Effect of SMYD3 on biological behavior and H3K4 methylation in bladder cancer

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Purpose: Our goal was to investigate the effect of SMYD3 on the biological behavior and histone 3 lysine-4 (H3K4) methylation of bladder cancer (BLAC).

Patients and methods: qRT-PCR identified that SMYD3 expression level in BLAC cell lines (T24, 5637, BUI-87 and J-82) and human normal uroepithelial cell line SV-HUC1. We also constructed green fluorescence protein lentiviral vector using the gene short hairpin RNA (shRNA) system. We used Western blot to analyze the SMYD3, H3K4me1, H3K4me2 and H3K4me3 expression levels in shRNA transfection lines. We also performed a colony-forming assay to determine colony-forming ability, cell counting kit-8 for cell proliferation detection, Transwell assay to determine cell migration and invasion and Annexin V-FITC/PI double staining to analyze cell apoptosis.

Results: The SMYD3 expression level was significantly higher in BLAC cell lines (T24, 5637, BUI-87 and J-82) than in human normal uroepithelial cell line SV-HUC1, and exhibited the highest expression level in T24 cells, among the cell lines tested. qRT-PCR and Western blot analysis results showed that SMYD3 was successfully suppressed in shRNA transfection lines, and identified that SMYD3 suppression resulted inhibited H3K4me2 and H3K4me3 but not H3K4me1. SMYD3 knockdown cells accelerated cell apoptosis and exhibited low cell colony-forming ability, proliferation ability, inhibition of cell migration and invasion compared with normal cells.

Conclusion: SMYD3 may be activated in BLAC cells to increase H3K4 activity to modulate cell proliferation, migration and invasion ability. The data will be a useful source for future therapy.

Keywords: SMYD3, H3K4 methylation, bladder cancer, cell proliferation

Introduction

Bladder cancer has been listed as common cancer, and nearly 60% of the incident cases are reported from the developed western countries.1 The etiology of BLAC is unclear, but is a good etiological model of genetic susceptibility and interactions between genetic and epigenetic factors in cancer.2 Smoking is the most relative risk factor of bladder cancer, and the duration and intensity of smoking are correlated with morbidity and mortality, respectively.3 Approximately, 20% of BLAC incidence is caused by occupational carcinogenic substances such as paints and hair dyes.4 Few oncogenes, tumor, tumor suppressor genes and cell cycle regulators, including epidermal growth factor receptors and erb-b2 receptor tyrosine kinase 2 were identified in BLAC cells, thereby facilitating the development of targeted therapy in therapeutics.5–7

Almost 90% of the BLAC began from urothelial cells which prevent water and toxin exchanges between blood and urine.8 Nonmuscle-invasive bladder cancer
of newly diagnosed BLAC, thereby showing favorable prognosis, while the remaining 10–20% of patients with MIBC shows poor outcome of approximately 50% of 5-year disease-free survival, because of the invaded muscle layer and/or lymphatic spread or distant organ metastasis. However, patients with NMIBC need lifetime follow-up and evaluation despite aggressive interventions because they are of high risk of recurrence and progression to MIBC. Therefore, the identification of histone modifications is often upregulated BLAC cell apoptosis, migration and invasion has not been described well in the previous studies. However, the molecular mechanism of SMYD3 regulating BLAC cell apoptosis, migration and invasion has not been described. Thus, in this study, we aimed to elucidate the epigenetic regulations of SMYD3 particularly on H3K4 methylation regulating biological behavior of BLAC cells.

Materials and methods

Cell culture

The human urothelial carcinoma cells lines T24, 5637, BUI-87, and J8 were purchased from BeNa, Beijing, China Culture Collection (BNCC102175, BNCC100680, BNCC100982, BNCC101656, respectively), cultured in DMEM with 10% inactivated FBS and antibiotics. All cells were cultured in a humidified atmosphere of 5% CO2 at 37°C. Among the cell lines, T24 cells were selected as the main cell lines because of the maximally expressed SMYD3 detected by RT-PCR.

Lentivirus vector construction and cell transfection

The short hairpin RNA (shRNA) sequences of SMYD3 gene (shRNA-SMYD3-1,-2,-3/NC) were designed and synthesized by Sangon (Shanghai, China). Then, these sequences were all cloned into the pLVX-shRNA-Puro reporter vector. The Lipofectamine 2000 reagent (Invitrogen, Waltham, MA, USA) was used to shRNA-1,-2,-3 reporter plasmid (50 nmol/L) when 293T cells reached 80–90% confluence. At 24 hrs after transfection, transfection efficiency was measured by qRT-PCR. The primer sequences are as follows: shRNA-SMYD3-1 forward: 5′-GATCCGTTGATGAAAAGTTGGCAAACCTCAAGAGTTGCAAATCTTCATC-3′ and reverse: 5′-AATTCGAAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′; shRNA-SMYD3-2 forward: 5′-GATCCTGCTTGAATCTGGTTGCAAAAATGAGTTGGCAAACCTCAAGAGTTGCAAATCTTCATC-3′ and reverse: 5′-AATTCGAAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′; shRNA-SMYD3-3 forward: 5′-GATCCGCTTGGTTTCAAGAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′ and reverse: 5′-AATTCGAAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′; shRNA-NC forward: 5′-GATCCGCTTGGTTTCAAGAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′ and reverse: 5′-AATTCGAAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′; shRNA-NC forward: 5′-GATCCGCTTGGTTTCAAGAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′ and reverse: 5′-AATTCGAAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′; shRNA-NC forward: 5′-GATCCGCTTGGTTTCAAGAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′ and reverse: 5′-AATTCGAAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′; shRNA-NC forward: 5′-GATCCGCTTGGTTTCAAGAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′ and reverse: 5′-AATTCGAAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′; shRNA-NC forward: 5′-GATCCGCTTGGTTTCAAGAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′ and reverse: 5′-AATTCGAAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′; shRNA-NC forward: 5′-GATCCGCTTGGTTTCAAGAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′ and reverse: 5′-AATTCGAAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′; shRNA-NC forward: 5′-GATCCGCTTGGTTTCAAGAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′ and reverse: 5′-AATTCGAAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′; shRNA-NC forward: 5′-GATCCGCTTGGTTTCAAGAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′ and reverse: 5′-AATTCGAAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′; shRNA-NC forward: 5′-GATCCGCTTGGTTTCAAGAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′ and reverse: 5′-AATTCGAAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′; shRNA-NC forward: 5′-GATCCGCTTGGTTTCAAGAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′ and reverse: 5′-AATTCGAAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′; shRNA-NC forward: 5′-GATCCGCTTGGTTTCAAGAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′ and reverse: 5′-AATTCGAAGAAATTTGGAACCTTCCTTAAGACATGGACAC-3′; shRNA-NC forward:

H3K4 in cancer. However, the mechanism of SMYD3 in BLAC cell progression is still elusive. SMYD3 oncogenic function has been described well in the previous studies. Among the many types of histone modifications, lysine methylation deregulation is the most important in carcinogenesis.
reverse: 5’-AATTCAAAAAACAGAATCTGTAATGACATT TGCCAATCTCTTGAATTGGCAAATGTCATTACGAGTT CTGG-3’. We collected the supernatant of cells rich in lentivirus particles and then obtained the high titer-concentrated lentivirus solution. Virus titers were measured and calibrated in 293T cells.

For transfection, three different shRNA-SMYD3 virus transfections were performed when T24 cells reached 80–90% confluence. We selected the multiplicity of infection (MOI) value of 5 for lentivirus infection. At 72 hrs after transfection, we added the puromycin (5 µg/mL) after 1 week and collected the cells and detected via qPCR and Western blot. The bright field and fluorescence images were captured by a fluorescence microscope at ×100 magnification.

**RNA extraction and quantitative RT-PCR**

The collected cells were lysed in 0.5 mL of NucleoZol reagent (Gene Company Ltd., HongKong, China) and vortexed for 1 min. We added 200 µL of RNase-free water to each sample, vortexed for 15 s, stood for 15 mins at room temperature and centrifuged at 12,000 rpm for 15 mins. We obtained the supernatant, added 500 µL of lysopropylation and 500 µL of isopropylene glycol mixed well and centrifuged at 12,000 rpm for 10 mins. After centrifugation, we displaced the alcohol cleaning steps by using 75% ethanol. Total RNA was measured using Nanodrop (Thermo, Shanghai, China) and preserved at −80°C until use. cDNA synthesis and qRT-PCR were performed using qPCR mix reverse transcription kit (Promega, Fitchburg, WI, USA) according to the manufacturer’s instructions. The primer sequences are as follows: SMYD3 forward: 5’-GAAAAGTTCGCAACCGCAAA-3’ and reverse: 5’-TGAGAGCATCGCATCAGCTT-3’ and GAPDH forward: 5’-GTGCAAGGCTGAGAACGGGAA-3’ and reverse: 5’-AAATGAGCCCCAGCCTTCTC-3’. The expression levels of the target genes were calculated by comparative delta-delta CT method (2−ΔΔCT).

**Cell migration and invasion assay**

Transwell assay was used to detect cell migration and invasion ability. All cells were seeded at a density of 1×10^5/mL at the transwell chamber (Corning Incorporated, Corning, NY, USA). The chamber was filled with serum-free cell culture medium containing 10% FBS and cultured at 37°C for 24 h. After culture, the cells were dyed with a crystal violet solution and observed. Matrigel was melted and uniformly placed in a chamber for invasion assay. The cells were inoculated at 1×10^5/mL at the transwell chamber. The procedures were the same as described above.

**Cell proliferation assay**

Cell proliferation was measured using cell counting kit-8 (Dojindo, Jiuzhou, Japan) assay. The cells were inoculated at 1×10^5/mL in 96-well plates and each group was detected at 0, 24, 48, 72, and 96 hrs. The OD of each plate and their cell proliferation ability were measured. For colony formation assay, the cells were inoculated at 200 per well into 6-well plates and cultured at 37°C for 2 weeks. The cell plates were stained with crystal violet solution and observed.

**Flow cytometry**

To detect cell apoptosis, we performed flow cytometry. The cells were transfected with shRNA-NC, shRNA-SMYD3-3, and control. Each group was stained using Annexin V Alexa Fluor 488/PI apoptotic test kit (Beijing Solay Science & Technology Co., Ltd, Beijing, China) according to the manufacturer’s protocol and analyzed by fluorescence-activated cell sorting (FACS; BD, New York, USA).

**Western blot analysis**

Cells were harvested in an ice-cold lysis buffer (7 M urea, 2 M thiourea, 2% 3-[3-Chloamidopropyl]dimethylammonio] propanesulfonate (CHAP)S, 40 mM Tris base, 40 mM dithiothreitol, and 1% protease inhibitor) to obtain whole-cell extracts. The membranes were incubated with the following primary antibodies (all antibodies from Abcam, Cambridge, MA, USA): anti-SMYD3, anti-H3K4me1, anti-H3K4me2, anti-H3K4me3, and anti-β-actin. The membranes were washed two times with PBS and incubated with an anti-mouse or anti-rabbit horseradish peroxidase-conjugated secondary antibody (1:2000; Cell Signalling Technology, Danvers, MA, USA) for 1 hr.

**Statistical analysis**

The data of each group were presented as the mean ± SD. All data were analyzed using SPSS 22.0 software (SPSS, Chicago, IL, USA). Statistical analysis was conducted using one-way ANOVA. Quantitative data were compared by the one-sample t-test. P<0.05 was considered statistically significant.
Results
SMYD3 is upregulated in BLAC cell lines
To investigate SMYD3 function in BLAC, we examined the endogenous expression level of SMYD3 in BLAC cells. qRT-PCR results showed that SMYD3 level was higher in the BLAC cell lines T24, 5637, BUI-87, and J-82 than in human normal uroepithelial cell line SV-HUC1. The expression levels of T24, 5637, BUI-87 and J-82 were 3.66±0.451, 2.09±0.337, 1.18±0.132 and 2.50±0.214, respectively. T24 cell line showed the highest SMYD3 expression level compare to the other cell lines (Figure 1). Thus, T24 cell line was selected for further experiments.

SMYD3 was efficiently knocked down in bladder cancer cells by shRNA transfection
To analyze SMYD3 function in BLAC, we generated the cells knockdown of SMYD3 by using shRNA to demonstrate the role of SMYD3 in BLAC cells. The results showed that shRNA-NC, shRNA-SMYD3-1, shRNA-SMYD3-2, and shRNA-SMYD3-3 were successfully generated which was verified by green fluorescence protein (GFP) signal detection (Figure 2A). Consequently, the SMYD3 expression level was examined by qRT-PCR. The result showed that SMYD3 expression was effectively suppressed by shRNA-SMYD3-1, −3, and the inhibition rates of the normal control expression level were 0.62% and 37%, respectively (Figure 2A). Western blot analysis was performed to verify the qRT-PCR results. The data indicate that Western blot results were similar with qRT-PCR data with best suppression in shRNA-SMYD3-3 cells (Figure 2B).

SMYD3-mediated H3K4 di- or trimethylation in BLAC
To analyze SMYD3 function in H3K4 methylation status, we performed Western blot analysis to analyze H3K4me1, H3K4me2 and H3K4me3 levels when silencing SMYD3. The results indicated that SMYD3 silencing induced significant change in H3K4me2 and H3K4me3 but not H3K4me1, thereby showing H3K4me2 and H3K4me3 expression level downregulation (Figure 3).

SMYD3 inhibited T24 cell proliferation and colony formation. Proliferation and colony formation are important factors for cancer cell development. Therefore, SMYD3 effects on T24 cell proliferation and colony formation were investigated. The shRNA-SMYD3-3 group exhibited significantly lower proliferation rate and was negatively correlated with time than the control and shRNA-NC groups. The cell proliferation rates in shRNA-NC were 91.64%±4.76, 79.44%±3.46, 70.45%±3.63, and 67.22%±7.10, respectively, after 24, 48, 72, and 96 hrs, respectively, compared with control or shRNA-NC (Figure 4A). The cell proliferation rate in the control and shRNA-NC groups was also similar (Figure 4A).

Next, colony formation was examined in three groups. The colony numbers in the control, shRNA-NC, and shRNA-SMYD3-3 groups were 280±30, 268±25, and 160±17, respectively, thereby indicating that SMYD3 suppression significantly inhibited T24 cell colony formation (Figure 4B).

SMYD3 inhibited T24 cell migration and invasion. We also examined the SMYD3 effects on BLAC cell migration and invasion. Transwell assay was used to analyze T24 cell migration and invasion after 48 hrs of virus transfection. The migration assay showed that SMYD3 suppression inhibited cell migration by 38.6% compared with the control and shRNA-NC groups (Figure 5A). Cell invasion ability was similar to migration, and SMYD3 suppression significantly inhibited cell invasion. The inhibition rate in the shRNA-SMYD3-3 group was 48.83% compared with the control and shRNA-NC groups (Figure 5B).

SMYD3-induced T24 cell apoptosis
Given that SMYD3 suppression inhibited cell proliferation, colony formation, cell migration and invasion, apoptosis rate in control, shRNA-NC, and shRNA-SMYD3-3 groups were
evaluated by FACS. The FACS result showed that cell death rate was significantly higher in shRNA-SMYD3-3 cells than in control and shRNA-NC cells. The cell apoptosis rate was 4.65%, 4.78%, and 16.84%, in the control, shRNA-NC and shRNA-SMYD3-3 groups, respectively (Figure 6).

**Discussion**

BLAC is one of the types of cancer that severely affect male patients worldwide. SMYD3 is a methyltransferase member that induced H3K4 di- and trimethylation in cancer. SMYD3 upregulation was identified in many types of cancer cells including colorectal carcinoma, hepatocellular carcinoma, prostate cancer and breast cancer and plays an oncogenic role. SMYD3 upregulation attenuates cancer progression by promoting cancer cell biological function. In this study, qRT-PCR was performed to analyze SMYD3 expression level in the BLAC cell lines T24, 5637, BUI-87, and J-82 and in human normal uroepithelial cell line SV-HUC1.

qRT-PCR was also used to investigate SMYD3 role in BLAC cells. Similar to other cancer types, the accumulation of SMYD3 was high in BLAC cell lines, especially in T24 line compared with that in normal uroepithelial cell line. This result suggested that SMYD3 may play an important role in cancer cell development. Further experiments by using the tumor and adjacent tissues will be conducted to examine SMYD3 expression further.

To test SMYD3 function in BLAC cells, we determined lentivirus-mediated knockdown in bladder cell lines. In T24 cells, SMYD3 successfully was suppressed by shRNA system, and transfection efficiency was visually analyzed by GFP detection in the construct. The data indicated that SMYD3 suppression inhibited cell proliferation, colony formation, cell migration, and invasion. The cell proliferation, colony formation, migration and
invasion are key steps of cancer cells, and the inhibition rates were all >30%, thereby suggesting these steps are tightly controlled by SMYD3. We also analyzed whether the SMYD3 suppression-mediated inhibition of the T24 cells is associated with cell death/apoptosis. The FACS results clearly indicated that SMYD3 suppression induced T24 cell apoptosis which may inhibit BLAC proliferation, migration, invasion, and colony formation cell line T24. These results suggested that SMYD3 was negatively regulated cell apoptosis which may alter cell migration, invasion, and proliferation.

SMYD3 is a member of the SMYD family and control the di- or trimethylation of histone H3K4 in cancer cells, and SMYD3 is abundant in cancer cells compared with that in normal cells, thereby suggesting that SMYD3-mediated methylation at H34K significantly changed the downstream target gene expressions levels. In our analyses, cell proliferation, migration, invasion, and colony formation were positively regulated by SMYD3, and apoptosis was negatively regulated by SMYD3. Further study will be needed to analyze the target genes of SMYD3 in cancer development, will be important to understand the regulatory basis of cancer cell behavior, and may be a key point to demonstrate that SMYD3-mediated apoptosis signaling regulates BLAC cell migration, proliferation, and invasion.

Figure 3 SMYD3 effects on H3K4 levels. Western blot analysis was performed to analyze H3K4me1, H3K4me2, and H3K4me3 levels. β-actin was used as the loading control. The relative H3K4me1, H3K4me2, and H3K4me3 levels against β-actin shown were calculated. Significant differences between the control and shRNA-SMYD3-3 groups were shown. Statistical analysis was calculated with unpaired Student’s t-test; n≥3, ***P≤0.001.

Abbreviations: H3K4, histone 3 lysine-4; shRNA, short hairpin RNA.
Figure 4 SMYD3 suppression inhibited T24 cell proliferation. (A) Cell proliferation was analyzed by measuring cell OD of the control, shRNA-NC, and shRNA-SMYD3-3 groups by the cell counting kit-8 assay. (B) Colony formation in control, shRNA-NC, and shRNA-SMYD3-3 was analyzed. Significant differences between the control group and shRNA-SMYD3-3 were shown. Statistical analysis was calculated with unpaired Student's t-test. n≥3, ***P≤0.001.

Abbreviation: shRNA, short hairpin RNA.

Figure 5 SMYD3 knockdown inhibited T24 cell migration and invasion. (A) The cells of the control, shRNA-NC, and shRNA-SMYD3-3 groups were photographed and cell migration counts shown were calculated. Significant differences between groups were shown (P<0.01). (B) The cells of the control, shRNA-NC, and shRNA-SMYD3-3 groups were photographed and cell invasion counts were calculated. Significant differences between groups were revealed. Statistical analysis was calculated with unpaired Student's t-test; n≥3, **P≤0.01, ***P≤0.001.

Abbreviation: shRNA, short hairpin RNA.
Also, SMYD3 is also commonly induced in the type of tumor tissues, thereby indicating that SMYD3 may be a considerable therapeutic target for cancer drug development.

**Abbreviations**

NMIBC, non-muscle-invasive bladder cancer; SMYD, SET and MYND domain-containing proteins; SMYD3, SMYD family members; H4K5, histone 4 lysine-5; H3K4, histone 3 lysine-4; shRNA, short hairpin RNA; GFP, green fluorescence protein.

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**Author contributions**

All authors contributed to data analysis, drafting or revising the article, gave final approval of the version to be published, and agree to be accountable for all aspects of the work.

**Disclosure**

The authors report no conflicts of interest in this work.

**References**

1. Ferlay J, Soerjomataram I, Dikshit R, et al. Cancer incidence and mortality worldwide: sources, methods and major patterns in GLOBOCAN 2012. *Int J Cancer*. 2015;136(5):E359–E386. doi:10.1002/ijc.29210

2. Gu J, Wu X. Genetic susceptibility to bladder cancer risk and outcome. *Per Med*. 2011;8(3):365–374. doi:10.2217/pme.11.15

3. Antoni S, Ferlay J, Soerjomataram I, Znaor A, Jemal A, Bray F. Bladder cancer incidence and mortality: a global overview and recent trends. *Eur Urol*. 2017;71(1):96–108. doi:10.1016/j.eururo.2016.06.010

4. Wu X, Ros MM, Gu J, Kiemeneij L. Epidemiology and genetic susceptibility to bladder cancer. *BJU Int*. 2008;102(9b):1207–1215. doi:10.1111/j.1464-410X.2008.07961.x

5. Groenendijk FH, de Jong J, Fransen van de Putte EE, et al. ERBB2 mutations characterize a subgroup of muscle-invasive bladder cancers with excellent response to neoadjuvant chemotherapy. *Eur Urol*. 2016;69(3):384–388. doi:10.1016/j.eururo.2015.01.014

6. Kaufman DS, Shipley WU, Feldman AS. Bladder cancer. *Lancet*. 2009;374(9685):239–249. doi:10.1016/S0140-6736(09)60491-8

7. Black PC, Agarwal PK, Dinney CP. Targeted therapies in bladder cancer – an update. *Urol Oncol*. 2007;25(5):433–438. doi:10.1016/j.urolonc.2007.05.011

8. Van Batavia J, Yamany T, Molotkov A, et al. Bladder cancers arise from distinct urothelial sub-populations. *Nat Cell Biol*. 2014;16(10):982. doi:10.1038/nchb.3308

9. Nargund VH, Tanabalat C, Kabir M. Management of non-muscle-invasive (superficial) bladder cancer. In: *Seminars in Oncology*. Elsevier; 2012.doi:10.1053/j.seminoncol.2012.08.001.

10. Rosenberg JE, Carroll PR, Small EJ. Update on chemotherapy for advanced bladder cancer. *J Urol*. 2005;174(1):14–20. doi:10.1097/01.ju.0000162039.38023.5f

11. Li H-T, Duymich CE, Weisenberger DJ, Liang G. Genetic and epigenetic alterations in bladder cancer. *Int Neuroanterol J*. 2016;20(Suppl 2):S84. doi:10.5213/inj.1632752.376

12. Sarris ME, Moulos P, Haroniti A, Giakountis A, Talianidis I. Smyd3 is a transcriptional potentiator of multiple cancer-promoting genes and required for liver and colon cancer development. *Cancer Cell*. 2016;29(3):354–366. doi:10.1016/j.ccell.2016.01.013

13. Chen LB, Xu JY, Yang Z, et al. Silencing SMYD3 in hepatoma demethylates RIZI promoter induces apoptosis and inhibits cell proliferation and migration. *World J Gastroenterol*. 2007;13(43):5718. doi:10.3748/wjg.v13.i43.5718
14. Bannister AJ, Kouzarides T. Regulation of chromatin by histone modifications. Cell Res. 2011;21(3):381. doi:10.1038/cr.2011.22
15. Huang L, Xu A-M. SET and MYND domain containing protein 3 in cancer. Am J Transl Res. 2017;9(1):1.
16. Wen KX, Milic J, El-Khodor B, et al. The role of DNA methylation and histone modifications in neurodegenerative diseases: a systematic review. PLoS One. 2016;11(12):e0167201. doi:10.1371/journal.pone.0167201
17. Hassan YI, Zempleni J. A novel, enigmatic histone modification: biotinylation of histones by holocarboxylase synthetase. Nat Rev. 2008;66(12):721–725. doi:10.1038/nrj.1753-4887.2008.00127.x
18. Kondo Y. Epigenetic cross-talk between DNA methylation and histone modifications in human cancers. Yonsei Med J. 2009;50(4):455–463. doi:10.3349/ymj.2009.50.4.455
19. Copeland RA, Solomon ME, Richon VM. Protein methyltransferases as a target class for drug discovery. Nat Rev Drug Discov. 2009;8(9):724–732. doi:10.1038/nrd2974
20. Pachaiyappan B, Woster PM. Design of small molecule epigenetic modulators. Bioorg Med Chem Lett. 2014;24(1):21–32. doi:10.1016/j.bmcl.2013.11.001
21. Liu Q, Wang MW. Histone lysine methyltransferases as anti-cancer targets for drug discovery. Acta Pharmacol Sin. 2016;37(10):1273. doi:10.1038/aps.2016.30
22. Qian C, Zhou MM. SET domain protein lysine methyltransferases: structure, specificity and catalysis. Cell Mol Life Sci. 2006;63(23):2755–2763. doi:10.1007/s00018-006-6274-5
23. Rea S, Eisenhaber F, O’Carroll D, et al. Regulation of chromatin structure by site-specific histone H3 methyltransferases. Nature. 2000;406(6796):593. doi:10.1038/35020557
24. Leinhart K, Brown M. SET/MYND lysine methyltransferases regulate gene transcription and protein activity. Genes. 2011;2(1):210–218. doi:10.3390/genes2010210
25. Calpena E, Palau F, Espínos C, Galindo MI, Du S. Evolutionary history of the Smyd gene family in metazoa: a framework to identify the orthologs of human Smyd genes in drosophila and other animal species. PLoS One. 2015;10(7):e0134106. doi:10.1371/journal.pone.0134106
26. Peseiro A, Germani A, Sanese P, et al. A SMYD3 small-molecule inhibitor impairing cancer cell growth. J Cell Physiol. 2015;230(10):2447–2460. doi:10.1002/jcp.24975
27. Hamamoto R, Silva FP, Tsume M, et al. Enhanced SMYD3 expression is essential for the growth of breast cancer cells. Cancer Sci. 2006;97(2):113–118. doi:10.1111/j.1349-7006.2006.00146.x
28. Liu C, Wang C, Wang K, et al. SMYD3 as an oncogenic driver in prostate cancer by stimulation of androgen receptor transcription. J Natl Cancer Inst. 2013;105(22):1719–1728. doi:10.1093/jnci/djt304
29. Frank B, Hemminki K, Wappenschmidt B, et al. Variable number of tandem repeats polymorphism in the SMYD3 promoter region and the risk of familial breast cancer. Int J Cancer. 2006;118(11):2917–2918. doi:10.1002/ijc.21696
30. Chadwick RB, Jiang G-L, Bennington GA, et al. Candidate tumor suppressor RIZ is frequently involved in colorectal carcinogenesis. Proc Natl Acad Sci. 2000;97(6):2662–2667. doi:10.1073/pnas.040579497
31. Liu Y, Luo X, Deng J, Pan Y, Zhang L, Liang H. SMYD3 overexpression was a risk factor in the biological behavior and prognosis of gastric carcinoma. Tumor Biol. 2015;36(4):2685–2694. doi:10.1007/s13277-014-2191-x
32. Ren TN, Wang J-S, He Y-M, Xu C-L, Wang S-Z, Xi T. Effects of SMYD3 over-expression on cell cycle acceleration and cell proliferation in MDA-MB-231 human breast cancer cells. Med Oncol. 2011;28(1):91–98. doi:10.1007/s12032-010-9718-6
33. Hamamoto R, Furukawa Y, Morita M, et al. SMYD3 encodes a histone methyltransferase involved in the proliferation of cancer cells. Nat Cell Biol. 2004;6(8):731. doi:10.1038/ncb1151
34. Van Aller GS, Reynoard N, Barbash O, et al. Smyd3 regulates cancer cell phenotypes and catalyzes histone H4 lysine 5 methylation. Epigenetics. 2012;7(4):340–343. doi:10.4161/epi.19506
35. Sims RJ III, Nishioka K, Reinberg D. Histone lysine methylation: a signature for chromatin function. Trends Genet. 2003;19(11):629–639. doi:10.1016/j.tig.2003.09.007