



# Prognostic significance of chemokines CCL11 and CCL5 modulated by low-density lipoprotein cholesterol in colon cancer patients with normal body mass index

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**Background:** Many studies have shown an elevated level of cholesterol in colon tumors as compared to normal tissue. Obesity and high low-density lipoprotein cholesterol (LDL-C) are known risk factors for colon cancer. However, the role of LDL-C in colon cancer patients with normal body mass index (BMI) remains elusive.

**Methods:** Levels of serum cholesterol and oxysterols were quantified by ultra-performance liquid chromatography-tandem mass spectrometer (UPLC-MS/MS) from 129 individuals with normal BMI, including 32 with solitary polyp, 36 with multiple polyps, and 31 with adenocarcinoma as well as 32 healthy controls. In vitro, colon cancer cells were treated with LDL-C and assayed for chemokines via RNA-Seq and mitochondrial morphology via transmission electron microscopy and immunofluorescence. Additionally, correlation analysis was performed between LDL-C-induced chemokines and the overall survival of colon cancer patients from the Cancer Genome Atlas (TCGA), the Genotype-Tissue Expression (GTEx), and the Human Protein Atlas (HPA) database.

**Results:** The serum cholesterol level was significantly higher in colon adenocarcinoma patients with normal BMI than that in healthy controls ( $P < 0.001$ ). LDL-C potentiated colon cancer cell invasion and resistance to glucose-deprivation in vitro via chemokine-mediated signaling, mainly upregulation of CC chemokine ligand (CCL) 5 and downregulation of CCL 11. By analyzing the RNA expression data of colorectal cancer from TCGA, GTEx, and HPA, we demonstrated that the CCL5 level in colorectal adenocarcinoma tissues was significantly increased relative to adjacent normal tissues ( $P = 0.01$ ) while the CCL11 level was decreased ( $P = 0.01$ ). Both increased CCL5 and decreased CCL11 showed a negative correlation with the 5-year overall survival in tumor node metastasis (TNM) stage II colon cancer patients ( $P = 0.0032$ ,  $0.026$  for CCL5 and CCL11, respectively).

**Conclusions:** Our study supports the idea that LDL-C regulates the expression of CCL5 and CCL11 chemokines, which may have predictive values for survival in colon cancer patients with normal BMI, especially for patients in TNM stage II.

**Keywords:** Cholesterol; chemokines; colon cancer; overall survival; CCL5; CCL11

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## Introduction

Hypercholesterolemia promotes the incidence of colon cancer and indicates a poor overall prognosis (1-3). Altered cholesterol metabolism is emerging as an important process in cancer metabolism. In mammals, cholesterol is either absorbed from dietary sources or synthesized *de novo* in the liver, from which it is transported by apolipoproteins (low-density lipoprotein cholesterol, LDL-C) to the systemic circulation (4). LDL-C is a spherical particle with a diameter of 220 nm and a mass of ~3,000 kDa. Each particle contains ~1,500 molecules of cholesterol ester in an oily core that is shielded from the aqueous serum by a hydrophilic coat composed of ~800 molecules of phospholipids, ~500 molecules of unesterified cholesterol, and 1 molecule of a 500 kDa protein, apoB (5). Cholesterol is essential for membrane biogenesis and cell proliferation (6), and both cholesterol and its metabolite are demonstrated to be vital for cancer progression. For instance, aberrant cholesterol ester accumulation was found in advanced prostate cancers with PTEN loss and PI3K/AKT activation (7). Cholesterol-metabolites, such as 27-hydroxycholesterol (27-OHC) could increase breast cancer metastasis (8). Although the pivotal role of cholesterol in colon cancer initiation, recurrence, and metastasis in obesity or overweight patients has been extensively studied (1), few studies have explored the role of cholesterol in colon adenoma and colon cancer with normal body mass index (BMI). However, retrospective studies revealed that patients with recurred colon cancer after curative surgery were generally with normal BMI and showed increased levels of cholesterol in colon tumors as compared to normal tissue (9). Several mechanisms are involved in the altered level of intracellular cholesterol: upregulation of rate-limiting enzyme of cholesterol synthesis, increased uptake of extracellular cholesterol by LDL receptor-mediated endocytosis, and decreased expression of cholesterol exporter (9). Recently, we demonstrated that LDL-C receptor expression levels were significantly higher in colon cancer tissues relative to adjacent normal tissues (10). It is unknown whether LDL-C play a vital role in colon cancer patients with normal BMI.

Colon cancer prognosis is largely dependent on the stage and histological grade. However, patients with TNM

stage II colon cancers show significantly different clinical outcomes even if they have similar histopathologic features. For example, 50–60% of stage II colon cancer patients who undergo curative resection experience local recurrence or distant metastases (11,12). Therefore, risk assessment is generally performed for stage II patients, and adjuvant chemotherapy is recommended for patients with high-risk features. However, the benefit of adjuvant chemotherapy does not improve survival by more than 5%. According to the latest guidelines of colon cancer (NCCN guidelines Version 4. 2019), the high-risk features include poorly differentiated histology (exclusive of those that are microsatellite instability-high), lymphatic/vascular invasion, bowel obstruction, perineural invasion, localized perforation, and close/indeterminate/or positive margins. The current prognostic factors are largely dependent on the features of the primary tumor. However, the contributions of systematic metabolic abnormalities, such as cholesterol dyshomeostasis, to tumor recurrence and tumor metastasis are not fully assessed (13).

Growing evidence suggests that chronic inflammation, regulated by a complex network of chemokines and their receptors, intensively correlates with colon cancer incidence and prognosis (14). About 25% of cancers appear due to chronic infection or chronic inflammation, and all solid tumors contain an inflammatory microenvironment (15). Metabolic transformation has important regulatory functions in chronic inflammation, and inflammation-induced epigenetic switches promote tumorigenesis (16). Increased inflammation is associated with obesity which contributes to the occurrence and development of colon cancer. Epidemiological studies have outlined the interlink between serum cholesterol (hypercholesterolemia) and colorectal cancer incidence. The statin use was observed to reduce the incidence and cancer-related mortality of colorectal cancer (17-19). The underlying mechanisms of anticancer effect induced by statins are related to the regulation of immune response (20). However, the association of chemokines and serum cholesterol (whether cholesterol can induce chemokines or not, which chemokines can cholesterol induce) is poorly understood. We hypothesized that LDL-C might induce the alterations of chemokines to promote the progression of colon adenomatous polyps to adenocarcinoma.

In this study, we quantified the levels of serum cholesterol and oxysterols in colon adenomatous polyps and adenocarcinoma patients with normal BMI (defined with BMI 18.5 to 24 kg/m<sup>2</sup>). Our study also measured the alterations of chemokines and mitochondrial reactive oxygen species (ROS) as well as morphology changes in colon cancer cells treated with LDL-C. Furthermore, an analysis of correlation was performed between chemokines induced by LDL-C and overall survival of colon cancer patients. We present the following article in accordance with the MDAR checklist (available at <http://dx.doi.org/10.21037/atm-20-1604>).

## Methods

### *Serum cholesterol and oxysterols measurement*

The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013) and was approved by the Hospital Institutional Review Board (2019-ERR-450) of the Second Affiliated Hospital of Zhejiang University School of Medicine. Informed consent was taken from all the patients. Briefly, we collected serum samples from 129 individuals who completed colonoscopy, including 30 healthy controls, 32 solitary polyp, 36 multiple polyps, and 31 adenocarcinoma patients with normal BMI (defined with BMI 18.5 to 24 kg/m<sup>2</sup>). Moreover, patient characteristics, including age, sex, BMI, hypertension, diabetes mellitus, current smoking status, liver function, serum triglycerides, and serum free fatty acids, were collected for baseline assessment.

The serum cholesterol and oxysterols were quantified by using ultra performance liquid chromatography-tandem mass spectrometer (UPLC-MS/MS), as previously described by McDonald *et al.* (21). In this study, cholesterol (CAS 57-88-5, C3045, Sigma-Aldrich), 22(R)-hydroxycholesterol (22R-OHC, CAS 17954-98-2, H9384, Sigma-Aldrich), 22(S)-hydroxycholesterol (22S-OHC, CAS 22348-64-7, H5884, Sigma-Aldrich), 25-Hydroxycholesterol (25-OHC, CAS 2140-46-7, H1015, Sigma-Aldrich), 27-hydroxycholesterol (27-OHC, CAS 20380-11-4, 700021P, avanti polar lipids), and 7 $\alpha$ -hydroxycholesterol (7 $\alpha$ -OHC, CAS 566-26-7, 700034P, avanti polar lipids) were used as standard. The Waters ACQUITY UPLC was coupled to an AB Sciex Triple Quad TM 6500. Cholesterol and oxysterols were resolved with a binary solvent gradient using a BEH C8 column (2.1 mm  $\times$  100 mm, 1.7  $\mu$ m, Waters). The mobile phases were (A) 70% acetonitrile

with 5 mM NH<sub>4</sub>OAc (73594, Sigma-Aldrich) and (B) 1:1 isopropyl alcohol: acetonitrile with 5 mM NH<sub>4</sub>OAc. The gradient was started at 0% B and ramped to 100% B over 2 min, hold at 100% B for 1.5 min, and returned to 0% B for a 2 min. The flow rate was 0.5 mL/min, and the column was maintained at 50 °C. MS instrument was operated in scheduled multiple reaction monitoring mode.

### *Cell culture*

Three colon cancer cell lines (RKO, SW480, and LoVo) were purchased from the Cell Bank of Type Culture Collection of the Chinese Academy of Sciences (Shanghai). SW480 cells were cultured in Leibovitz's L-15 medium, while RKO and LoVo cells were maintained in complete Eagle's minimum essential medium and F12K medium, respectively. Cells were supplemented with 10% FBS, 100 U/mL penicillin, and 100  $\mu$ g/mL streptomycin in a 5% CO<sub>2</sub> environment at 37 °C. All the cells were mycoplasma-free and routinely checked with the PCR Mycoplasma detection kit (K0103, HuaAn Biotechnology).

### *Intracellular cholesterol and oxysterol measurement*

Colon cancer cell lines (RKO, SW480, and LoVo) were incubated with LDL-C (100  $\mu$ g/mL) for 72 hrs, collected and washed with PBS. One mL of the 1:1 mixture of dichloromethane: methanol solution with 50  $\mu$ g/mL butylated hydroxytoluene was added to the samples. Then, the samples were homogenized, flushed with in N<sub>2</sub>, placed in a 30 °C ultrasonic bath for 10 min, and centrifuged 3,500 rpm for 5 min at room temperature. The organic layer was collected and assayed for the intracellular cholesterol and oxysterol as stated in supplementary methods (Appendix 1).

### *Measurement of cellular ROS*

Cellular ROS with or without LDL-C (100  $\mu$ g/mL) treatment was detected using specific ROS probes by confocal microscope and flow cytometry. For flow cytometric measurement, cells were incubated with 2',7'-Dichlorodihydrofluorescein diacetate (DCFH-DA, 10  $\mu$ M, D6883, Sigma) for 30 min at 37 °C, after which the cells were washed and suspended in ice-cold PBS and analyzed for fluorescence intensity using a 485 nm excitation beam (FACS ArrayBioanalyzer, BD biosciences). FlowJo v 7.6 quantified the mean fluorescence intensity. For confocal measurement, ROS measurement is assayed by DCFH-DA,

4-amino-5-methylamino-2,7-difluorofluorescein (DAF-FM, D2321, Sigma), dihydroethidium (DHE, D7008, Sigma), MitoSOX™ Red mitochondrial superoxide indicator (MitoSOX Red, M36008, Invitrogen), Hydroxyl Radical and Peroxynitrite Sensor (HPF, H36004, Invitrogen), or mitochondria peroxy yellow 1 (MitoPY1, 4428, Tocris Bioscience) according to manufactures' instruction. Briefly, cells were loaded with DCFH-DA (10  $\mu$ M for 30 minutes), DAF-FM (10  $\mu$ M for 30 minutes), DHE (5  $\mu$ M for 30minutes), MitoSOX Red (2.5  $\mu$ M for 10 minutes), HPF (10  $\mu$ M for 30 minutes), or MitoPY1(10  $\mu$ M for 30 minutes), washed with ice-cold Hank's Balanced Salt Solution (HBSS, pH 7.2), and then observed under a Zeiss LSM710 laser confocal microscope (Carl Zeiss, Germany) equipped with Zen software to process the image.

#### *Transmission electron microscopy*

RKO, SW480, and LoVo colon cancer cells were incubated with or without LDL-C (100  $\mu$ g/mL) for 72 hrs and fixed in 2.5% glutaraldehyde in 0.1 M sodium phosphate buffer overnight. The samples were treated with 1.5% osmium tetroxide, dehydrated with acetone, and embedded in durcupan resin. Samples were post-stained with lead citrate and examined in a TECNAI 10 electron microscope (Philips, The Netherlands) at 60 kV.

#### *Immunofluorescence*

The cellular mitochondrion was detected by MitoTracker™ Red FM (M22425, Invitrogen) according to the protocols of the suppliers. In brief, RKO cells were cultured on coverslips inside 12-well plate filled with Eagle's minimum essential medium with or without LDL-C (100  $\mu$ g/mL) for 72 hrs, washed with pre-warmed HBSS (37 °C), and incubated with pre-warmed staining solution containing MitoTracker™ Red FM (100 nM) for 30 mins. Then cells were washed carefully with pre-warmed culture medium and fixed with 3.7% paraformaldehyde for 15 min at room temperature. Nuclei were counterstained with DAPI. All post-fixed sections were mounted and viewed under Zeiss LSM 710 laser confocal microscope.

#### *Transwell invasion assay*

Transwell assay was conducted with invasion chamber (8- $\mu$ m pore size) (Corning Costar, Cambridge, MA, USA) coated with 40  $\mu$ l Matrigel mixture (BD Biosciences, matrigel:

serum-free culture medium=1:7) under the instructions of manufacturer. All colon cancer cell lines ( $1 \times 10^5$  cells) were incubated with or without LDL-C (100  $\mu$ g/mL), N-acetylcysteine (NAC, 4 mM) or SkQ1 (100 nM) for indicated time at 37 °C. The cells were stained with crystal violet, and observed under a phase-contrast microscope (Carl Zeiss, Axiovert-S100, Germany). The extents of invasion were analyzed by ImageJ software (NIH).

#### *RNA-Seq transcriptional profiling*

The RNA-Seq for whole genome-wide gene expression profiles of RKO, SW480, and LoVo colon cancer cells with or without LDL-C (100  $\mu$ g/mL) 72 hr incubation was performed by Novogene (Beijing, China). Gene Ontology (GO) and KEGG pathways enrichment analysis of differentially expressed genes (DEGs) were implemented by the cluster Profiler R package, in which gene length bias was corrected.

#### *Survival analysis*

Kaplan-Meier plots summarize results from analysis of correlation between mRNA expression and patient survival from Human Protein Atlas database (<http://www.proteinatlas.org>) using best separation, as we previously reported (22). The cut-off values of CCL11 and CCL5 mRNA expression level were 1.01 FPKM and 21.02 FPKM, respectively. Patients were divided based on level of expression into one of the two groups "low" or "high". After balancing age, gender and tumor stage, the 5-year survival for patients with high expression or low expression and log-rank P value were displayed.

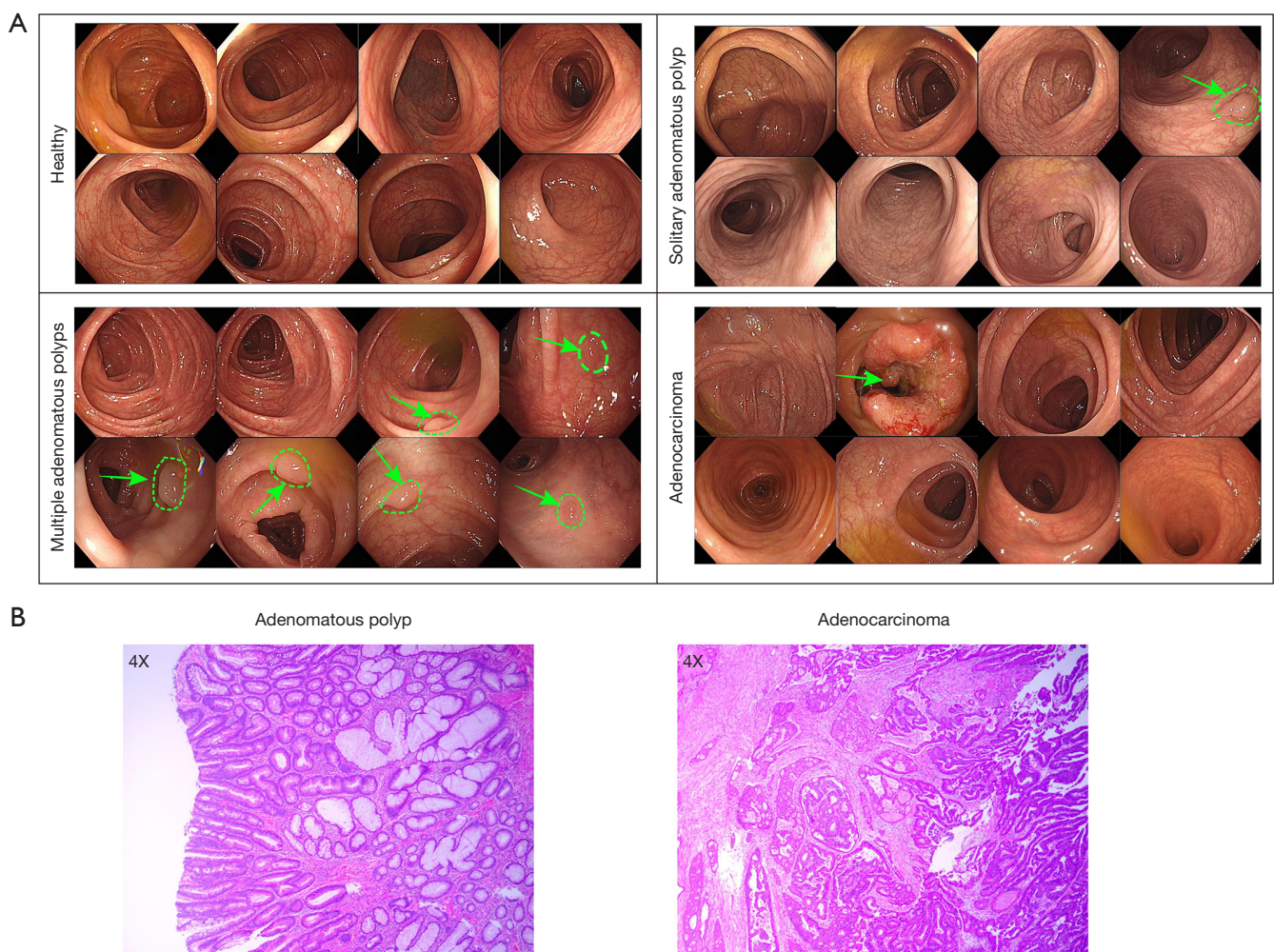
#### *Statistical analysis*

All data were analyzed using the InStat software (GraphPad, CA, USA) and displayed as mean  $\pm$  SD. Two-tailed Student's *t*-test was used for statistical analysis, and significance was defined at \*\*\**P*<0.001, \*\**P*<0.01, \**P*<0.05.

## **Results**

### *Serum cholesterol level increases significantly in colon adenomatous polyp and adenocarcinoma patients with normal body-mass index*

Altered cholesterol metabolism and its metabolites such as

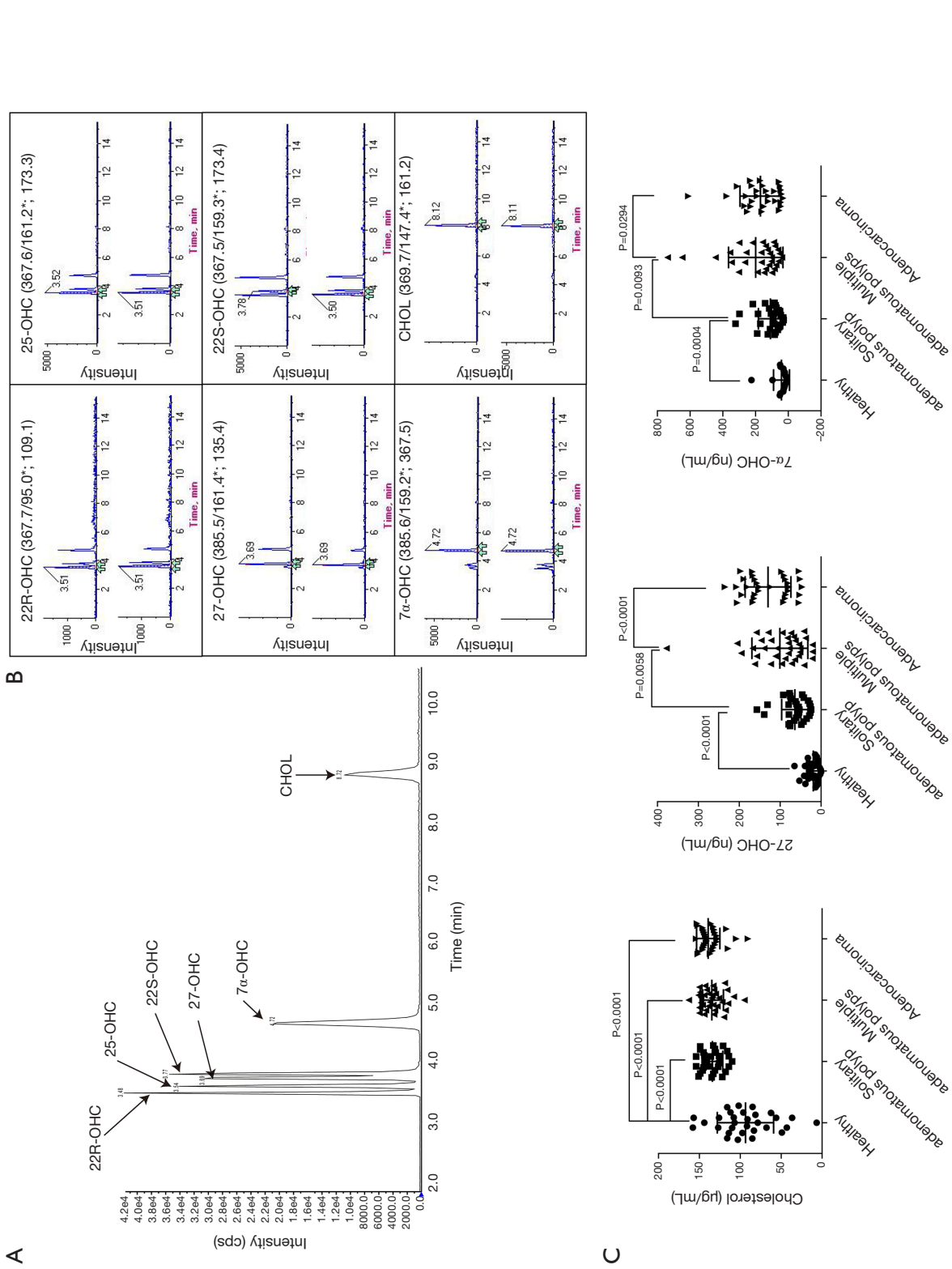


**Figure 1** Clinical features of recruited patients. (A) Colonoscopy findings of healthy controls, solitary colon adenomatous polyp, multiple colon adenomatous polyps and colon cancer patients. The polyps or cancer locations were highlighted by green arrow and dotted oval. (B) The pathological structure of samples from colon adenoma and colon adenocarcinoma patients were stained with hematoxylin/eosin (HE). The colon adenoma was from solitary or multiple colon polyps patients.

oxysterols have been implicated in tumorigenesis and cancer metastasis. We measured the serum cholesterol and 5 extensively investigated oxysterols comprised of 22R-OHC, 22S-OHC, 25-OHC, 27-OHC, and 7 $\alpha$ -OHC, in 129 individuals with normal BMI, including 32 with solitary polyp, 36 with multiple polyps, and 31 with adenocarcinoma as well as 32 healthy controls using UPLC-MS/MS (Figures 1,2A,B, Figure S1). It is well appreciated that risk factors for colorectal cancer include smoking, the consumption of red and processed meats, alcohol consumption, diabetes mellitus, low levels of physical activity, metabolic syndrome, obesity/high BMI, and inflammatory bowel disease. Our data showed that there were no

significant differences in multi-factors, including age, sex, BMI, hypertension, diabetes mellitus, current smoking, liver function, serum triglycerides, and serum free fatty acids of recruited patients (Table 1). As shown in Figure 2C, levels of serum cholesterol, 27-OHC, and 7 $\alpha$ -OHC were significantly increased in adenomatous polyp(s) and adenocarcinoma patients than that in healthy controls ( $P < 0.001$ ). Of note, the serum cholesterol level was approximately 1,000 times higher than those of the serum oxysterols.

As serum cholesterol is largely dependent on serum LDL-C level, we thus evaluated the effect of LDL-C on the production of oxysterols in colon cancer cells. It showed that the levels of 27-OHC, 7 $\alpha$ -OHC, and 25-OHC were



**Figure 2** Serum cholesterol level increased in the colon polyp and colon adenocarcinoma patients. (A) Chromatograms of standard mixes of cholesterol (CHOL), 22R-OHC, 22S-OHC, 25-OHC, 27-OHC and 7α-OHC. (B) Mass spectra of CHOL and representative oxysterols. (C) Serum cholesterol, 27-OHC, and 7α-OHC levels in 129 individuals with normal BMI, including 30 healthy controls, 32 solitary polyps, 36 multiple polyps, and 31 adenocarcinoma patients.

**Table 1** Baseline characteristics of participants in this study

Characteristic	Healthy (n=30)	Single polyp (n=32)	Multiple polyps (n=36)	Adenocarcinoma (n=31)	P value					
					(H vs. Sp)	(H vs. Mp)	(H vs. Ad)	(Sp vs. Mp)	(Sp vs. Ad)	(Mp vs. Ad)
Age (y)	62±11 <sup>1</sup>	58±10	59±11	60±13	0.14	0.27	0.52	0.70	0.50	0.73
Sex (M/F)	14/16	17/15	17/19	16/15	0.80	1.00	0.80	0.81	1.00	0.81
Smoking (yes/no)	14/16	16/16	20/16	17/14	0.81	0.62	0.61	0.81	0.80	1.00
BMI (kg/m <sup>2</sup> )	22.37±2.86	23.61±2.08	22.85±3.07	22.29±3.12	0.07	0.51	0.92	0.27	0.07	0.47
Diastolic blood pressure, mmHg	126±17	131±17	130±19	126±19	0.20	0.28	0.90	0.87	0.28	0.36
Systolic blood pressure, mmHg	78±8	80±11	78±12	76±8	0.50	0.99	0.22	0.53	0.10	0.32
Serum biochemistry tests										
Blood glucose (mmol/L)	4.71±0.57	5.01±0.76	4.87±0.64	5.34±1.42	0.08	0.29	0.06	0.43	0.27	0.09
Plasma triglycerides (mmol/L)	1.11±0.49	1.34±0.47	1.48±0.91	1.45±1.16	0.07	0.05	0.15	0.42	0.61	0.91
Blood free fatty acids (μmol/L)	389.39±210.96	412.67±186.17	419.57±166.44	517.80±307.51	0.65	0.53	0.07	0.88	0.11	0.12
Apo A1 (g/L)	1.27±0.27	1.23±0.13	1.11±0.17	1.12±0.28	0.70	0.13	0.15	0.06	0.17	0.93
Apo B (g/L)	0.81±0.18	0.81±0.13	0.79±0.17	0.87±0.27	0.97	0.77	0.48	0.75	0.41	0.40
ALT (IU/L)	21.39±14.66	20.91±9.67	24.83±20.75	17.33±5.55	0.88	0.44	0.16	0.33	0.08	0.06
AST (IU/L)	22.48±9.82	22.28±5.88	26.94±24.41	20.43±4.29	0.92	0.34	0.30	0.30	0.16	0.15
ALP (IU/L)	78.21±36.10	80.63±18.69	78.29±41.08	91.17±26.39	0.74	0.99	0.12	0.77	0.07	0.15
GGT (IU/L)	27.10±36.38	23.91±13.94	36.49±42.55	29.73±24.77	0.65	0.35	0.75	0.12	0.25	0.45
Bilirubin (mg/dL)	14.45±9.01	13.03±4.47	15.09±5.28	12.89±5.97	0.43	0.73	0.43	0.09	0.92	0.12
Indirect bilirubin (mg/dL)	2.68±1.80	2.29±0.81	2.68±1.13	2.33±1.56	0.27	1.00	0.42	0.11	0.89	0.31
Direct bilirubin (mg/dL)	11.51±7.51	10.74±3.70	11.96±4.14	10.23±3.84	0.61	0.76	0.41	0.21	0.59	0.09

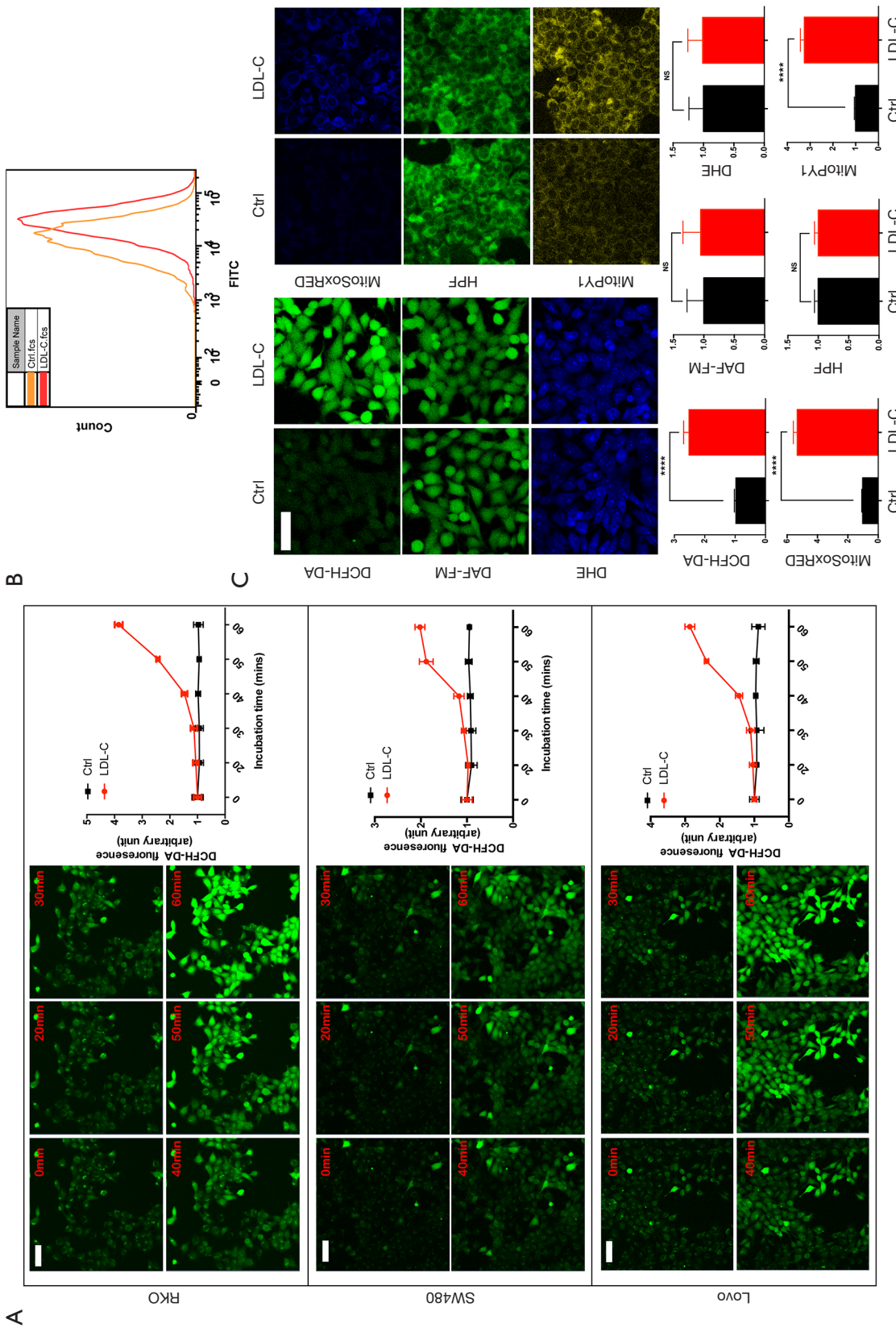
Multi-factors, including age, sex, body mass index, hypertension, diabetes mellitus, current smoking, liver function, serum triglycerides, and serum free fatty acids of recruited participants were measured. <sup>1</sup>, mean ± SD (all such values). ApoA1, apolipoprotein A1; ApoB, apolipoprotein B; ALT, alanine aminotransferase; AST, aspartate aminotransferase; ALP, alkaline phosphatase; GGT,  $\gamma$ -glutamyl transferase; H, healthy; Sp, single polyp; Mp, multiple polyps; Ad, adenocarcinoma.

significantly increased in RKO, SW480, and LoVo colon cancer cells after incubation with LDL-C (Figure S2). Therefore, the results suggested that the elevated oxysterols might be the results of increased LDL-C.

#### ***Colon cancer cells with LDL-C incubation have elevated mitochondrial ROS levels and fissed mitochondria***

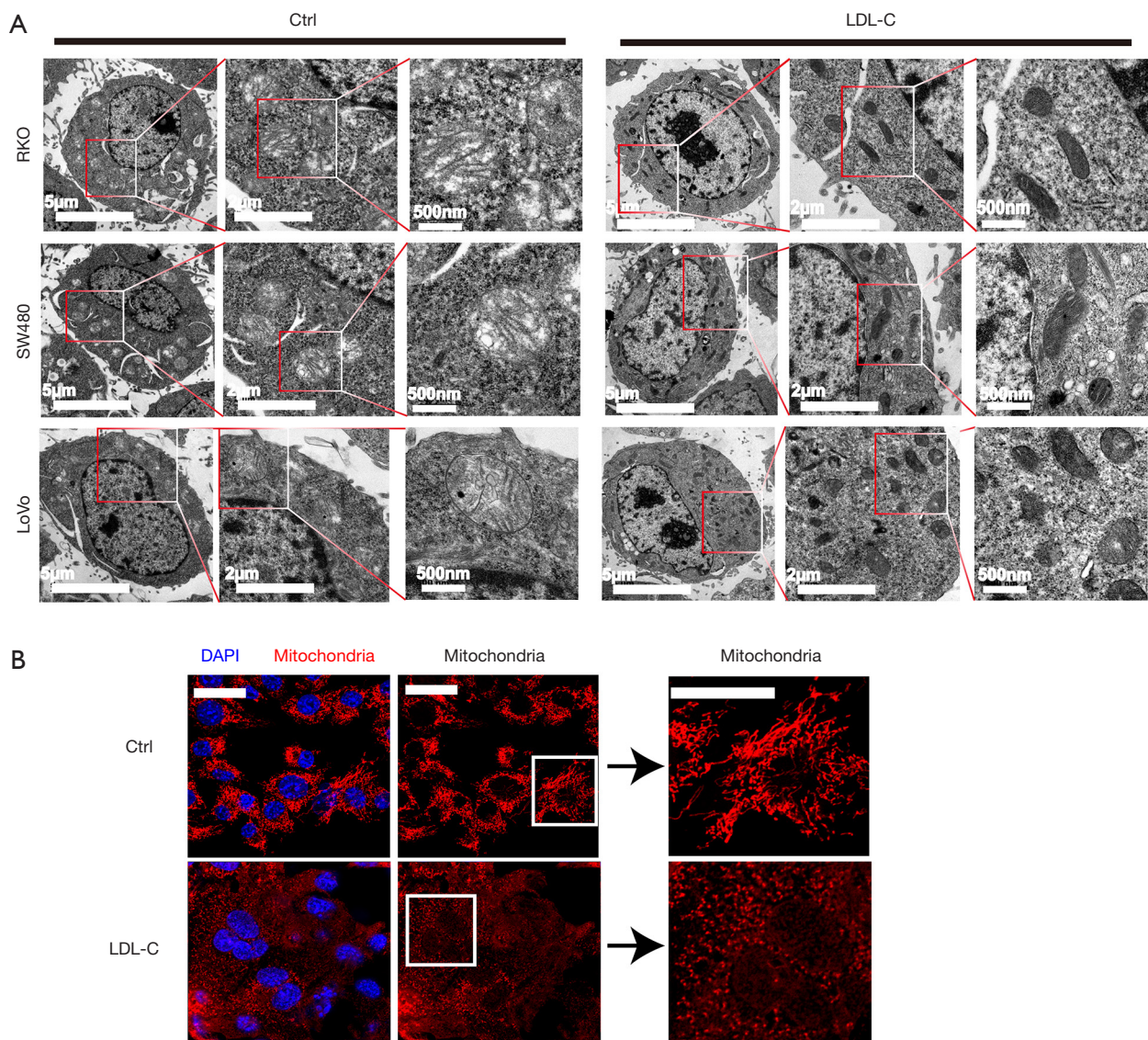
As oxysterols are largely dependent on the oxidation of cholesterol, we analyzed the redox status indicated by ROS

specific probes detected by confocal microscopy and flow cytometry. LDL-C dramatically increased cellular ROS level and maintained at high levels for 60 minutes (Figure 3A,B). Moreover, we detected the ROS composition and distribution by available ROS probes (Figure 3C). DCFH-DA fluorescence mainly reflects the total ROS level, which was much higher in cells incubated with LDL-C. The intramitochondrial superoxide probed by MitoSox RED and mitochondrial hydrogen peroxide indicated by MitoPY1 were also significantly increased by LDL-C treatment.



**Figure 3** LDL-C significantly increased mitochondrial ROS level. (A) The total cellular ROS level measured by DCFH-DA was elevated significantly when incubated with LDL-C. RKO, SW480, and LoVo colon cancer cells were incubated with LDL-C (100 µg/mL) at the indicated time points. Cellular ROS was probed by DCFH-DA. Scale bar = 50 µm. (B) The RKO cellular ROS level, probed by DCFH-DA, was measured by flow cytometry. (C) The composition of ROS in RKO cells when incubated with 100 µg/mL LDL-C. ROS levels were assayed by DCFH-DA, DHE, MitoSOXTM Red mitochondrial superoxide indicator, DAF-FM, or HPF, according to manufactures' instruction. Scale bars = 20 µm. \*\*\*\*P<0.0001. LDL-C, low-density lipoprotein cholesterol.





**Figure 4** LDL-C induced changes in mitochondrial morphology. (A) Representative photographs of cellular mitochondria by transmission electron microscopy. RKO, SW480, and LoVo cells were incubated with or without LDL-C (100 µg/mL) for 72 hrs. (B) Representative confocal images of mitochondrial morphology were detected by MitoTracker™ Red FM in RKO cells. Scale bar =10 µm. LDL-C, low-density lipoprotein cholesterol.

However, the levels of cellular hydroxyl radical and peroxynitrite (indicated by HPF fluorescence), the extra-mitochondrial superoxide (reflected by DHE fluorescence) and nitric oxide (indicated by DAF-FM fluorescence) were comparable in cells with and without LDL-C incubation. These results showed that LDL-C mainly induced mitochondrial superoxide and hydrogen peroxide.

Mitochondria are the main source of ROS within most mammalian cells (23). Mitochondrial structures can

dynamically change between fission morphologies (discrete ovoid structures) and fused morphologies (elongated tubular networks). We further detected the morphology of mitochondria by transmission electron microscopy. The mitochondria in colon cancer cell lines (RKO, SW480, and LoVo) were predominantly fused morphologies with lucent-swelling matrix as reviewed by Arismendi-Morillo (24). When incubated with LDL-C, the mitochondria structure changed to condensed small morphologies (Figure 4A).

Furthermore, the morphology of mitochondria indicated by MitoTracker RED FM was also changed from tubular shape to spherical or elliptical pattern after LDL-C incubation (Figure 4B). Interestingly, the condensed mitochondria have been demonstrated to be related to hypoxia-tolerance and adequate ATP production (24), and fragmented mitochondria have increased ROS level in tumor-infiltrating NK cells (25). Taken together, our data showed that LDL-C incubation increased mitochondrial ROS level and resulted in the morphological changes of mitochondria.

#### ***LDL-C promotes colon cancer cell invasion and resistance to glucose deprivation***

To determine the effect of LDL-C on cell invasion, colon cancer cells (RKO, SW480, and LoVo) were incubated with or without LDL-C and analyzed using the Transwell invasion assay. Compared with the control group, colon cancer cells incubated with LDL-C had significantly increased invasion potential, which was inhibited by antioxidants such as NAC or SkQ1 (Figure 5A). LDL-C significantly prolonged the survival time of colon cancer cells under glucose depletion (Figure 5B). These results showed that LDL-C played a vital role in colon cancer cell invasion and resistance to glucose deprivation.

#### ***LDL-C downregulates RNA level of CCL11 and upregulates RNA level of CCL5***

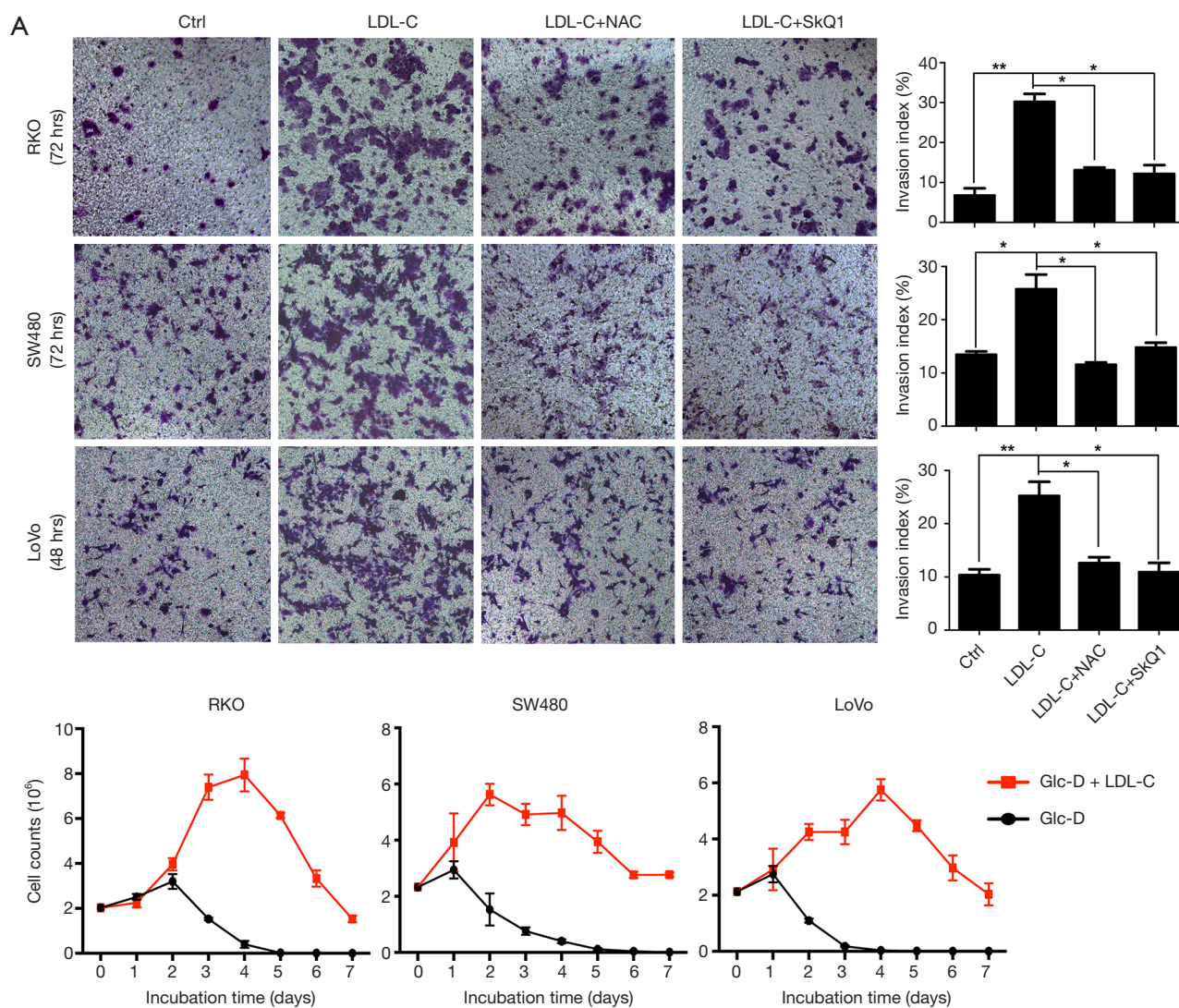
To explore genes and gene networks that are regulated by LDL-C, we performed RNA-seq analysis of RKO, SW480, and LoVo cells with or without LDL-C incubation. Using false discovery rate (FDR) <0.05 and fold change >2 as the significant cutoffs, we found 655, 207, and 258 DEGs in RKO, SW480, and LoVo, respectively. To further understanding the function of these DEGs, gene ontology (GO) and KEGG term enrichment analysis were performed. For genes that were up-regulated in LDL-C incubation group, the G-protein coupled receptor (GPCR) signaling, chemokine-mediated signaling, and integral component of serum membrane were significantly enriched GO terms (Figure 6A). On the other hand, linolenic acid metabolism was the most significantly enriched KEGG term (Figure S3A). For genes that were down-regulated in LDL-C incubation group, protein processing in the endoplasmic reticulum and cell cycle were significantly enriched KEGG terms (Figure S3B). Additionally, protein serine/threonine kinase activity, protein phosphorylation,

and related signaling such as ERK1/ERK2 cascade and MAPK pathway were significantly enriched GO terms (Figure S4). Of note, chemokines and chemokine-mediated signaling were among the highly enriched GO categories in the up-regulated DEGs.

In general, chemokines, produced by various lymphoid and nonlymphoid cells, are assigned to several groups on the basis of their major biological functions as well as structural criteria. We further analyzed the C-C motif ligand subfamily (CCL), CXC ligand subfamily (CXCL), and CX3C ligand subfamily (CX3CL) as well as their related chemokine receptors (Figure 6B, Figures S5-S7). As shown in Figure 6B, LDL-C upregulated RNA levels of *CCL5* and downregulated *CCL11* expression. Moreover, we measured the RNA expression level of *CCL11* and *CCL5* in colon cancer patients from gene expression profiling interactive analysis 2 (GEPIA 2, <http://gepia2.cancer-pku.cn/index.html>) and found that the *CCL5* expression level in colon and rectal adenocarcinoma tissues was significantly higher than that in normal tissues (matched TCGA normal and GTEx data), while the *CCL11* level decreased (Figure 6C).

#### ***Decreased CCL11 and increased CCL5 expression levels in tumor tissues show a negative correlation with the 5-year overall survival of TNM stage II colon cancer patients***

High chemokines concentrations, such as CXCL10, might be an independent marker for predicting hepatic metastasis and correlate with poor survival in colorectal cancer (11). We detected the RNA expression levels of *CCL11* and *CCL5* in colon cancer tissues from GEPIA 2. We found that the RNA expression level of *CCL11* was significantly lower in colon cancer and rectal cancer tissues than that in normal tissues (Figure 7A). The *CCL5* RNA expression was dramatically higher in colon cancer and rectal cancer tissues compared with normal tissue, although there was no significant statistical difference in the rectal cancer group (Figure 7B). Moreover, by analyzing the mRNA expression level of *CCL11* or *CCL5* and survival data of colon cancer patients from Kaplan-Meier plotter in the Human Protein Atlas database (HPA, <http://www.proteinatlas.org>), we found that a lower expression of *CCL11* or a higher expression of *CCL5* was negatively correlated with 5-year overall survival in TNM stage II colorectal cancer patients (Figure 7C,D and Figure S8). It suggested that decreased *CCL11* or increased *CCL5* RNA expression level might be useful prognostic markers for relatively early-stage colon cancer patients, especially TNM stage II.



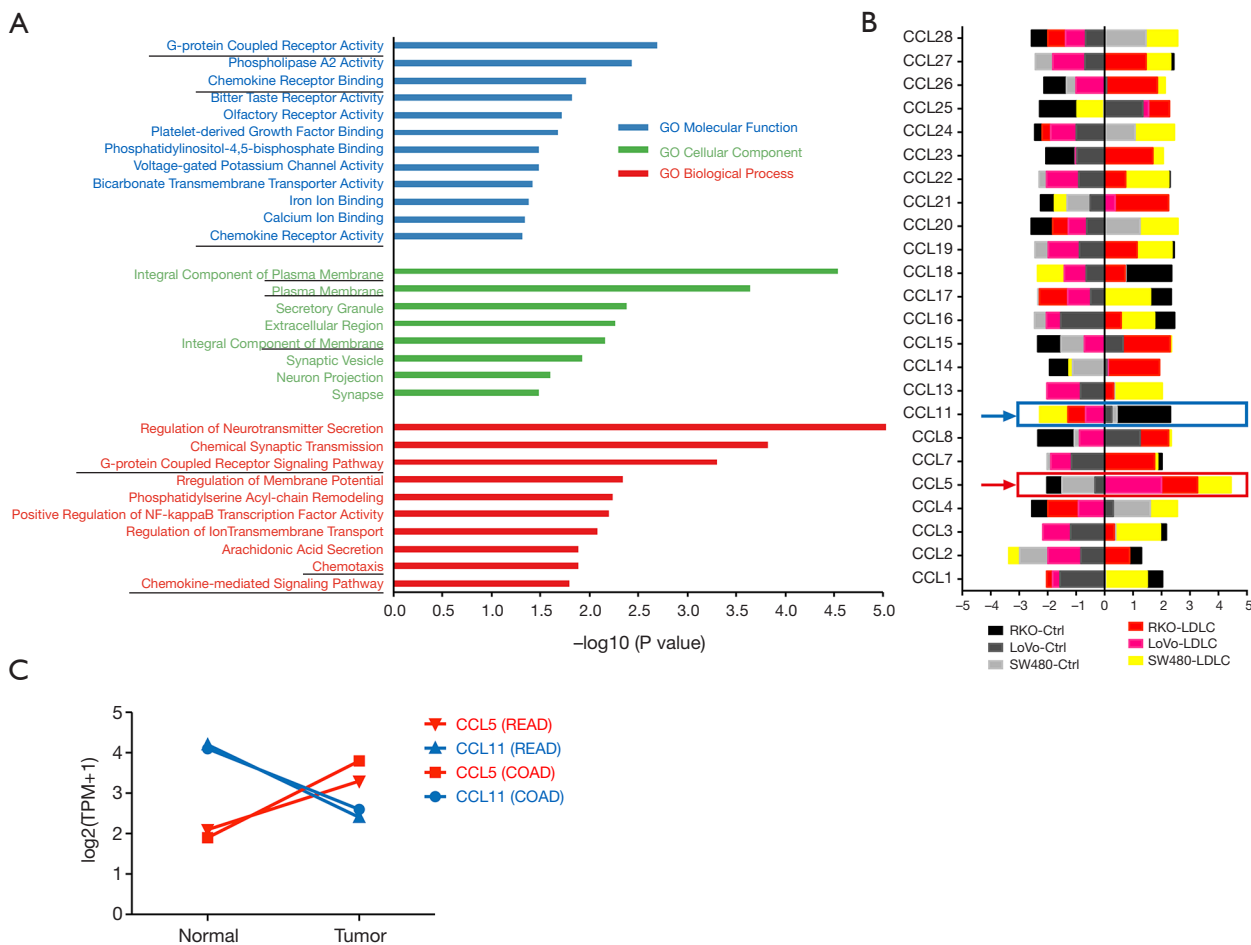
**Figure 5** LDL-C significantly increased the cell invasion ability and resistance to glucose-deprivation. (A) RKO, SW480, and LoVo cells were incubated with LDL-C (100  $\mu\text{g}/\text{mL}$ ), NAC (4 mM) or SkQ1 (100 nM). Representative microscopic images of cells that migrated through the transwell in the migration assay. (Giemsa stain, magnification  $\times 200$ ). Adjacent histograms represent the invasion index of these cells under indicated conditions.  $**P < 0.01$ ,  $*P < 0.05$ . (B) The cell proliferation profile of RKO, SW480, and LoVo cells was generated by incubation with glucose-deprivation medium (Glc-D), or glucose-deprivation medium with 100  $\mu\text{g}/\text{mL}$  LDL-C (Glc-D + LDL-C). LDL-C, low-density lipoprotein cholesterol.

## Discussion

Colon cancer is strongly associated with chronic inflammation and abnormal cholesterol metabolism. Herein, we demonstrated that serum cholesterol level was significantly elevated in colon adenomatous polyp and colon adenocarcinoma patients with normal BMI. LDL-C induced downregulation of *CCL11* expression and upregulation of *CCL5* expression, which were both

negatively correlated with the 5-year overall survival of TNM stage II colon cancer patients.

Cholesterol is the main structural component of cell membranes, contributing to the unique biophysical properties of the lipid raft microdomains which regulate phosphorylation cascades originating from membrane-bound proteins, such as GPCR. Abnormal cholesterol metabolism might affect various cellular events and

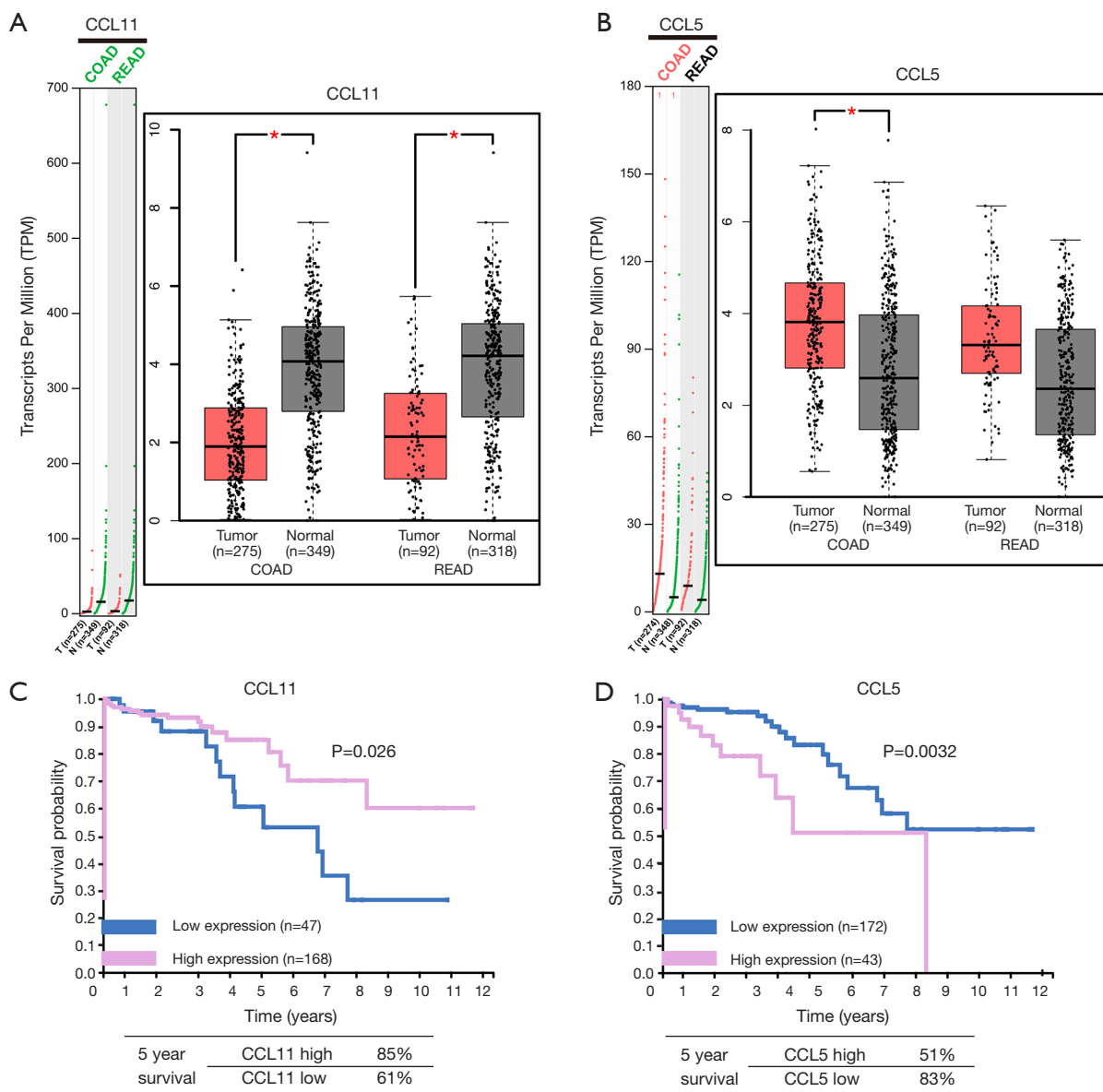


**Figure 6** Significantly enriched GO terms ( $P < 0.05$ ) in the up-regulated genes. (A) GO terms belonging to molecular functions, cellular components, and biological processes were shown in blue, green, and red, respectively. GO terms were sorted based on P values. (B) The RNA expression changes of CCL chemokine family when incubated with LDL-C (100  $\mu\text{g}/\text{mL}$ ). In members of the CCL family, *CCL5* was upregulated (highlighted by red rectangle box) while *CCL11* was downregulated (highlighted by blue rectangle box). (C) The RNA expression level of *CCL5* in colon and rectal adenocarcinoma tissues was higher than that in normal tissues (matched TCGA normal and GTEx data), while the *CCL11* level decreased. Data from GEPIA 2 (<http://gepia2.cancer-pku.cn/#analysis>). COAD, colon adenocarcinoma; READ, rectum adenocarcinoma; LDL-C, low-density lipoprotein cholesterol.

impair homeostasis (26,27). Our RNA-seq data showed cell membrane and GPCR could be regulated by LDL-C in colon cancer cells. Moreover, increased intracellular cholesterol levels shut down cholesterol synthesis and facilitate its export via activation of LXR receptors by oxysterols (28). Oxysterols, 27-carbon derivatives of cholesterol created by enzymatic or radical oxidation, play an important role in malignancies (29). Recently, a number of studies showed that increased levels of oxysterols, such as 7 $\alpha$ -OHC and 27-OHC, can promote cancer progression via combining with oxysterol receptors (8). Herein, we

showed LDL-C significantly increased mitochondrial ROS, which could induce the oxysterols production (such as 27-OHC, 7 $\alpha$ -OHC, and 25-OHC) via radical oxidation. Consequently, the pathologic role of cholesterol in colon cancer might be attributed to the impact on biophysical properties of cellular membrane receptors such as GPCR and the influence of oxysterol production via ROS.

Tumor microenvironment is enriched with cholesterol, and the important role of cholesterol in cell immune response has received considerable critical attention. For example, Ma *et al.* demonstrated that cholesterol



**Figure 7** The decreased CCL11 and increased CCL5 were negatively associated with 5-year overall survival of colorectal cancer patients. (A) The RNA expression level of CCL11 in colon adenocarcinoma and rectal adenocarcinoma tissues was lower than that in normal tissues. Data from GEPIA 2. \*P=0.01. (B) The RNA expression level of CCL5 in colon adenocarcinoma tissues was higher than that in normal tissues. Data from GEPIA 2. \*P=0.01. (C) The KM plotter was used to analyze the relationship between mRNA expression level of CCL11 and 5-year overall survival of colorectal cancer patients. Decreased CCL11 was negatively associated with 5-year overall survival of TNM stage II colorectal cancer patients (P value = 0.026, the cut-off value was 1.01 FPKM). Data from HPA database. (D) Increased CCL5 level was significantly associated with worse 5-year overall survival of TNM stage II colon cancer patients (P value = 0.0032, the cut-off value was 21.02 FPKM). Data from HPA database. COAD: colon adenocarcinoma; READ: rectum adenocarcinoma; GEPIA 2: <http://gepia2.cancer-pku.cn/#analysis>; HPA: <http://www.proteinatlas.org>.

could induce CD8<sup>+</sup> T cell exhaustion in the tumor microenvironment (30) and Yang *et al.* argued that reduced cholesterol could potentiate the anti-tumor response of CD8<sup>+</sup> T cells (31). Moreover, increased accumulation of cholesterol in cells during acute and chronic inflammation mediated by cytokines was observed in primates and humans. Inflammation, mediated by TNF- $\alpha$ , IL-1, or IL-6, can decrease cholesterol clearance by inhibiting lipoprotein lipase (32). Enhanced LDL-C oxidation has also been documented during infection and inflammation (33). In this study, we found that LDL-C downregulated CCL11 and upregulated CCL5 in colon cancer cells. Chemokines can be classified into inflammatory chemokines, homeostatic chemokines, and dual chemokines. Inflammatory chemokines are induced by inflammatory processes, while homeostatic chemokines are constitutively present in some, primarily lymphoid, organs. Dual chemokines are expressed in both homeostatic and inflammatory situations. CCL5 is an inflammatory chemokine, while CCL11 belongs to dual chemokines. CCL11 displays chemotactic activity for eosinophils, but not mononuclear cells or neutrophils via interacting with agonistic receptors (CCR3, CCR5) and antagonistic receptors (CXCR3, CCR2). CCL5 functions as a chemoattractant for blood monocytes, memory T helper cells, and eosinophils via interacting with agonistic receptors (CCR1, CCR3, and CCR5) (34). As shown in [Figure S9](#), CCR3 and CCR2 are associated with BDCA4<sup>+</sup> dendritic cells, CD33<sup>+</sup> myeloid cells, and CD14<sup>+</sup> monocytes cells, while CCR5 activates BDCA4<sup>+</sup> dendritic cells and CD8<sup>+</sup> T cells, and CXCR3 is associated with BDCA4<sup>+</sup> dendritic cells. The downregulation of CCL11 and upregulation of CCL5 could recruit and activate BDCA4<sup>+</sup> dendritic cells, CD33<sup>+</sup> myeloid cells, and CD14<sup>+</sup> monocytes. Dendritic cells, often called “nature’s adjuvants” and thus have become the natural agents for antigen delivery. They are at the center of the immune system owing to their ability to control both immune tolerance and immunity (35,36). Interestingly, recent studies demonstrated that BDCA4<sup>+</sup> dendritic cells, such as plasmacytoid DCs, were shown to correlate with poor prognosis in both ovarian and breast cancers (37,38). In addition, CD33<sup>+</sup> myeloid cells had an obvious immune inhibitory effect on T cells in lung cancer (39). Moreover, CD14<sup>+</sup> monocytes (mainly CD14<sup>+</sup>HLA-DR<sup>low/-</sup> monocytes) showed an immunosuppressive effect in multiple cancers, including lymphoma, multiple myeloma, glioblastoma, prostate cancer, and renal cell carcinoma (40).

To summarize, our study revealed the novel role of

cholesterol in regulating local chemokines such as CCL5 and CCL11 in the colon cancer. Our data suggests that CCL11 and CCL5 levels in tumor tissues might be potential prognostic markers for colon cancer, especially in TNM stage II patients.

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## Footnote

**Reporting Checklist:** The authors have completed the MDAR checklist. Available at <http://dx.doi.org/10.21037/atm-20-1604>

**Data Sharing Statement:** Available at <http://dx.doi.org/10.21037/atm-20-1604>

**Conflicts of Interest:** All authors have completed the ICMJE uniform disclosure form (available at <http://dx.doi.org/10.21037/atm-20-1604>). The authors have no conflicts of interest to declare.

**Ethical Statement:** The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The protocols for serum cholesterol and oxysterols measurements of different patients were approved by the Committee of Clinical Experimental Centre at the Second Affiliated Hospital of Zhejiang University School of Medicine, and conducted in accordance with relevant national guidelines and with patients’ consent (ID: 2019-ERR-450).

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