

LOXL 2 Promotes The Epithelial–Mesenchymal Transition And Malignant Progression Of Cervical Cancer

This article was published in the following Dove Press journal:
OncoTargets and Therapy

Jing Tian^{1,2,*}
He-Xi Sun^{3,*}
Ying-Chun Li⁴
Li Jiang⁵
Shan-Ling Zhang⁶
Quan Hao^{1,2}

¹Department of Gynecological Oncology, Tianjin Medical University Cancer Institute and Hospital, National Clinical Research Center for Cancer, Tianjin, People's Republic of China; ²Key Laboratory of Cancer Prevention and Therapy, Tianjin's Clinical Research Center for Cancer, Tianjin, People's Republic of China; ³Department of Obstetrics and Gynecology, The First Affiliated Hospital of Xiamen University, Xiamen, People's Republic of China;

⁴Department of Gynecology II, Cangzhou Central Hospital, Cangzhou, People's Republic of China; ⁵Department of Gynecology and Obstetrics, First Hospital of Qinhuangdao, Qinhuangdao, People's Republic of China;

⁶Comprehensive Surgery Department, Tianjin Taishan Cancer Hospital and International Personalized Cancer Center, Tianjin, People's Republic of China

*These authors contributed equally to this work

Correspondence: Quan Hao
Department of Gynecological Oncology, Tianjin Medical University Cancer Institute and Hospital, National Clinical Research Center for Cancer, No. 1 Huanhuxi Road, Hexi District, Tianjin 300060, People's Republic of China
Tel +86 130 1139 7857
Email haoquandoc@1967@126.com

Purpose: Increasing evidence suggests that lysyl oxidase-like 2 (LOXL2) contributes to tumor progression. However, the role of LOXL2 in cervical cancer still remains unclear.

Patients and methods: We used the TCGA database to analyze the expression of LOXL2 in cervical cancer and its role on survival. The effects of LOXL2 on cervical cancer metastasis and EMT were verified by transwell and wound healing assay. Western blot assay was used to detect the effect of LOXL2 on EMT-related gene expression. In addition, we used animal experiments to observe the role of LOXL2 on tumor genesis and metastasis in cervical cancer.

Results: Here we found that LOXL2 participates in epithelial–mesenchymal transition-related cervical cancer progression. LOXL2 ablation in cervical cancer cells inhibited cell metastatic ability, whereas LOXL2 overexpression promoted cell metastasis. In addition, more clinical data from TCGA revealed that LOXL2 is closely related to the prognosis and is highly expressed in highly malignant and metastatic cervical tumors.

Conclusion: Taken together, our findings established a pathophysiologic role and new function for LOXL2 in cervical cancer metastasis.

Keywords: cervical cancer, LOXL2, epithelial–mesenchymal transition, metastasis

Introduction

The extracellular matrix (ECM) is a highly complex network of glycosaminoglycan, proteins and proteoglycans. Increasing evidence suggests that the ECM plays important roles in the proliferation,^{1,2} differentiation³ and migration^{4,5} of cancer cells. Degradation of the ECM alters the topography of the matrix, thereby allowing the invasion and migration of cancer cells. Lysyl oxidase-like 2 (LOXL2) belongs to the lysyl oxidase (LOX) family that can catalyze the crosslinking of ECM components. Thus, LOX family members play an essential role in tissue homeostasis contributing to ECM remodeling.⁶ Studies have implicated LOX and LOXL2 in the progression and metastasis of several types of carcinomas.^{7–10}

Cervical cancer is a common female malignancy worldwide and is responsible for over 300,000 deaths worldwide each year.¹¹ The overall prognosis of cervical cancer remains poor because of tumor metastasis or recurrence. During tumor metastasis, the loss of epithelial features and acquisition of mesenchymal characteristic increase the invasion and migration of cancer cells.^{12,13} During epithelial–mesenchymal transition (EMT), the degradation of the ECM enables tumor cells to migrate, invade and spread to various secondary sites.^{4,14–18}

The present study investigated the function of LOXL2 in cervical cancer during EMT. We found that LOXL2 is closely associated with unfavorable prognosis in cervical cancer. The expression of LOXL2 was up-regulated in cervical cancer, especially in highly malignant and metastatic cervical tumors. In vitro knock-down of LOXL2 revealed a direct correlation between tumorigenesis and distant metastasis in cervical cancer cells. In vivo experiments indicated that LOXL2 promotes tumorigenesis and EMT-related metastasis in cervical cancer. These results indicate the function of LOXL2 in cervical cancer, suggesting that LOXL2 is a valuable therapeutic target.

Materials And Methods

Cell Lines And Plasmids

Cervical cancer cell lines HeLa, CaSki, SiHa and C-33A were purchased from Cell Bank of Shanghai Institutes for Biological Sciences (Shanghai, China). HeLa and Caski cells were cultured in RPMI 1640. HepG2, SiHa and C-33A cells were cultured in MEM medium supplemented with 10% fetal bovine serum (FBS) at 37 °C in an incubator with 5% CO₂. LOXL2 expression and interference plasmids were purchased from ORIGENE (CAT: RC200455, Beijing, China). All plasmids and control vectors were transfected into the cells by Lipofectamine 2000 (CAT: 11668027, Invitrogen, USA).

Clinical Data Analysis

A total of 291 cervical cancer clinical data from TCGA (The Cancer Genome Atlas) were used to analyze the survival time and expression of LOXL2 and EMT-related markers. The patient samples selected were divided according to clinical stage and pathological grading. The expression levels of LOXL2 and EMT markers in these samples were then analyzed.

Cell Migration Assay

Treated cells were plated in 24-well culture plates. After 24 h, a straight scratch was created in the center of each well. The distance of wound closure at 24 h was measured and normalized by wound length at 0 h. Each experiment was performed in triplicate.

Cell Invasion Assays

For transwell assay, cells in serum-free medium were seeded on the upper chamber coated with Matrigel (CAT: 356234, BD Biosciences). Medium with 10% FBS was added below the chamber. After 24 h, invasive cells on the lower surface of the chamber were stained with 0.1%

crystal violet. Passed cells were photographed under the microscope and then counted.

Xenograft Tumor Model

Mice were purchased from the Animal Center of the Chinese Academy of Science (Shanghai, China). After treatment, about 5×10⁶ SiHa and HeLa cells were injected subcutaneously in each BALB/c nude mouse. Tumor volumes were serially measured with a digital caliper every 3 days. On day 27, the mice were sacrificed. Tumor tissues were collected and fixed with 10% formalin for hematoxylin–eosin or immunohistochemical (IHC) staining. The remaining tissues were stored in a deep freezer at –80 °C for protein analysis.

Western Blot Analysis

Harvested cells and tumor tissues were lysed, and the protein concentration was determined using bicinchoninic acid assay. The lysates were separated by electrophoresis and then transferred onto polyvinylidene difluoride membranes (CAT: ISEQ00010, Millipore). The membranes were blocked and then incubated with primary antibodies of LOXL2 (CAT: ab96233, Abcam, UK), E-cadherin (CAT: AF0131, Affinity, China), Vimentin (CAT: AF7013, Affinity, China) and Collagen I (CAT: AF7001, Affinity, China). GAPDH (CAT: 5174, CST, USA) was used as the loading control. After 2 h, the membranes were incubated with a horseradish peroxidase-labelled secondary antibody. Protein expression was assessed by enhanced chemiluminescence substrate (Millipore).

IHC Assay And Analysis

The tissue sections were sequentially treated in a microwave and then blocked. After being incubated with primary and secondary antibodies, the samples were stained with 3,3'-diaminobenzidine and hematoxylin. The results were captured with a microscope (Olympus, Japan). Negative controls were prepared using phosphate-buffered saline in lieu of the first antibody. The results were read by two separate pathologists without any knowledge on the samples. Both intensity and percentage of the positive cells were determined and multiplied (staining index). A staining index of < 6 was considered low expression, whereas a staining index of > 6 was defined as high expression.

Statistical Analysis

All statistical analyses were performed with GraphPad Prism V.6.0 (GraphPad Software, San Diego, California, USA). Data were expressed as mean ± SE of mean. Comparisons between two groups were performed by Student's *t*-test,

whereas comparisons among three or more groups were conducted using ANOVA with Dunnett's post-test. Differences were considered significant at $P < 0.05$.

Compliance With Ethical Standards

This article does not contain any studies with human participants performed by any of the authors. All animal experiments in this study were confirmed that ethical and legal approval was obtained prior to the commencement of the study. All the works meets the standards set out in NC3Rs primates guidelines. All procedures performed in studies involving animals were in accordance with the ethical standards of the institution or practice at which the studies were conducted. All experimental protocols were approved by the Institutional Animal Care and Use Committee (IACUC) at Tianjin medical university cancer institute and hospital.

Results

LOXL2 Highly Expressed In Metastatic Cervical Cancer And Associated With Unfavorable Prognosis

In total, 291 cervical cancer (CESC) samples from the TCGA database were analyzed. As shown in Figure 1A, IHC results

revealed that the expression of LOXL2 was higher in the CESC tissue () than in normal tissue. This up-regulation of LOXL2 was correlated with unfavorable prognosis in cervical cancer (Figure 1B). However, further analysis suggested that LOXL2 is selectively highly expressed in cervical cancer of high malignancy and metastatic cervical cancer but not highly expressed in all CESC (Figure 1C–F). As shown in Figure 1D, LOXL2 is selectively expressed in poorly differentiated, high-grade cervical cancer (Grade3 and Grade 4). Furthermore, LOXL2 is highly expressed in patients with metastatic cervical cancer (M1) than that in non-metastatic (M0) patients (Figure 1F).

LOXL2 Correlated With EMT In Cervical Cancer

To further validate the function of LOXL2 in cervical cancer, we used GSEA analysis to find that LOXL2 contributes mainly to EMT, stemness and tumorigenesis, especially in EMT (Figure 2A). These results suggest that LOXL2 is crucial for EMT-related cervical cancer metastasis. Analysis of the relationship between LOXL2 and EMT-related factors in cervical cancer showed that LOXL2 positively correlated with the expression of vimentin, MMPs,

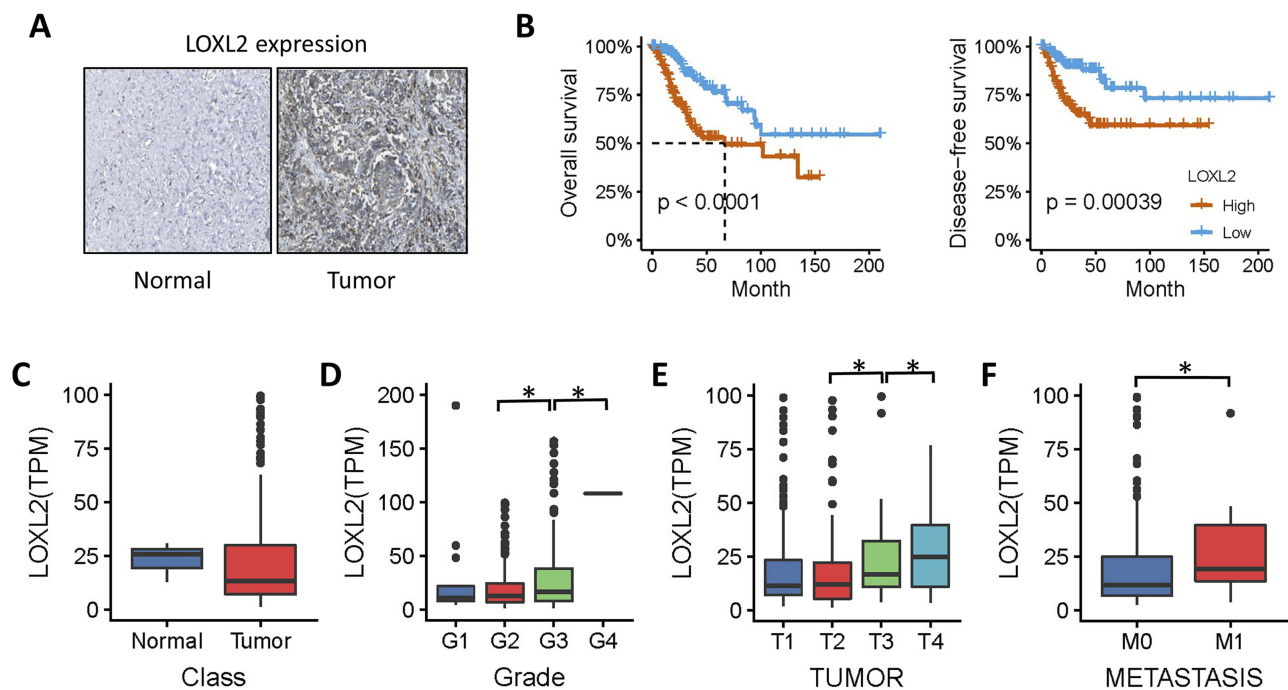


Figure 1 LOXL2 correlated with cervical cancer metastasis.

Notes: (A) Immunohistochemical detection of LOXL2 in cervical cancer and normal tissues. (B) Patients with cervical cancer were divided into high-expression and low-expression groups, and then overall survival and disease-free survival of the two groups were compared. (C–F) Expression of LOXL2 obtained from TCGA data in cervical cancer. (C) The expression of LOXL2 between normal tissues and cervical cancer specimens. (D, E) Expression of LOXL2 in different pathological grades, clinical stages of cervical cancer. (F) Expression of LOXL2 between metastasis and non-metastatic cervical cancer. *Differences were considered significant at $P < 0.05$.

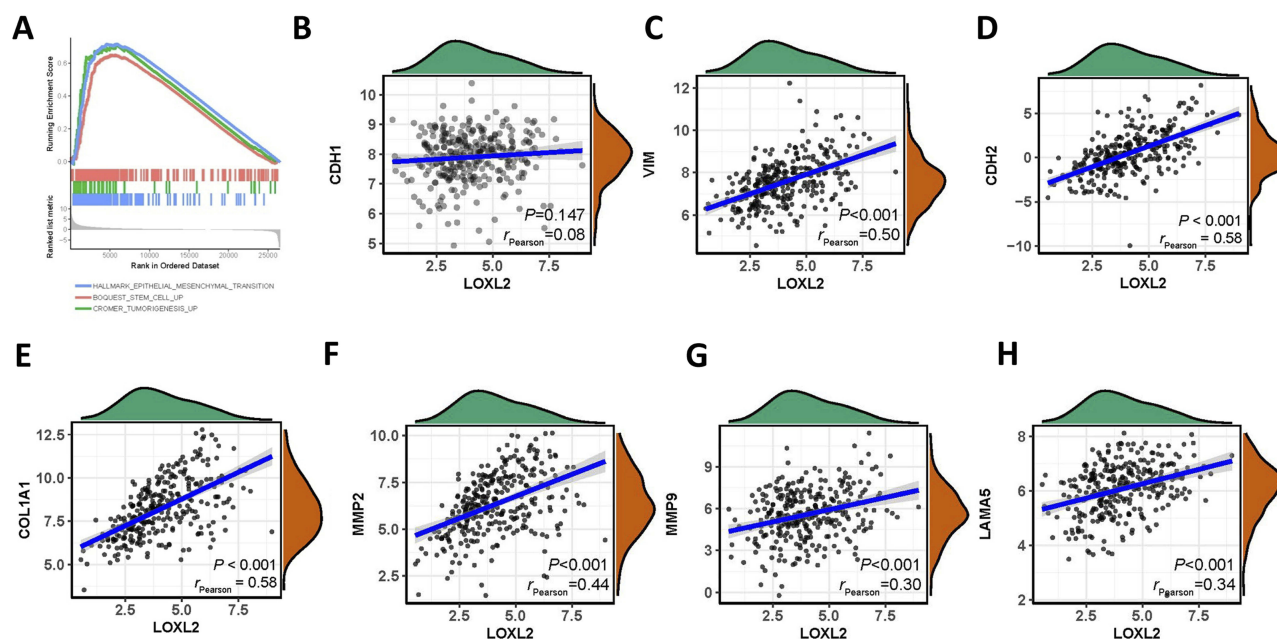


Figure 2 LOXL2 contributed to EMT.

Notes: (A) Gene set enrichment analysis of LOXL2-related cell function. (B–H) Correlation between LOXL2 and EMT-related genes, E-cadherin, vimentin, MMP2, MMP9, collagen I and LAMA5, in cervical cancer.

LAMA2 and collagen. These results confirm the relationship between LOXL2 and EMT and cervical cancer progression (Figure 2B–H).

Knock-Down Of LOXL2 In Vitro Inhibits Cervical Cancer Cell Migration And Invasion

To examine the role of LOXL2 in the EMT of cervical cancer cells, we first selected high LOXL2-expressing cells, HeLa and CaSki, knocked down the expression of LOXL2 (Figure 3A) and then tested the migration and invasion of cervical cancer cells by transwell and healing analyses. Results showed that LOXL2 knock-down can inhibit the migration and invasion of cervical cancer cells (Figure 3B–C). In addition, Western blot analysis revealed that LOXL2 knock-down decreased vimentin, MMPs and collagen but up-regulated the expression of E-cadherin (Figure 3D). The above results confirmed that LOXL2 is closely related to the metastasis and EMT of cervical cancer cells.

Ectopic Expression Of LOXL2 In Vitro Promotes EMT And Cervical Cancer Migration And Invasion

We selected two other cervical cancer cells with low expression of LOXL2, C-33A and SiHa, to verify the effect of

LOXL2 up-regulation on the invasion and EMT of cervical cancer cells. LOXL2 expression plasmids were transfected into these two cells (Figure 4A). Results showed that LOXL2 up-regulation can significantly promote the migration and invasion of cervical cancer cells (Figure 4B–C). In addition, we observed the down-regulation of the EMT marker E-cadherin and the up-regulation of vimentin by immunofluorescence experiments (Figure 4D). These results further reveal the important biological role of LOXL2 in the EMT and metastasis of cervical cancer cells.

LOXL2 Promotes Tumorigenesis And Metastasis Of Cervical Cancer In Vivo

In vitro and TCGA results revealed that LOXL2 can promote the metastasis and EMT progression of cervical cancer. To further determine the function of LOXL2 in cervical cancer, we changed the expression of LOXL2 in HeLa and SiHa cells and inoculated the obtained stable cell strain into mice to monitor tumor growth and metastasis. Results showed that the tumorigenic and metastatic abilities of the HeLa cells were inhibited after knocking down the expression of LOXL2 (Figure 5A and B). In SiHa cells, overexpression of LOXL2 promoted the tumorigenesis and metastasis of the cervical cancer cells (Figure 5D and E). LOXL2 protein levels in solids tumors were detected (Figure 5C and F).

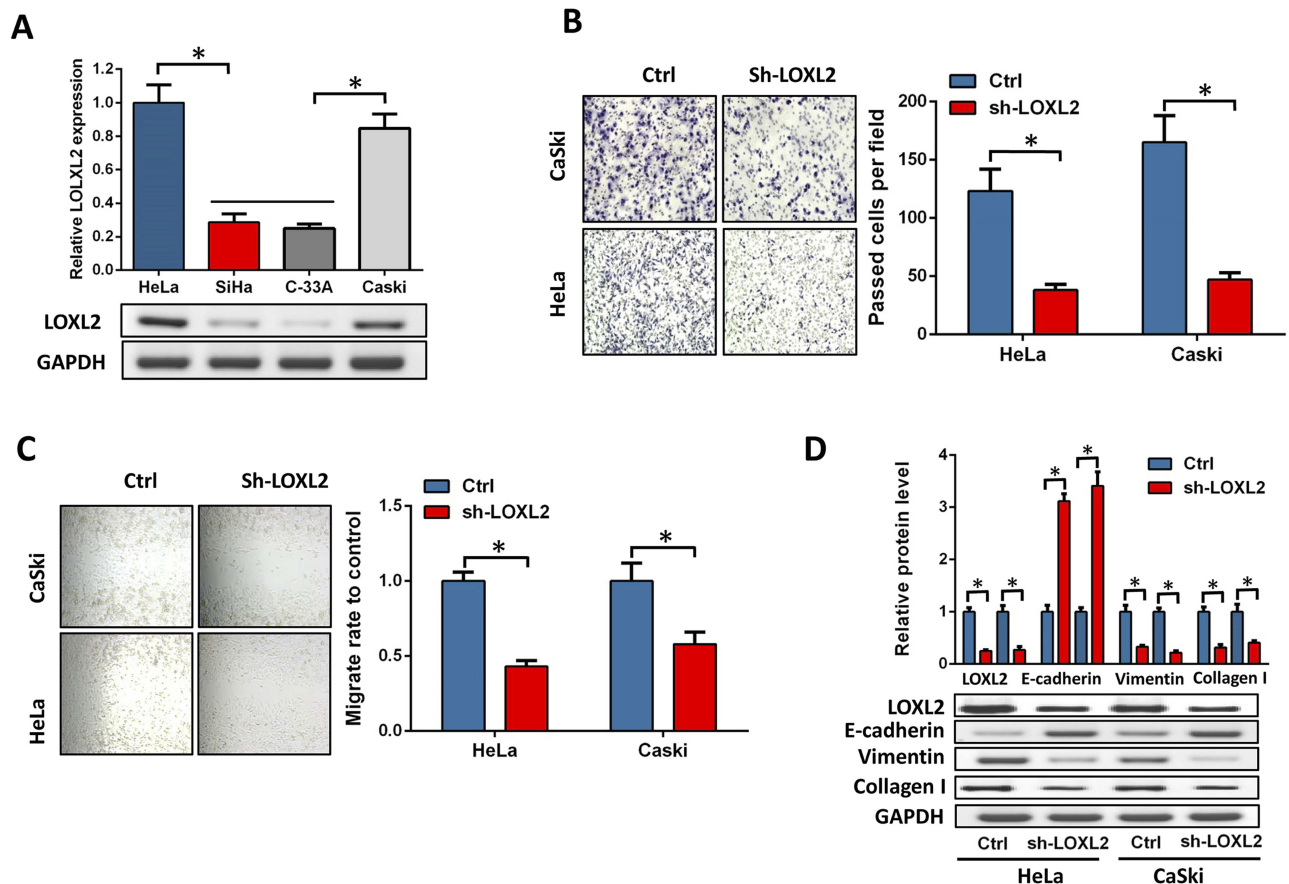


Figure 3 LOXL2 depression inhibited cervical cancer invasion.

Notes: (A) Expression of LOXL2 in cervical cancer cell lines HeLa, SiHa, C-33A and CaSki. (B, C) HeLa and CaSki cells, invasion (B) and migration ability (C) were detected after knock-down of LOXL2. (D) Expression of EMT marker and collagen protein in cervical cancer cells after knock-down of LOXL2. *Differences were considered significant at $P < 0.05$.

LOXL2 Contributes To EMT In Cervical Cancer Progression

To further validate the effect of LOXL2 on EMT in cervical cancer, we detected the expression of LOXL2 and EMT-related proteins in solid tumors by using IHC. After the expression of LOXL2 was disturbed, the expression of E-cadherin was up-regulated and the expression of vimentin, MMPs and collagen was down-regulated. However, the expression of these proteins was reversed after LOXL2 overexpression (Figure 6A). IHC staining results were statistically analyzed based on staining intensity (Figure 6B and C).

Discussion

Metastasis and recurrence are the greatest challenge in cancer therapy. Many studies have revealed that the EMT of carcinoma cells plays a crucial role in tumor metastasis.^{19–23} The acquisition of mesenchymal cell traits

promotes disease progression and enhances the metastatic phenotype. The main features of EMT are decreased cell adhesion and enhanced mobility.²⁰ LOXL2 has been suggested to contribute to the metastasis of breast cancer and regulated by EMT regulatory transcription factor Snail1.⁹ In lung cancer, LOXL2 is regulated by ZEB1/miR-200 and promotes collagen deposition tumor metastasis.²⁴ In cervical cancer, EMT also plays an important role in tumor progression and metastasis. Here, we reveal the role of LOXL2 in cervical cancer EMT and metastasis. Although the effect of LOXL2 on the survival of cervical cancer is obvious, the expression of LOXL2 in cervical cancer with low malignancy is not much different from that in normal tissues. Interestingly, LOXL2 is significantly up-regulated in high-grade cervical cancer, similar to its expression in metastatic tumors. This finding shows that LOXL2 is closely related to the late metastasis of cervical cancer. Further analysis of the available data revealed that LOXL2

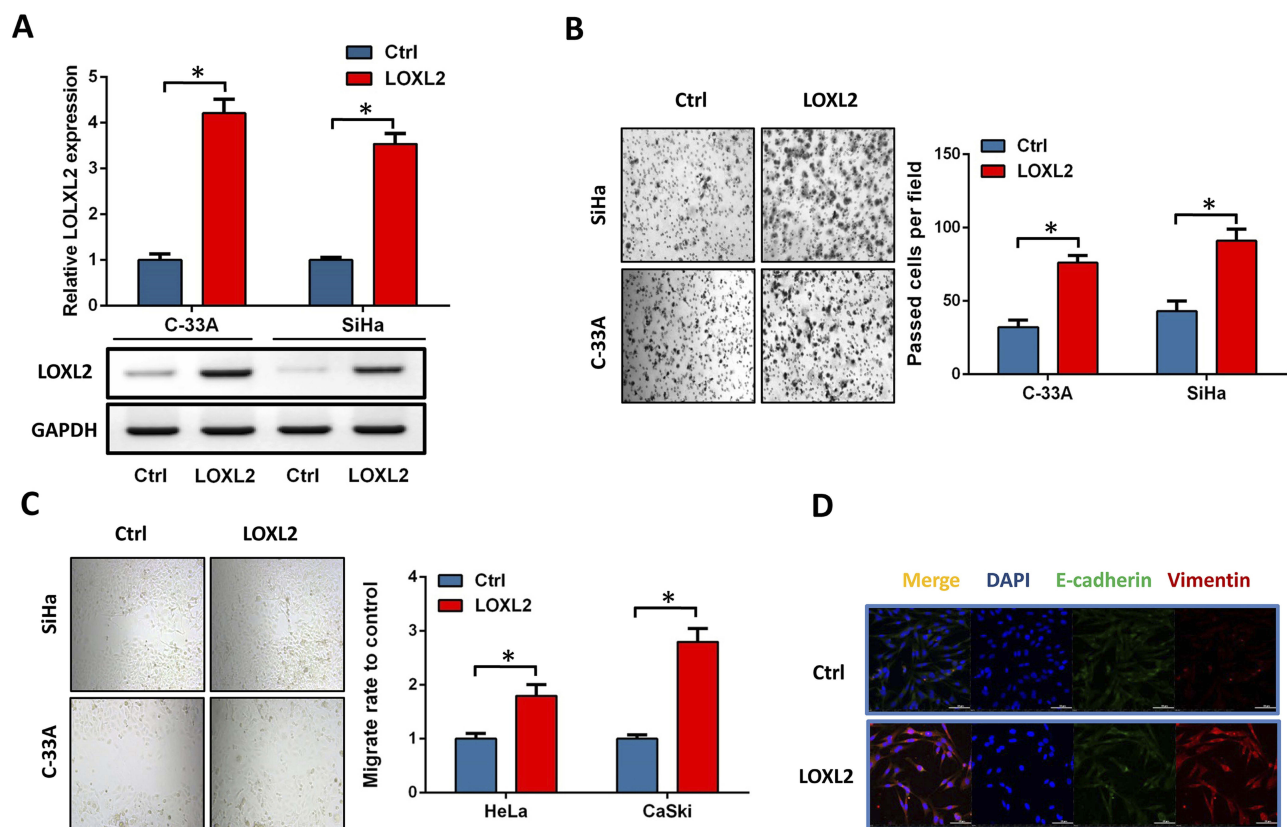


Figure 4 LOXL2 promoted cervical cancer invasion and EMT.

Notes: (A) Expression of LOXL2 in SiHa and C-33A after transfection with LOXL2 expression plasmid. (B, C) SiHa and C-33A cells, invasion (B) and migration ability (C) were analyzed after overexpression of LOXL2. (D) After overexpression of LOXL2, immunofluorescence was used to detect the expression and cell localization of E-cadherin and vimentin. *Differences were considered significant at $P < 0.05$.

is closely related to the tumorigenesis and EMT of cervical cancer. Therefore, we hypothesized that LOXL2 promotes its metastasis by driving the EMT of cervical cancer. This likelihood was then confirmed in our experiments. Both in vivo and in vitro experiments have shown that LOXL2-induced cervical cancer metastasis is accompanied by corresponding changes in EMT markers.

EMT-dependent tumor invasion and metastasis are continuous processes. Tumor cells first shed from the primary site and activate the cell secreting enzymes to degrade the ECM, thereby forming a transfer channel that assists the tumor cells to enter the blood vessel. The cells extravasate to the secondary sites and then continue to proliferate to form metastases.^{20,25–27} ECM degradation is crucial during EMT. LOXL2 as a lysyl oxidase can catalyze the crosslinking of ECM components.²⁴ The dysregulation of LOXL2 promotes tumor progression through intracellular and extracellular mechanisms, including collagen fibre reorganization and crosslinking,²⁸ which are crucial for EMT. In breast

cancer, LOX-mediated collagen crosslinking can directly increase tumor cell proliferation, thereby enhancing metastatic colonization and growth.²⁹ However, LOXL2 may not be a decisive factor in tumor metastasis because its expression is regulated by EMT-inducing factors. In the present study, our results confirmed that the abnormal expression of LOXL2 is closely related to the malignant progression of cervical cancer, especially to tumor metastasis. High expression of LOXL2 is accompanied by up-regulation of collagen and MMPs, which are important in tumor EMT and metastasis.

In summary, LOXL2 contributes to cervical cancer progression. Clinical data point to the abnormally high expression of LOXL2 in high-grade and metastatic cervical cancer. Our functional experiments also confirmed its important function in cervical cancer metastasis and association with EMT. Therefore, the role of LOXL2 in the malignant progression of cervical cancer promotes its metastasis. Our findings suggest that LOXL2 is a new therapeutic target for cervical cancer metastasis.

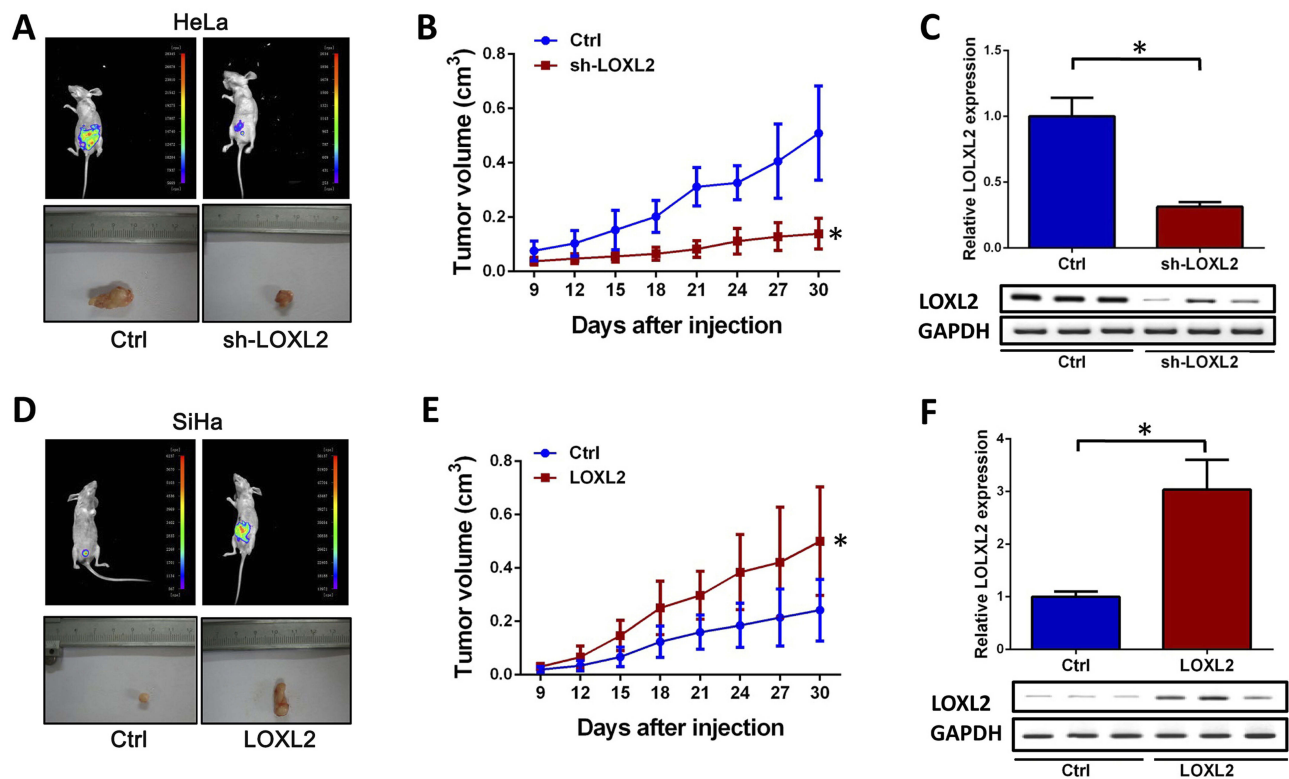


Figure 5 LOXL2 contributed tumorigenesis and metastasis in cervical cancer.

Notes: Stable cell line obtained by transfecting HeLa cells with LOXL2 interference plasmid, experimental results after inoculation of mice (A–C). (A) Tumor size and metastasis after knock-down of LOXL2. (B) Tumor volume was measured every 3 days, and tumor volumes were calculated. (C) Detection of protein expression level of LOXL2 in tumor tissues by immunoblotting. (D–F) Stable cell line obtained by transfecting SiHa cells with LOXL2 expression plasmid, experimental results after inoculation of mice. (D) Tumor size and metastasis. (E) Tumor volume was measured every 3 days, and tumor volume was calculated. (F) Detection of protein expression level of LOXL2 in solid tumor tissues by immunoblotting. *Differences were considered significant at P < 0.05.

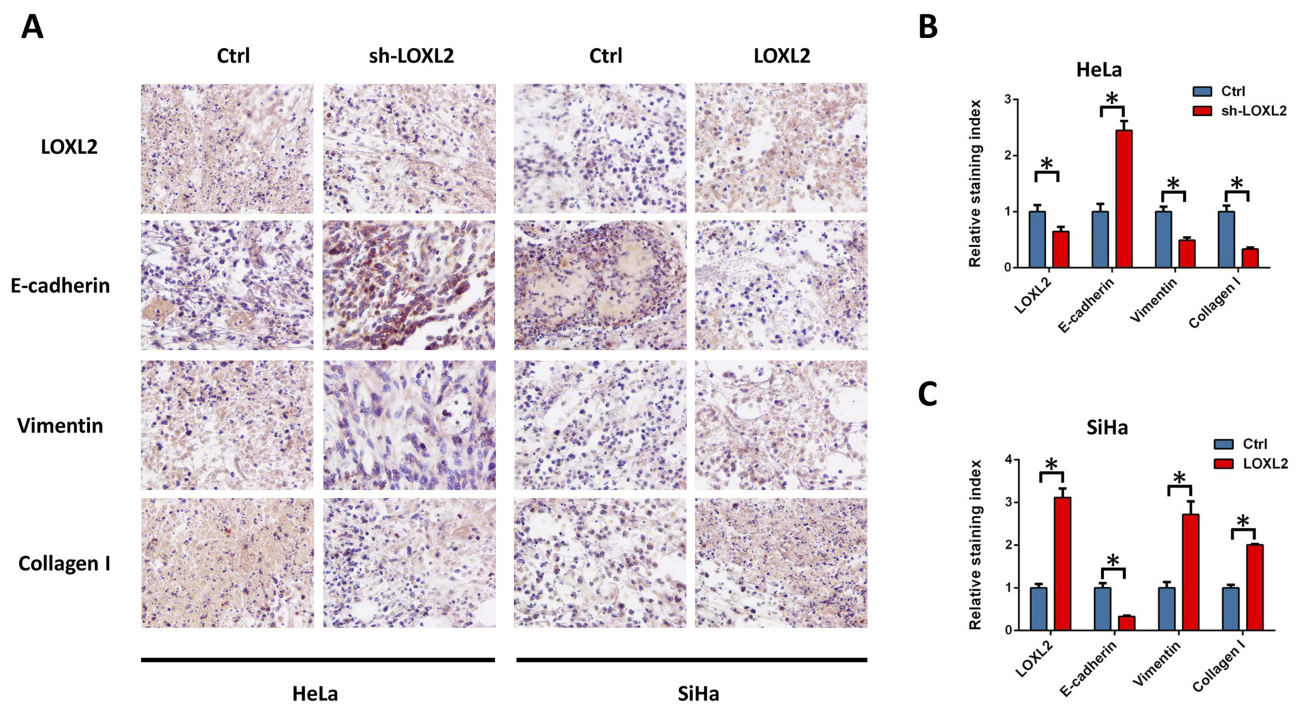


Figure 6 Effect of LOXL2 on the expression of EMT related genes in solid tumors.

Notes: After the mice were sacrificed, tissues were collected for protein expression detection. (A) The expression of LOXL2, E-cadherin, vimentin and collagen I was detected by IHC staining. (B, C) Analysis of staining intensity. *Differences were considered significant at P < 0.05.

Disclosure

The authors report no conflicts of interest in this work.

References

- Shin JW, Mooney DJ. Extracellular matrix stiffness causes systematic variations in proliferation and chemosensitivity in myeloid leukemias. *Proc Natl Acad Sci USA*. 2016;113:12126–12131. doi:10.1073/pnas.1611338113
- Seo BR, Bhardwaj P, Choi S, et al. Obesity-dependent changes in interstitial ECM mechanics promote breast tumorigenesis. *Sci Transl Med*. 2015;7:301ra130. doi:10.1126/scitranslmed.3010467
- Lam WA, Cao L, Umesh V, Keung AJ, Sen S, Kumar S. Extracellular matrix rigidity modulates neuroblastoma cell differentiation and N-myc expression. *Mol Cancer*. 2010;9:35. doi:10.1186/1476-4598-9-35
- Gilkes DM, Semenza GL, Wirtz D. Hypoxia and the extracellular matrix: drivers of tumour metastasis. *Nat Rev Cancer*. 2014;14:430–439. doi:10.1038/nrc3726
- Santiago-Medina M, Yang J. MENA promotes tumor-intrinsic metastasis through ECM remodeling and haptotaxis. *Cancer Discov*. 2016;6:474–476. doi:10.1158/2159-8290.CD-16-0231
- Kanapathipillai M, Mammoto A, Mammoto T, et al. Inhibition of mammary tumor growth using lysyl oxidase-targeting nanoparticles to modify extracellular matrix. *Nano Lett*. 2012;12:3213–3217. doi:10.1021/nl301206p
- Wong CC, Tse AP-W, Huang Y-P, et al. Lysyl oxidase-like 2 is critical to tumor microenvironment and metastatic niche formation in hepatocellular carcinoma. *Hepatology*. 2014;60:1645–1658. doi:10.1002/hep.27320
- Tang H, Leung L, Saturno G, et al. Lysyl oxidase drives tumour progression by trapping EGF receptors at the cell surface. *Nat Commun*. 2017;8:14909. doi:10.1038/ncomms14909
- Salvador F, Martin A, López-Menéndez C, et al. Lysyl oxidase-like protein LOXL2 promotes lung metastasis of breast cancer. *Cancer Res*. 2017;77:5846–5859. doi:10.1158/0008-5472.CAN-16-3152
- Millanes-Romero A, Herranz N, Perrera V, et al. Regulation of heterochromatin transcription by Snail1/LOXL2 during epithelial-to-mesenchymal transition. *Mol Cell*. 2013;52:746–757. doi:10.1016/j.molcel.2013.10.015
- Cohen PA, Jhingran A, Oaknin A, Denny L. Cervical cancer. *Lancet*. 2019;393:169–182. doi:10.1016/S0140-6736(18)32470-X
- Micalizzi DS, Christensen KL, Jedlicka P, et al. The Six1 homeoprotein induces human mammary carcinoma cells to undergo epithelial-mesenchymal transition and metastasis in mice through increasing TGF-beta signaling. *J Clin Invest*. 2009;119:2678–2690. doi:10.1172/JCI37815
- Qureshi R, Arora H, Rizvi MA. EMT in cervical cancer: its role in tumour progression and response to therapy. *Cancer Lett*. 2015;356:321–331. doi:10.1016/j.canlet.2014.09.021
- Oudin MJ, Jonas O, Kosciuk T, et al. Tumor cell-driven extracellular matrix remodeling drives haptotaxis during metastatic progression. *Cancer Discov*. 2016;6:516–531. doi:10.1158/2159-8290.CD-15-1183
- Wei SC, Fattet L, Tsai JH, et al. Matrix stiffness drives epithelial-mesenchymal transition and tumour metastasis through a TWIST1-G3BP2 mechanotransduction pathway. *Nat Cell Biol*. 2015;17:678–688. doi:10.1038/ncb3157
- Wei SC, Yang J. Forcing through Tumor Metastasis: the Interplay between Tissue Rigidity and Epithelial-Mesenchymal Transition. *Trends Cell Biol*. 2016;26:111–120. doi:10.1016/j.tcb.2015.09.009
- Jiang L, Yan Q, Fang S, et al. Calcium-binding protein 39 promotes hepatocellular carcinoma growth and metastasis by activating extracellular signal-regulated kinase signaling pathway. *Hepatology*. 2017;66:1529–1545. doi:10.1002/hep.29312
- Ho TH, Serie DJ, Parasramka M, et al. Differential gene expression profiling of matched primary renal cell carcinoma and metastases reveals upregulation of extracellular matrix genes. *Ann Oncol*. 2017;28:604–610. doi:10.1093/annonc/mdw652
- Krebs AM, Mitschke J, Lasierra Losada M, et al. The EMT-activator Zeb1 is a key factor for cell plasticity and promotes metastasis in pancreatic cancer. *Nat Cell Biol*. 2017;19:518–529. doi:10.1038/ncb3513
- Pastushenko I, Blanpain C. EMT Transition States during Tumor Progression and Metastasis. *Trends Cell Biol*. 2019;29:212–226. doi:10.1016/j.tcb.2018.12.001
- Mittal V. Epithelial mesenchymal transition in tumor metastasis. *Annu Rev Pathol*. 2018;13:395–412. doi:10.1146/annurev-pathol-020117-043854
- Neelakantan D, Zhou H, Oliphant MU, et al. EMT cells increase breast cancer metastasis via paracrine GLI activation in neighbouring tumour cells. *Nat Commun*. 2017;8:15773. doi:10.1038/ncomms15773
- Neelakantan D, Zhou H, Oliphant MU, et al. Publisher Correction: EMT cells increase breast cancer metastasis via paracrine GLI activation in neighbouring tumour cells. *Nat Commun*. 2018;9:4720. doi:10.1038/s41467-018-07168-z
- Peng DH, Ungewiss C, Tong P, et al. ZEB1 induces LOXL2-mediated collagen stabilization and deposition in the extracellular matrix to drive lung cancer invasion and metastasis. *Oncogene*. 2017;36:1925–1938. doi:10.1038/onc.2016.358
- Singh M, Yelle N, Venugopal C, Singh SK. EMT: mechanisms and therapeutic implications. *Pharmacol Ther*. 2018;182:80–94. doi:10.1016/j.pharmthera.2017.08.009
- Brabletz T, Kalluri R, Nieto MA, Weinberg RA. EMT in cancer. *Nat Rev Cancer*. 2018;18:128–134. doi:10.1038/nrc.2017.118
- Shibue T, Weinberg RA. EMT, CSCs, and drug resistance: the mechanistic link and clinical implications. *Nat Rev Clin Oncol*. 2017;14:611–629. doi:10.1038/nrclinonc.2017.44
- Erler JT, Bennewith KL, Nicolau M, et al. Lysyl oxidase is essential for hypoxia-induced metastasis. *Nature*. 2006;440:1222–1226. doi:10.1038/nature04695
- Cox TR, Bird D, Baker AM, et al. LOX-mediated collagen cross-linking is responsible for fibrosis-enhanced metastasis. *Cancer Res*. 2013;73:1721–1732. doi:10.1158/0008-5472.CAN-12-2233

OncoTargets and Therapy

Dovepress

Publish your work in this journal

OncoTargets and Therapy is an international, peer-reviewed, open access journal focusing on the pathological basis of all cancers, potential targets for therapy and treatment protocols employed to improve the management of cancer patients. The journal also focuses on the impact of management programs and new therapeutic

agents and protocols on patient perspectives such as quality of life, adherence and satisfaction. The manuscript management system is completely online and includes a very quick and fair peer-review system, which is all easy to use. Visit <http://www.dovepress.com/testimonials.php> to read real quotes from published authors.

Submit your manuscript here: <https://www.dovepress.com/oncotargets-and-therapy-journal>