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Hypermethylation of the TGF- β target, *ABCA1* is associated with poor prognosis in ovarian cancer patients

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Abstract

Background: The dysregulation of transforming growth factor- β (TGF- β) signaling plays a crucial role in ovarian carcinogenesis and in maintaining cancer stem cell properties. Classified as a member of the ATP-binding cassette (ABC) family, *ABCA1* was previously identified by methylated DNA immunoprecipitation microarray (mDIP-Chip) to be methylated in ovarian cancer cell lines, A2780 and CP70. By microarray, it was also found to be upregulated in immortalized ovarian surface epithelial (IOSE) cells following TGF- β treatment. Thus, we hypothesized that *ABCA1* may be involved in ovarian cancer and its initiation.

Results: We first compared the expression level of *ABCA1* in IOSE cells and a panel of ovarian cancer cell lines and found that *ABCA1* was expressed in HeyC2, SKOV3, MCP3, and MCP2 ovarian cancer cell lines but downregulated in A2780 and CP70 ovarian cancer cell lines. The reduced expression of *ABCA1* in A2780 and CP70 cells was associated with promoter hypermethylation, as demonstrated by bisulfite pyro-sequencing. We also found that knockdown of *ABCA1* increased the cholesterol level and promoted cell growth *in vitro* and *in vivo*. Further analysis of *ABCA1* methylation in 76 ovarian cancer patient samples demonstrated that patients with higher *ABCA1* methylation are associated with high stage ($P = 0.0131$) and grade ($P = 0.0137$). Kaplan-Meier analysis also found that patients with higher levels of methylation of *ABCA1* have shorter overall survival ($P = 0.019$). Furthermore, tissue microarray using 55 ovarian cancer patient samples revealed that patients with a lower level of *ABCA1* expression are associated with shorter progress-free survival ($P = 0.038$).

Conclusions: *ABCA1* may be a tumor suppressor and is hypermethylated in a subset of ovarian cancer patients. Hypermethylation of *ABCA1* is associated with poor prognosis in these patients.

Keywords: Ovarian cancer, Epigenetics, *ABCA1*

Background

Ovarian cancer is the most lethal tumor in women and the second most frequent gynecological malignancy [1]. As ovarian cancer has few symptoms early in its course, patients are generally diagnosed with advanced-stage tumors. Despite advances in chemotherapy, the poor

prognosis for patients with late-stage ovarian cancer is reflected by the 5-year survival rate of less than 20% [2]. Current prognostic indicators using clinicopathological variables, including stage and grade, neither accurately predict clinical outcomes nor provide biological insight into the disease. Thus, a better understanding of the molecular changes in ovarian cancer would provide insight for better diagnosis and prognosis of this deadly disease.

The transforming growth factor- β (TGF- β) signaling pathway plays an important role in the regulation of ovarian growth [3]. During ovulation, the ovarian surface epithelial (OSE) cell covering the ovary undergoes

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rupture, followed by proliferation-mediated repair. This growth is inhibited by TGF- β , which plays a key role in preventing overproliferation of OSE cells [4]. In this regard, the dysregulation of TGF- β signaling may be an early step in the development of epithelial ovarian cancer. This is in agreement with the observation that resistance to TGF- β signaling is commonly seen in ovarian cancer, suggesting that reduced responsiveness to TGF- β is a key event in ovarian cancer [5].

Epigenetic alterations, including DNA methylation and histone modifications, play an important role in controlling gene expression [6,7]. Moreover, in cancer, aberrant epigenetic modifications are frequently found to be responsible for the silencing of tumor suppressor genes. Our previous studies using genome-wide techniques have identified several direct targets of TGF- β in immortalized ovarian surface epithelial (IOSE) cells [8]. These targets are silenced epigenetically in ovarian cancer and are associated with poor prognosis in ovarian cancer patients [9-11]. Restoration of the genes inhibited tumor growth, thus suggesting that they are tumor suppressors.

In order to identify additional genes that are hypermethylated in ovarian cancer, we performed methylated DNA immunoprecipitation microarray (mDIP-Chip) in IOSE cells and a panel of ovarian cancer cell lines. Our result showed that *ABCA1*, which is upregulated by TGF- β [8] and is a major regulator of cellular cholesterol [12], is hypermethylated in a subset of ovarian cancer cell lines. Further analysis demonstrated that *ABCA1* methylation was associated with poor prognosis in ovarian cancer patients. These results suggested that *ABCA1* may be a tumor suppressor and can serve as a prognostic indicator in ovarian cancer.

Results

ABCA1 is epigenetically silenced in ovarian cancer cells

Our previous studies demonstrated that novel TGF- β targets, *FBXO32* and *RunX1T1*, are epigenetically silenced by promoter hypermethylation in ovarian cancer [10,11]. To identify additional genes regulated by TGF- β that exhibited promoter hypermethylation in ovarian cancer, we performed mDIP-Chip in IOSE cells and a panel of ovarian cancer cell lines [13]. One of the genes, *ABCA1*, which exhibited promoter methylation in a subset of ovarian cancer cell lines but not in IOSE cells, was selected for further analysis. This gene was also previously found to be upregulated in IOSE cells after TGF- β treatment [8].

To confirm our microarray result, we first examined the mRNA expression level of *ABCA1* in various ovarian cancer cell lines (Figure 1A). The result showed that *ABCA1* was repressed in A2780 and CP70 cells. Although treatment of HDAC inhibitor (TSA) or EZH2 inhibitor (GSK343) alone did not result in any significant

re-expression of *ABCA1*, treatment of demethylating agent, 5aza, alone resulted in a robust re-expression of *ABCA1* in CP70 ovarian cancers, suggesting that DNA methylation is responsible for the suppression of *ABCA1* in CP70 cells (Figure 1B). These results were confirmed by bisulfite pyro-sequencing such that CpG sites around the transcriptional start site (TSS) of *ABCA1* were heavily methylated in A2780 and CP70 ovarian cancer cells, while such methylation was either undetectable or low in IOSE cells or other ovarian cancer cells (Figure 1C). Taken together, these results suggested that promoter hypermethylation may be responsible for the transcriptional repression of *ABCA1* in ovarian cancer.

Depletion of *ABCA1* increases cholesterol level in ovarian cancer cells

As *ABCA1* is responsible for cholesterol efflux, we first measured the effect of *ABCA1* depletion on the cholesterol level of ovarian cancer cells. Lentiviral knockdown of *ABCA1* was performed in MCP3 (Figure 2A) and HeyC2 (Figure 2B) ovarian cancer cells. The result showed that more than 50% repression of *ABCA1* was observed in these cells. As expected, depletion of *ABCA1* resulted in a significant accumulation of cholesterol in MCP3 (Figure 3A, $P < 0.05$) and HeyC2 (Figure 3B, $P < 0.05$) cells.

Depletion of *ABCA1* promotes cell growth in ovarian cancer cells *in vitro* and *in vivo*

Dysregulation of cholesterol homeostasis has been shown to be related to cancer. Therefore, we hypothesized that *ABCA1* might act as a tumor suppressor in ovarian cancer. To confirm this hypothesis, we examined the effect of *ABCA1* depletion on the growth of ovarian cancer cells. Interestingly, depletion of *ABCA1* resulted in an increased cell growth in MCP3 (Figure 2C, $P < 0.001$) and HeyC2 (Figure 2D, $P < 0.05$) cells as demonstrated by colony formation assay. Further *in vivo* experiments also demonstrated that significant increased tumor growth was observed in *ABCA1*-depleted HeyC2 cells as compared to control (Figure 3C).

Hypermethylation of *ABCA1* associates with tumor progression in ovarian cancer patients

Having demonstrated that promoter hypermethylation of *ABCA1* can be observed in ovarian cancer cell lines, we then proceeded to examine if such epigenetic event can also be observed in ovarian cancer patient samples (Table 1, Figure 4A, B). Results from bisulphite pyro-sequencing showed that patients with a higher stage ($P = 0.026$) and grade ($P = 0.013$) but not age have a significantly higher level of *ABCA1* methylation.

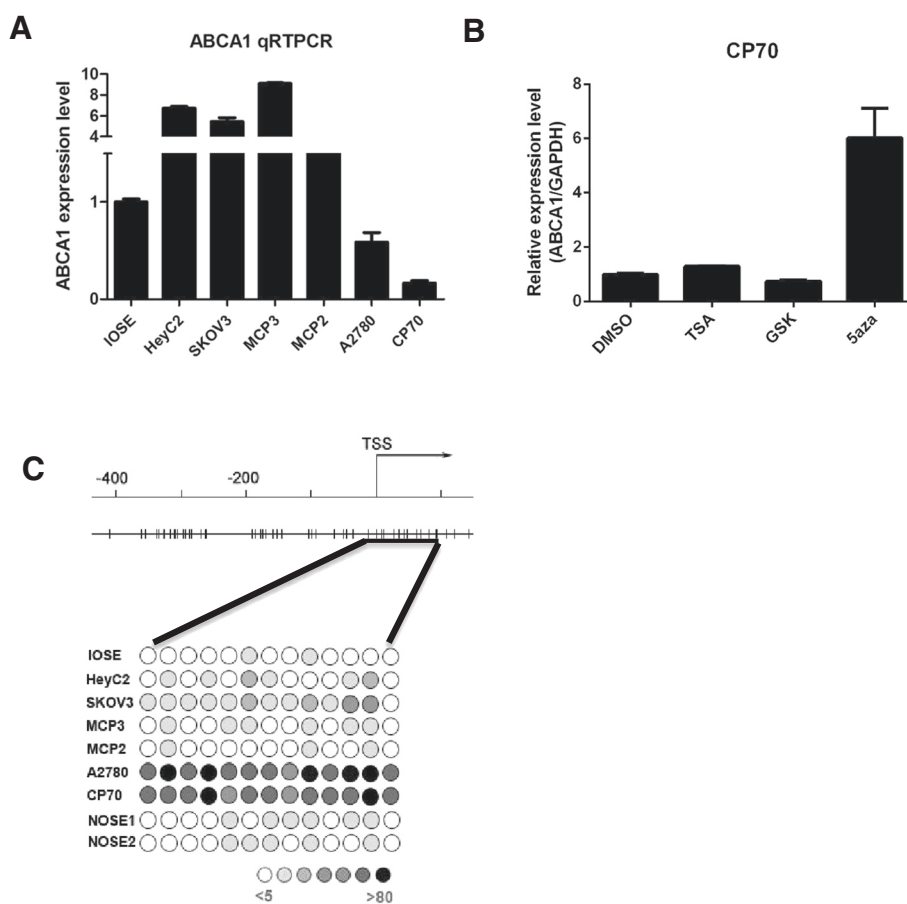


Figure 1 *ABCA1* expression and methylation level in IOSE cells and ovarian cancer cell lines. **(A)** Total RNA was isolated from ovarian cells and converted into cDNA for amplification with specific primers for *ABCA1*. The relative level of expression after quantitative real-time RT-PCR was compared to IOSE cells (set as one fold). Each bar represents mean \pm SD. **(B)** CP70 cells were treated with TSA (0.5 μ M, 12 h), GSK343 (1 μ M, 3 days), or 5aza (0.5 μ M, 3 days). The expression level of *ABCA1* was determined by RT-PCR. Treatment of 5aza, but not TSA or GSK, resulted in robust re-expression of *ABCA1* in CP70 cells. Each bar represents mean \pm SD. **(C)** The methylation status of the *ABCA1* promoter and TSS region was analyzed by bisulfite pyro-sequencing from -90 to +190 (black line underneath). The upper panel shows the *ABCA1* promoter and TSS region and the corresponding CpG sites (vertical bar), and the lower panel illustrates DNA methylation at the interrogated CpG site (circle) in IOSE cells, two NOSE samples, and ovarian cancer cell lines with intensity of gray color indicating methylation level.

Hypermethylation of *ABCA1* associates with poor prognosis in ovarian cancer patients

To further investigate if *ABCA1* methylation was predictive of survival in ovarian cancer patients, we performed Kaplan-Meier survival analyses. Using the baseline methylation level of *ABCA1* in IOSE cells (3%) as a cutoff, a significant association between patients with high *ABCA1* methylation and shorter overall survival (OS; $P = 0.019$) but not progression-free survival (PFS; $P = 0.1$) was observed (Figure 4C, D).

Because the above approaches based on a cutoff value may have biased the data analysis, the Cox proportional hazards model was used to analyze the predictive value of *ABCA1* methylation and other clinicopathological parameters on OS and PFS (Table 2). As expected, a higher stage (OS: hazard ratio: 11.321, $P = 0.02$; PFS: hazard ratio: 14.278, $P < 0.01$) and grade (OS: hazard ratio: 22.559,

$P = 0.03$; PFS: hazard ratio: 20.586, $P < 0.01$) but not age was significantly associated with poor prognosis. Interestingly, methylation of *ABCA1* is also associated with poor patient outcome in ovarian cancer (OS: hazard ratio: 1.106, $P = 0.033$; PFS: hazard ratio: 1.096, $P = 0.013$). However, this association was not observed in multivariate analysis, thus suggesting that other factors are also involved in the survival of ovarian cancer patients (Table 3). Taken together, methylation of *ABCA1* is partially associated with poor prognosis in ovarian cancer patients.

Low expression of *ABCA1* associates with poor prognosis in ovarian cancer patients

To further investigate the association between expression of *ABCA1* and survival of ovarian cancer patients, we performed tissue microarray on a different cohort containing

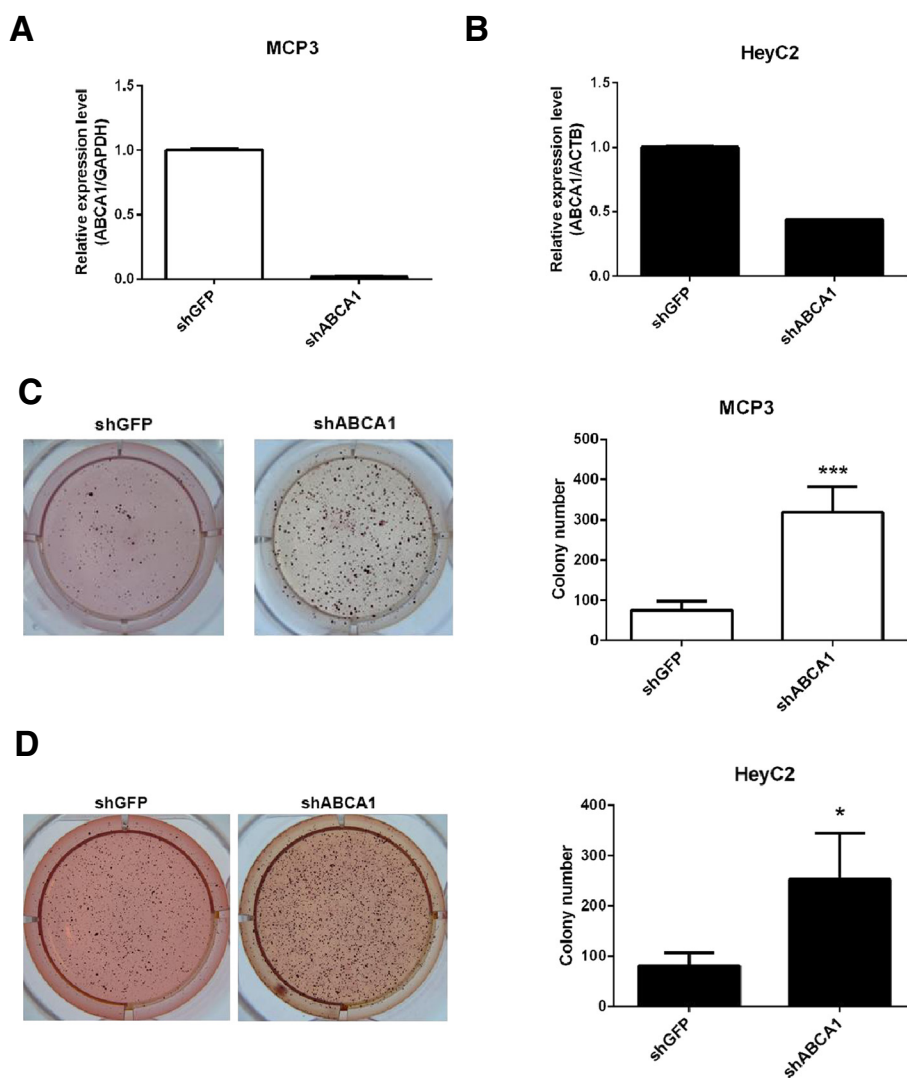


Figure 2 Effects of *ABCA1* knockdown on cell growth. Real-time RT-PCR expression of *ABCA1* in (A) MCP3 and (B) HeyC2 cells infected by lentivirus against shGFP (control) or sh*ABCA1*. Each bar represents mean \pm SD. The growth of *ABCA1* knockdown (C) MCP3 and (D) HeyC2 cells was examined by soft agar assay. Quantitative analysis of the soft agar assay is also shown. *** $P < 0.001$; * $P < 0.05$.

55 ovarian patient samples (Table 4, Figure 5A). Although expression of *ABCA1* is not associated with any clinicopathological parameters of the samples (Table 5), patients with low expression of *ABCA1* are associated with shorter progression-free survival (Figure 5B). Similarly, analysis of TCGA ovarian cancer RNA-Seq dataset [14] also found that patients with lower expression of *ABCA1* are associated with shorter overall survival (Figure 5C).

Discussion

In the current study, we demonstrated promoter hypermethylation of *ABCA1*, a cholesterol transporter in ovarian cancer cell lines and patient samples. This is a cancer-specific event as methylation of *ABCA1* was not observed in IOSE and normal ovarian surface epithelial

(NOSE) cells. Methylation of *ABCA1* was also negatively associated with its expression and increased cell growth *in vitro* and *in vivo*. Importantly, ovarian cancer patients with higher *ABCA1* methylation were associated with shorter survival. Result from tissue microarray and TCGA ovarian cancer RNA-Seq dataset also demonstrated that ovarian cancer patients with lower *ABCA1* expression were associated with shorter survival. Our results were also confirmed by a recent finding that *ABCA1* is epigenetically silenced by promoter methylation in prostate cancer cells. Hypermethylation of *ABCA1* is associated with high-grade prostate cancer [15]. Taken together, these results suggest that *ABCA1* may be a tumor suppressor and are epigenetically silenced in human cancer.

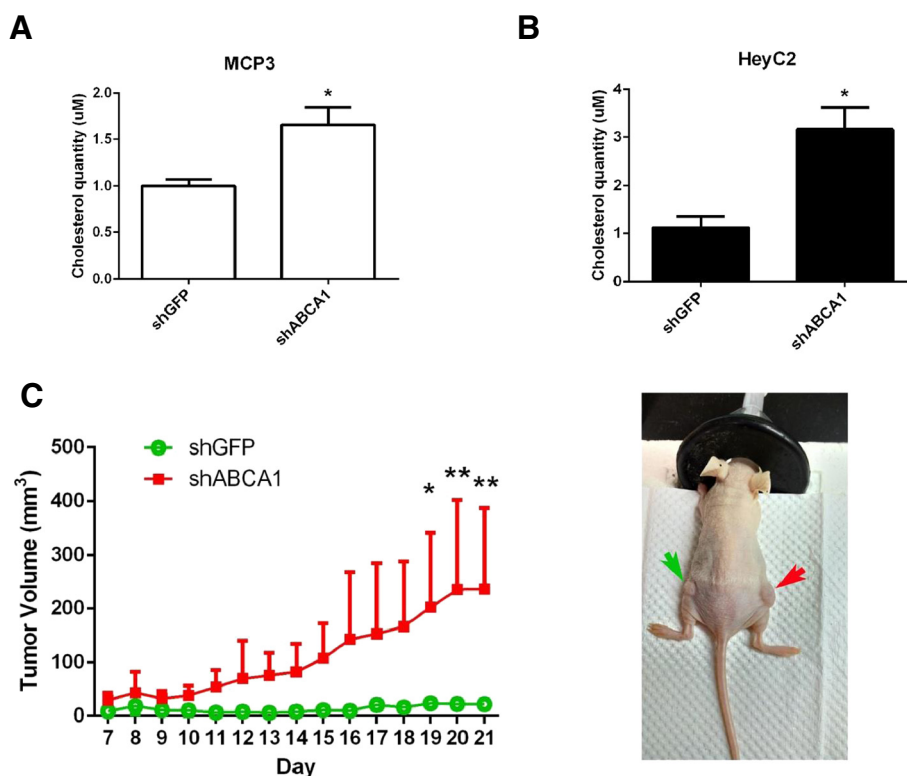


Figure 3 Effects of *ABCA1* knockdown on cholesterol level and ovarian cancer growth *in vivo*. The cholesterol level of *ABCA1* knockdown (A) MCP3 and (B) HeyC2 cells was measured by cholesterol quantitation assay. (C) The effect of *ABCA1* knockdown on tumor growth *in vivo* was determined by the nude mice model. HeyC2 cells stably infected with shABCA1 (red arrow) or shGFP (green arrow) were injected subcutaneously into athymic nude mice. One week later, tumor volumes were measured daily. From day 19, the volume of tumors with *ABCA1* knockdown was significantly reduced as compared to vector controls (**P* < 0.05; ***P* < 0.005). Data were expressed as mean ± SD (*n* = 3).

Table 1 Association between methylation of *ABCA1* and clinicopathological features of 76 ovarian cancer patients

	Methylation %	<i>P</i>
Age		
≥60	5.2 ± 3.01 ^a (53/76) ^b	0.379
<60	6.71 ± 5.34 (23/76)	
Stage ^c		
Low	4.36 ± 2.10 (27/76)	
High	6.52 ± 4.44 (49/76)	0.026 ^e
Grade ^d		
Low	4.71 ± 3.62 (29/76)	
High	6.26 ± 3.77 (47/76)	0.013

^aMean ± SD.

^bNumber in parentheses represents the number of cases.

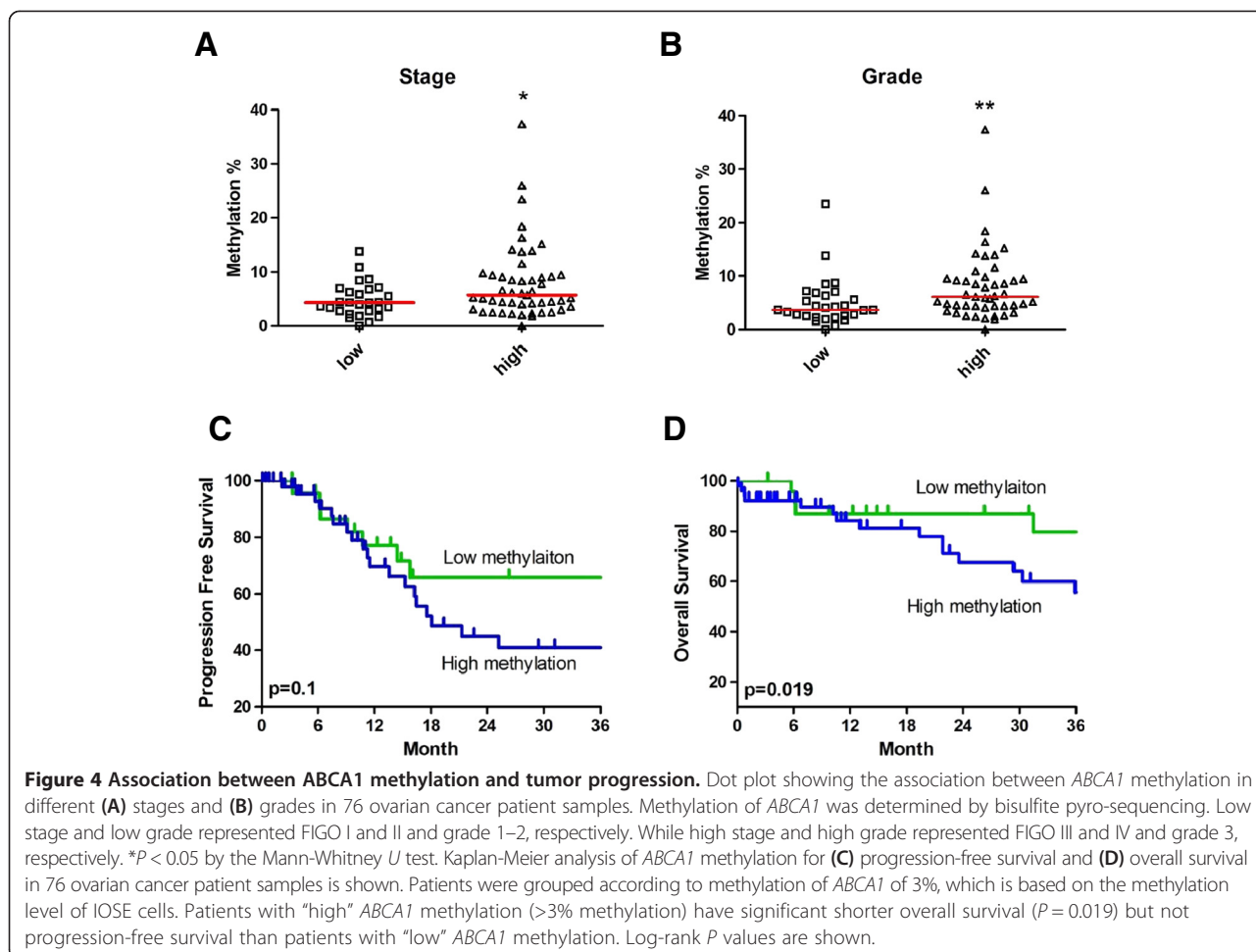
^cLow and high stages are defined as FIGO I and II and FIGO III and IV, respectively.

^dLow and high grades are defined as grade 1–2 and grade 3, respectively.

^eItalicized value indicates *P* < 0.05.

ABCA1, which belongs to the ATP-binding cassette (ABC) protein family, is responsible for cholesterol efflux and metabolism. It has been shown to be essential for the synthesis of high-density lipoprotein (HDL) particles by exporting cellular cholesterol out of the cell. Recent studies suggested that *ABCA1* may be a tumor suppressor [16]. For example, Smith and Land demonstrated that overexpression of *ABCA1* in colon cancer cells resulted in a decrease of cellular cholesterol and inhibition of tumor growth *in vitro* and *in vivo*. This growth inhibition may be due to apoptosis, as overexpression of *ABCA1* enhanced cytochrome C release from mitochondria.

Expression of *ABCA1* has been previously shown to be activated by the nuclear receptor liver X receptor (LXR) [17]. Interestingly, TGF-β could significantly increase the expression of *ABCA1* through activation of LXR signaling [18]. Together with our previous finding that *ABCA1* is a TGF-β target in IOSE cells, it is thus suggested that the growth inhibitory effect of TGF-β may be partly due to overexpression of *ABCA1* in IOSE cells. Epigenetic alteration of *ABCA1* may contribute to the resistance of TGF-β-mediated growth suppression in ovarian cancer cells [9].



Dysregulation of cholesterol homeostasis has been known to be related to cancer [19]. Several studies have demonstrated an elevated level of cholesterol in tumor as compared to normal tissue [20,21]. Recently, Li et al. also demonstrated that ovarian cancer patients with higher serum low-density lipoprotein (LDL) level were significantly associated with shorter progression-free survival and overall survival [22]. It may be due to the fact that lipid serves as an energy source for promoting cell growth and metastasis in ovarian cancer [23]. In this regard, numerous studies have demonstrated that cholesterol-lowering agents, such as statins, exhibit anti-tumor

activity against various cancers [24]. For example, statins have been shown to reduce tumor growth in xenograft models [25,26]. In ovarian cancer, a clinical study demonstrated that patients with statins are associated with improved survival [27]. This may be due to the growth inhibition and augmentation of apoptosis by statins in ovarian cancer cells [28-30]. Furthermore, inhibition of HMG-CoA reductase by statins can also lead to a decreased level of mevalonate, which is important for the synthesis of isoprenoids including geranyl pyrophosphate (GPP) and farnesyl pyrophosphate (FPP) [24,31]. Proper activation of several signaling molecules such as small

Table 2 Univariable analysis of survival by the Cox proportional hazards model

Variable	Overall survival		Progression-free survival	
	HR (95% CI)	<i>P</i>	HR (95% CI)	<i>P</i>
<i>ABCA1</i> methylation	1.106 (1.008–1.213)	0.033 ^a	1.096 (1.020–1.179)	0.013
Age	2.014 (0.712–5.701)	0.187	1.309 (0.579–2.963)	0.518
Stage	11.321 (2.48–51.679)	0.02	14.278 (4.233–48.154)	<0.01
Grade	22.559 (2.849–178.624)	0.03	20.586 (4.817–87.977)	<0.01

^aItalicized value indicates $P < 0.05$.

Table 3 Multivariate analysis of survival by the Cox proportional hazards model

	PFS		OS	
	HR (95% CI)	P	HR (95% CI)	P
ABCA1 methylation	1.013 (0.960–1.069)	0.636	1.016 (0.965–1.069)	0.554
Age	0.993 (0.961–1.025)	0.665	1.019 (0.988–1.051)	0.233
Stage	1.633 (1.159–2.302)	0.005	2.330 (1.196–4.538)	0.013
Grade	1.578 (0.557–4.473)	0.390	1.538 (0.340–6.963)	0.577

GTP-binding proteins Ras and Rho require prenylation of GPP and FPP. Thus, blocking of cholesterol metabolism would reduce cancer growth by suppression of the proliferation signal.

Conclusions

Promoter methylation of *ABCA1* was observed in ovarian cancer cell lines and patient samples. Ovarian cancer patients with higher methylation and lower expression of *ABCA1* were associated with shorter survival. The tumor suppressor function of *ABCA1* in ovarian cancer warrants further investigation.

Methods

Patient samples

Seventy-six treatment-naive ovarian cancer samples were obtained from Tri-Service General Hospital, Taipei, Taiwan (Table 6). Eight NOSE cell samples were acquired from patients during surgery for benign gynecological disease at

Table 4 Summary of clinicopathological data of 55 ovarian cancer patients in tissue microarray

	Ovarian cancer (n = 55)
Age at diagnosis (years)	
Median	51
Range	18–81
Stage	
FIGO (I–II)	22
FIGO (III–VI)	33
Grade	
I	9
II	14
III	32
Pathological type	
Clear cell	4
Serous	37
Mucinous	11
Endometrioid	3
Median survival (months)	
PFS	25.3
OS	36.7

PFS progression-free survival, OS overall survival.

either the Tri-Service General Hospital or Indiana University, USA. For this cohort of ovarian cancer patient samples, the median age at the time of diagnosis was 54 years (range, 18–90 years). Forty-nine cases (64.5%) were high stage (International Federation of Gynecology and Obstetrics (FIGO) stages III and IV), and 27 cases (35.5%) were low stage (FIGO stages I and II). Forty-seven cases (61.8%) were grade III, 13 cases (17.1%) were grade I, and 16 cases (21.1%) were grade II. All of the studies involving human ovarian epithelial samples were approved by the institutional review boards of the Tri-Service General Hospital, Taiwan, and Indiana University.

Cell culture

IOSE cells were derived by transducing the catalytic subunit of human telomerase and the papilloma virus subunit E7 into primary ovarian epithelial cells, as described previously [32]. The cells were maintained in a 1:1 mixture of Medium 199 (Sigma, St. Louis, MO) and 105 (Sigma) supplemented with 10% fetal bovine serum (FBS) (Invitrogen, Carlsbad, CA), 400 ng/ml hydrocortisone (Sigma), 10 ng/ml EGF, and 50 units/ml of penicillin/streptomycin (Invitrogen). The ovarian cancer cell lines A2780, CP70, MCP2, and MCP3 were propagated in RPMI 1640 (Invitrogen) containing 10% FBS. HeyC2 cells were cultured in Dulbecco's modified Eagle's medium (DMEM) containing 5% FBS, 1% NEAA, 1% Gln, and 1% HEPES. SKOV3 cells were cultured in McCoy's 5A containing 10% FBS, 1% NEAA, 1% Gln, and 1% HEPES.

DNA extraction, RNA extraction, and quantitative reverse transcription-PCR

DNA was extracted with the Tissue & Cell Genomic DNA Purification Kit (GeneMark, Taiwan). It was eluted in 50 μ l distilled water and stored at -20°C until use. Total RNA from cell lines was extracted using TRIzol (Invitrogen), as previously described. Briefly, 1 μ g of total RNA was treated with DNase I (amplification grade, Invitrogen) before first-strand cDNA synthesis using reverse transcriptase (Superscript II RT, Invitrogen). The real-time PCR reactions were carried out using the ABI StepOne real-time PCR system (Applied Biosystems, Foster City, CA) with specific primers (Additional file 1: Table S1). The relative expression of *ABCA1* was calculated using the comparative Ct method.

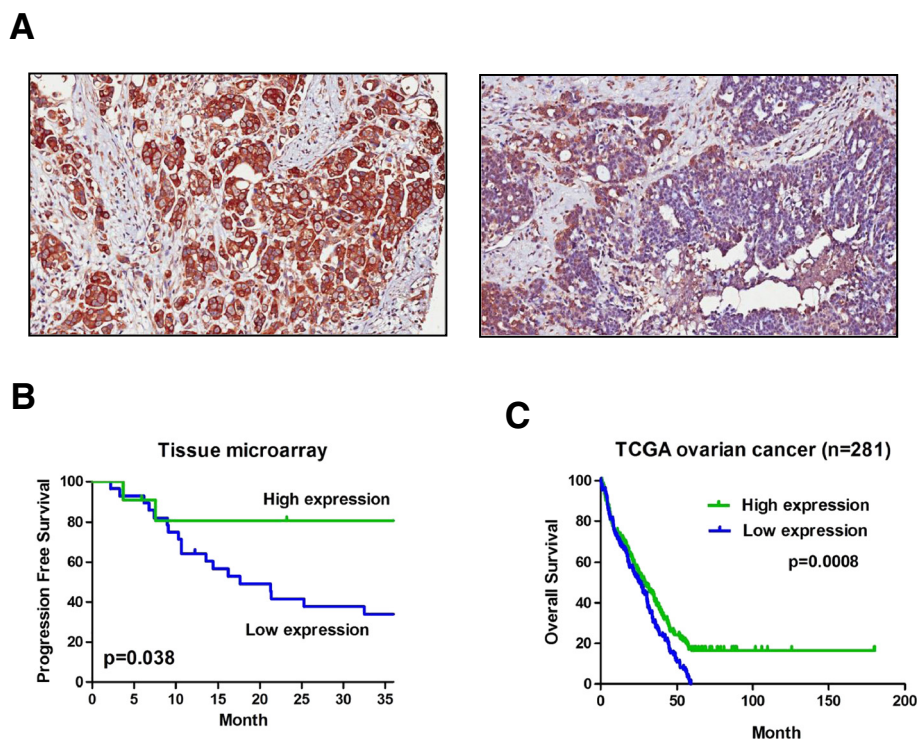


Figure 5 Association between expression of ABCA1 and survival in ovarian cancer patients. Expression of ABCA1 in 55 ovarian cancer patient samples was determined by IHC in tissue microarray. **(A)** Representative image of ovarian cancer showing high (left panel) and low (right panel) ABCA1 expression on the cell membrane or cytoplasm (×400). **(B)** Kaplan-Meier analysis found that patients with low ABCA1 expression have shorter progression-free survival than patients with high ABCA1 expression ($P = 0.038$). **(C)** Similar results can be observed in TCGA ovarian cancer RNA-Seq dataset that patients with low expression of ABCA1 are associated with shorter overall survival ($P = 0.0008$). Log-rank P values are shown.

Bisulfite conversion and pyro-sequencing

Bisulphite pyro-sequencing was performed as described previously [11]. Briefly, 0.5 μg of genomic DNA was bisulfite-modified using the EZ DNA Methylation Kit (Zymo Research, Orange, CA), according to the manufacturer’s protocol. The bisulfite-modified DNA was subjected

Table 5 Association between expression of ABCA1 and clinicopathological features of 55 ovarian cancer patients

	Expression score		
	High expression	Low expression	
Age			
≥60	11 ^a (20%)	26 (47.2%)	0.572
<60	5 (9.1%)	13 (23.6%)	
Stage			
Low	6 (10.9%)	16 (29.1%)	0.528
High	10 (18.2%)	23 (41.8%)	
Grade			
Low	3 (5.5%)	6 (10.9%)	0.522
High	13 (23.6%)	33 (60%)	

^aNumber of cases.

to PCR amplification using a tailed reverse primer in combination with a biotin-labeled universal primer. The PCR and sequencing primers were designed using PyroMark Assay Design 2.0 (Qiagen GmbH, Hilden, Germany). The ABCA1 TSS (−90 to +190) was PCR-amplified with specific primers (Additional file 1: Table S1) in a 25-μl reaction containing 2× RBC SensiZyme Hotstart Taq premix (RBC Bioscience, Taiwan). Prior to pyro-sequencing, 1.5 μl of each PCR reaction was analyzed on 1% agarose gel. The pyro-sequencing was performed on the PyroMark Q24 instrument (Qiagen) using the Pyro Gold Reagents (Qiagen), according to the manufacturer’s protocol. The methylation level of 11 CpG sites, which are located −13 to +95 with respect to the TSS, was measured. The methylation percentage of each cytosine was determined using the fluorescence intensity of cytosines divided by the sum of the fluorescence intensity of cytosines and thymines at each CpG site. *In vitro* methylated DNA (Millipore) was included as positive control for pyro-sequencing.

Knockdown of ABCA1 by shRNA

The small hairpin RNA (shRNA) of ABCA1 were acquired from the National RNAi Core Facility Platform at the

Table 6 Summary of clinicopathological data of 76 ovarian cancer patients

	Ovarian cancer (n = 76)
Age at diagnosis (years)	
Median	54
Range	18–90
Stage	
FIGO (I–II)	27
FIGO (III–VI)	49
Grade	
I	13
II	16
III	47
Pathological type	
Serous	48
Mucinous	23
Endometrioid	5
Median survival (months)	
PFS	11.51
OS	17.42

PFS progression-free survival, OS overall survival.

Institute of Molecular Biology/Genomic Research Center, Academia Sinica, Taiwan. Briefly, 293T cells were transfected with shRNA (TRCN0000029093), pMDG, and pCMVR 8.91 using the ProFection Mammalian Transfection System (Promega) to prepare the shABCA1 lentivirus. Infected ovarian cancer cells were selected by incubating with puromycin (2 µg/ml; Sigma) for at least 2 days.

Soft agar assay for colony formation

Trypsinized cells (1,000 cells) were seeded and mixed in 1.5 ml of 0.35% top layer agar supplemented with DMEM with 10% FBS. This suspension was overlaid on the bottom layer of 0.5% agar in DMEM with 10% FBS in a six-well plate. Plates were allowed to solidify and then incubated at 37°C for around 3 weeks. Colony formation was monitored daily by microscopic observation. At the end of the experiments, the plates were stained with iodine-tetrazolium (INT) stain (Sigma) for 48 h at 37°C. The number of colonies was counted.

Immunohistochemical analysis on ovarian tissue microarray

The paraffin-embedded ovarian cancer patients' tissue microarray were prepared and retrieved from the Department of Pathology, Tri-Service General Hospital as described previously [33]. The tissue microarray contained 55 samples of ovarian cancer patients (Table 4). The immunohistochemistry procedure followed a standard protocol, using a rabbit polyclonal anti-human ABCA1 antibody

(NB400-105, Novus Biologicals). All tissue microarray slides were examined and scored by two pathologists. Immunohistochemistry (IHC) scoring was determined by distribution of positively stained cell × intensity of the staining. A scoring of 60 was used as a cutoff value.

In vivo tumorigenicity assay

A total of three, 8-week-old, athymic nude mice (BALB/cByJNarl) were obtained from the National Laboratory Animal Center, Taiwan. All mice were kept under specific pathogen-free conditions using a laminar airflow rack with free access to sterilized food and autoclaved water. All experiments were performed under license from Animal Experimentation Ethics Committee of the National Chung Cheng University. HeyC2 cells (1×10^6) stably infected with pLKO.1/shABCA1 or pLKO.1/shGFP were re-suspended in 0.1 ml of medium and Matrigel (BD Biosciences, San Jose, CA) mixture (1:1). The cell suspension was then injected subcutaneously into the flank of each mouse (day 0). Tumor size was measured daily with calipers in length (*L*) and width (*W*). Tumor volume was calculated using the formula ($L \times W^2/2$). At the end of the experiment, all mice were sacrificed by cervical dislocation.

Analysis of cellular cholesterol content

Ovarian cancer cells (1×10^4) infected with shABCA1 or shGFP were seeded in a six-well dish and cultured for 48 h. After 48 h, the cells were washed with cold PBS twice and scraped. The cells were re-suspended in 10% RIPA buffer (50 mM HEPES-KOH, pKa 7.55, 500 mM LiCl, 1 mM EDTA, 0.1% NP-40, and 0.07% Na-deoxycholate) and kept on ice for 15 min. Cholesterol content was determined by the Amplitude™ Fluorimetric Cholesterol Quantitation Kit (AAT Bioquest, Sunnyvale, CA) according to the manufacturer's protocol. Fluorescence of cholesterol was detected by Ex/Em at 540/590 nm.

Statistical analysis

PFS and OS were assessed by Kaplan-Meier analysis using the log-rank test. Progression-free survival was defined as the duration from the day of diagnosis or chemotherapy to the detection of new lesions or progression of residual lesions. Overall survival was defined as the duration from the day of diagnosis to death. A DNA methylation level at 3%, which is the level of methylation in OSE cells, was used as a cutoff. Fisher's exact test or the Mann-Whitney *U* test was also used to compare parameters of different groups. All statistical calculations were performed using the statistical package SPSS version 13.0 for Windows (SPSS, Inc., Chicago, IL). *P* < 0.05 was considered to be statistically significant. For TCGA ovarian cancer RNA-Seq dataset, a mean RPKM value of 4 was used as a cutoff.

Additional file

Additional file 1: Table S1. Primer sequences used in the study. **Table S1.** lists all the primers for RT-PCR and bisulphite pyro-sequencing.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

JLC analyzed the methylation microarray, performed the bisulfite pyro-sequencing, conducted the cell line experiments, and drafted the manuscript. RLH performed the IHC on tissue microarray. JS and LYC assisted with the cell line and methylation studies. SJL assisted with the knockdown experiments. PSY co-designed the project and assisted with the methylation microarray. WTC assisted with the cholesterol analyses. YHL performed the *in vivo* tumorigenicity assay. YLL assisted with the *in vivo* tumorigenicity assay. TKC analyzed the IHC results. CIL coordinated the knockdown experiments. CKT and SFW coordinated the *in vivo* tumorigenicity assay. KPN provided the NOSE samples. THH co-designed the project. HCL provided the patient samples and clinicopathological data, assisted with the interpretation of the data, co-designed the project, and secured the funding. MWC performed the methylation microarray, assisted with the interpretation of the data, co-designed the project, secured the funding, and revised the manuscript. All authors read and approved the final manuscript.

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References

- Wakabayashi MT, Lin PS, Hakim AA. The role of cytoreductive/debulking surgery in ovarian cancer. *J Natl Compr Canc Netw*. 2008;6:803–10. quiz 811.
- Nossov V, Amneus M, Su F, Lang J, Janco JM, Reddy ST, et al. The early detection of ovarian cancer: from traditional methods to proteomics. Can we really do better than serum CA-125? *Am J Obstet Gynecol*. 2008;199:215–23.
- Wong AS, Leung PC. Role of endocrine and growth factors on the ovarian surface epithelium. *J Obstet Gynaecol Res*. 2007;33:3–16.
- Nilsson EE, Skinner MK. Role of transforming growth factor beta in ovarian surface epithelium biology and ovarian cancer. *Reprod Biomed Online*. 2002;5:254–8.
- Hu W, Wu W, Nash MA, Freedman RS, Kavanagh JJ, Verschraegen CF. Anomalies of the TGF-beta postrecep signaling pathway in ovarian cancer cell lines. *Anticancer Res*. 2000;20:729–33.
- Simon JA, Lange CA. Roles of the EZH2 histone methyltransferase in cancer epigenetics. *Mutat Res*. 2008;647:21–9.
- McKenna ES, Roberts CW. Epigenetics and cancer without genomic instability. *Cell Cycle*. 2009;8:23–6.
- Qin H, Chan MW, Liyanarachchi S, Balch C, Potter D, Souriraj JJ, et al. An integrative ChIP-chip and gene expression profiling to model SMAD regulatory modules. *BMC Syst Biol*. 2009;3:73.
- Chan MW, Huang YW, Hartman-Frey C, Kuo CT, Deatherage D, Qin H, et al. Aberrant transforming growth factor beta1 signaling and SMAD4 nuclear translocation confer epigenetic repression of ADAM19 in ovarian cancer. *Neoplasia*. 2008;10:908–19.
- Chou JL, Su HY, Chen LY, Liao YP, Hartman-Frey C, Lai YH, et al. Promoter hypermethylation of FBXO32, a novel TGF-beta/SMAD4 target gene and tumor suppressor, is associated with poor prognosis in human ovarian cancer. *Lab Invest*. 2010;90:414–25.
- Yeh KT, Chen TH, Yang HW, Chou JL, Chen LY, Yeh CM, et al. Aberrant TGFbeta/SMAD4 signaling contributes to epigenetic silencing of a putative tumor suppressor, RunX1T1 in ovarian cancer. *Epigenetics*. 2011;6:727–39.
- Fielding PE, Nagao K, Hakamata H, Chimini G, Fielding CJ. A two-step mechanism for free cholesterol and phospholipid efflux from human vascular cells to apolipoprotein A-1. *Biochemistry*. 2000;39:14113–20.
- Yeh CM, Shay J, Zeng TC, Chou JL, Huang TH, Lai HC, et al. Epigenetic silencing of ARNTL, a circadian gene and potential tumor suppressor in ovarian cancer. *Int J Oncol*. 2014;45:2101–7.
- The Cancer Genome Atlas Research Network. Integrated genomic analyses of ovarian carcinoma. *Nature*. 2011;474:609–15.
- Lee BH, Taylor MG, Robinet P, Smith JD, Schweitzer J, Sehayek E, et al. Dysregulation of cholesterol homeostasis in human prostate cancer through loss of ABCA1. *Cancer Res*. 2013;73:1211–8.
- Smith B, Land H. Anticancer activity of the cholesterol exporter ABCA1 gene. *Cell Rep*. 2012;2:580–90.
- Laffitte BA, Joseph SB, Walczak R, Pei L, Wilpitz DC, Collins JL, et al. Autoregulation of the human liver X receptor alpha promoter. *Mol Cell Biol*. 2001;21:7558–68.
- Hu YW, Wang Q, Ma X, Li XX, Liu XH, Xiao J, et al. TGF-beta1 up-regulates expression of ABCA1, ABCG1 and SR-BI through liver X receptor alpha signaling pathway in THP-1 macrophage-derived foam cells. *J Atheroscler Thromb*. 2010;17:493–502.
- Potter VR. The biochemical approach to the cancer problem. *Fed Proc*. 1958;17:691–7.
- Dessi S, Batetta B, Anchisi C, Pani P, Costelli P, Tessitore L, et al. Cholesterol metabolism during the growth of a rat ascites hepatoma (Yoshida AH-130). *Br J Cancer*. 1992;66:787–93.
- Kolanjiappan K, Ramachandran CR, Manoharan S. Biochemical changes in tumor tissues of oral cancer patients. *Clin Biochem*. 2003;36:61–5.
- Li AJ, Elmore RG, Chen IY, Karlan BY. Serum low-density lipoprotein levels correlate with survival in advanced stage epithelial ovarian cancers. *Gynecol Oncol*. 2010;116:78–81.
- Nieman KM, Kenny HA, Penicka CV, Ladanyi A, Buell-Gutbrod R, Zillhardt MR, et al. Adipocytes promote ovarian cancer metastasis and provide energy for rapid tumor growth. *Nat Med*. 2011;17:1498–503.
- Osmak M. Statins and cancer: current and future prospects. *Cancer Lett*. 2012;324:1–12.
- Gao J, Jia WD, Li JS, Wang W, Xu GL, Ma JL, et al. Combined inhibitory effects of celecoxib and fluvastatin on the growth of human hepatocellular carcinoma xenografts in nude mice. *J Int Med Res*. 2010;38:1413–27.
- Kochuparambil ST, Al-Husein B, Goc A, Soliman S, Somanath PR. Anticancer efficacy of simvastatin on prostate cancer cells and tumor xenografts is associated with inhibition of Akt and reduced prostate-specific antigen expression. *J Pharmacol Exp Ther*. 2011;336:496–505.
- Elmore RG, Ioffe Y, Scoles DR, Karlan BY, Li AJ. Impact of statin therapy on survival in epithelial ovarian cancer. *Gynecol Oncol*. 2008;111:102–5.
- Scoles DR, Xu X, Wang H, Tran H, Taylor-Harding B, Li A, et al. Liver X receptor agonist inhibits proliferation of ovarian carcinoma cells stimulated by oxidized low density lipoprotein. *Gynecol Oncol*. 2010;116:109–16.
- Liu H, Liang SL, Kumar S, Weyman CM, Liu W, Zhou A. Statins induce apoptosis in ovarian cancer cells through activation of JNK and enhancement of Bim expression. *Cancer Chemother Pharmacol*. 2009;63:997–1005.

30. Martirosyan A, Clendening JW, Goard CA, Penn LZ. Lovastatin induces apoptosis of ovarian cancer cells and synergizes with doxorubicin: potential therapeutic relevance. *BMC Cancer*. 2010;10:103.
31. Goldstein JL, Brown MS. Regulation of the mevalonate pathway. *Nature*. 1990;343:425–30.
32. Gillan L, Matei D, Fishman DA, Gerbin CS, Karlan BY, Chang DD. Periostin secreted by epithelial ovarian carcinoma is a ligand for alpha(V)beta(3) and alpha(V)beta(5) integrins and promotes cell motility. *Cancer Res*. 2002;62:5358–64.
33. Liu CY, Chao TK, Su PH, Lee HY, Shih YL, Su HY, et al. Characterization of LMX-1A as a metastasis suppressor in cervical cancer. *J Pathol*. 2009;219:222–31.

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