Maasalu K, Le VQ, Nguyen VH, Le NTN, Phung P, Martson A, Lattekivi F, Koks S. Analysis of the expression of repetitive DNA elements in osteosarcoma. *Front Genet* 2017;**8**:193
- McCarthy DJ, Chen Y, Smyth GK. Differential expression analysis of multifactor RNA-Seq experiments with respect to biological variation. *Nucleic Acids Res* 2012;**40**:4288-97
- Li J, Witten DM, Johnstone IM, Tibshirani R. Normalization, testing, and false discovery rate estimation for RNA-sequencing data. *Biostatistics* 2012;**13**:523-38
- Anders S, McCarthy DJ, Chen Y, Okoniewski M, Smyth GK, Huber W, Robinson MD. Count-based differential expression analysis of RNA sequencing data using R and bioconductor. *Nat Protoc* 2013;**8**:1765-86
- Benjamini YH. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *J R Stat Soc* 1995;**57**:289-300
- Dey-Rao R, Seiffert-Sinha K, Sinha AA. Genome-wide expression analysis suggests unique disease-promoting and disease-preventing signatures in pemphigus vulgaris. *Genes Immun* 2013;**14**:487-99
- Boise LH, Gonzalez-Garcia M, Postema CE, Ding L, Lindsten T, Turka LA, Mao X, Nunez G, Thompson CB. Bcl-x, a bcl-2-related gene that functions as a dominant regulator of apoptotic cell death. *Cell* 1993;**74**:597-608
- Narrandes S, Huang S, Murphy L, Xu W. The exploration of contrasting pathways in triple negative breast cancer (TNBC). *BMC Cancer* 2018;**18**:22

40. Wong ACH, Rasko JEJ, Wong JJ. We skip to work: alternative splicing in normal and malignant myelopoiesis. *Leukemia* 2018;**32**:1081–93
41. Hug N, Longman D, Caceres JF. Mechanism and regulation of the nonsense-mediated decay pathway. *Nucleic Acids Res* 2016;**44**:1483–95
42. He F, Jacobson A. Nonsense-Mediated mRNA decay: degradation of defective transcripts is only part of the story. *Annu Rev Genet* 2015;**49**:339–66
43. Popp MW, Maquat LE. Nonsense-mediated mRNA decay and cancer. *Curr Opin Genet Dev* 2018;**48**:44–50
44. Yousefi M, Karmaus W, Zhang H, Ewart S, Arshad H, Holloway JW. The methylation of the LEPR/LEPROT genotype at the promoter and body regions influence concentrations of leptin in girls and BMI at age 18 years if their mother smoked during pregnancy. *Int J Mol Epidemiol Genet* 2013;**4**:86–100
45. Inzucchi SE, Robbins RJ. Clinical review 61: effects of growth hormone on human bone biology. *J Clin Endocrinol Metab* 1994;**79**:691–4
46. Chia DJ. Minireview: mechanisms of growth hormone-mediated gene regulation. *Mol Endocrinol* 2014;**28**:1012–25
47. Wu S, Yang W, De Luca F. Insulin-Like growth Factor-Independent effects of growth hormone on growth plate chondrogenesis and longitudinal bone growth. *Endocrinology* 2015;**156**:2541–51
48. Tuzcu S, Durmaz SA, Carlioglu A, Demircan Z, Tuzcu A, Beyaz C, Tay A. The effects of high serum growth hormone and IGF-1 levels on bone mineral density in acromegaly. *Z Rheumatol* 2017;**76**:716–22
49. Cheng M, Huang W, Cai W, Fang M, Chen Y, Wang C, Yan W. Growth hormone receptor promotes osteosarcoma cell growth and metastases. *FEBS Open Bio* 2020;**10**:127–34
50. Zhu T, Goh EL, Graichen R, Ling L, Lobie PE. Signal transduction via the growth hormone receptor. *Cell Signal* 2001;**13**:599–616
51. Kopchick JJ, Andry JM. Growth hormone (GH), GH receptor, and signal transduction. *Mol Genet Metab* 2000;**71**:293–314
52. Banziger-Tobler NE, Halin C, Kajiya K, Detmar M. Growth hormone promotes lymphangiogenesis. *Am J Pathol* 2008;**173**:586–97
53. Li YS, Liu Q, He HB, Luo W. The possible role of insulin-like growth factor-1 in osteosarcoma. *Curr Probl Cancer* 2019;**43**:228–35
54. Nair PN, De Armond DT, Adamo ML, Strodel WE, Freeman JW. Aberrant expression and activation of insulin-like growth factor-1 receptor (IGF-1R) are mediated by an induction of IGF-1R promoter activity and stabilization of IGF-1R mRNA and contributes to growth factor independence and increased survival of the pancreatic cancer cell line MIA PaCa-2. *Oncogene* 2001;**20**:8203–14
55. Touvier T, Conte-Auriol F, Briand O, Cudejko C, Paumelle R, Caron S, Bauge E, Rouille Y, Salles JP, Staels B, Bailleul B. LEPROT and LEPROTL1 cooperatively decrease hepatic growth hormone action in mice. *J Clin Invest* 2009;**119**:3830–8
56. Jin H, Jin X, Cao B, Wang W. Berberine affects osteosarcoma via down-regulating the caspase-1/IL-1beta signaling axis. *Oncol Rep* 2017;**37**:729–36
57. Mori T, Sato Y, Miyamoto K, Kobayashi T, Shimizu T, Kanagawa H, Katsuyama E, Fujie A, Hao W, Tando T, Iwasaki R, Kawana H, Morioka H, Matsumoto M, Saya H, Toyama Y, Miyamoto T. TNFalpha promotes osteosarcoma progression by maintaining tumor cells in an undifferentiated state. *Oncogene* 2014;**33**:4236–41
58. Wu Z, Yang W, Liu J, Zhang F. Interleukin-6 upregulates SOX18 expression in osteosarcoma. *Oncotargets Ther* 2017;**10**:5329–36
59. Robl B, Botter SM, Boro A, Meier D, Neri D, Fuchs B. Evaluation of F8-TNF-alpha in models of early and progressive metastatic osteosarcoma. *Transl Oncol* 2017;**10**:419–30
60. Itoh H, Kadomatsu T, Tanoue H, Yugami M, Miyata K, Endo M, Morinaga J, Kobayashi E, Miyamoto T, Kurahashi R, Terada K, Mizuta H, Oike Y. TET2-dependent IL-6 induction mediated by the tumor microenvironment promotes tumor metastasis in osteosarcoma. *Oncogene* 2018;**37**:2903–20
61. Zhang C, Ma K, Li WY. IL-6 promotes cancer stemness and oncogenicity in U2OS and MG-63 osteosarcoma cells by upregulating the OPN-STAT3 pathway. *J Cancer* 2019;**10**:6511–25

(Received June 29, 2020, Accepted July 21, 2020)