

# Synthesis and cardiovascular protective effects of quercetin 7-O-sialic acid

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Received: January 10, 2016; Accepted: July 4, 2016

## Abstract

Oxidative stress and inflammation play important roles in the pathogenesis of cardiovascular disease (CVD). Oxidative stress-induced desialylation is considered to be a primary step in atherogenic modification, and therefore, the attenuation of oxidative stress and/or inflammatory reactions may ameliorate CVD. In this study, quercetin 7-O-sialic acid (QA) was synthesized aiming to put together the cardiovascular protective effect of quercetin and the recently reported anti-oxidant and anti-atherosclerosis functions of *N*-acetylneuraminic acid. The biological efficacy of QA was evaluated *in vitro* in various cellular models. The results demonstrated that 50  $\mu$ M QA could effectively protect human umbilical vein endothelial cells (HUVEC, EA.hy926) against hydrogen peroxide- or oxidized low-density lipoprotein-induced oxidative damage by reducing the production of reactive oxygen species. QA attenuated hydrogen peroxide-induced desialylation of HUVEC and lipoproteins. QA decreased lipopolysaccharide-induced secretion of tumour necrosis factor- $\alpha$  (TNF- $\alpha$ ) and monocyte chemoattractant protein-1 (MCP-1), and it significantly reduced the expression of intercellular adhesion molecule-1, vascular cell adhesion molecule-1, TNF- $\alpha$  and MCP-1. Furthermore, QA effectively promoted cholesterol efflux from Raw 264.7 macrophages to apolipoprotein A-1 and high-density lipoprotein by up-regulating ATP-binding cassette transporter A1 and G1, respectively. Results indicated that the novel compound QA exhibited a better capacity than quercetin for anti-oxidation, anti-inflammation, cholesterol efflux promotion and biomolecule protection against desialylation and therefore could be a candidate compound for the prevention or treatment of CVD.

**Keywords:** cardiovascular disease • anti-oxidation • anti-inflammation • cholesterol efflux • quercetin • sialic acid

## Introduction

Cardiovascular disease (CVD) is currently the largest cause of death worldwide. The World Health Organization estimated that by 2030, there will be a 27% increase in the number of patients who die from CVD. Therefore, in spite of many advances in our understanding of vascular disease onset and progression, it should also be apparent that there is a continuous need to improve and develop new strategies for the treatment of vascular dysfunction in CVD [1, 2].

Sialic acids are nine-carbon sugars that are typically found at the terminal end of mammalian glycolipids and glycoproteins, and they play an important role during development, regeneration and pathogenesis [3,4]. Furthermore, *N*-acetylneuraminic acid has been indicated to be the predominant form of sialic acid. Because sialic acids

are so widespread on cell surfaces or as circulatory molecules, their alterations may have diverse effects on the pathogenesis of CVD [5, 6]. Oxidative stress is involved in the pathogenesis and progression of CVD [7]. Reactive oxygen species (ROS) have been shown to alter biological macromolecules, such as by desialylation [8, 9], which is a possible primary step of atherogenic modification [10]. Desialylation may lead to cellular dysfunction [11] and uptake of circulatory asialoglycoprotein by the hepatocyte asialoglycoprotein receptor [12]. Interestingly, although desialylation occurs in glycoconjugates during CVD progression, serum total sialic acid increases. Serum total sialic acid has been shown to serve as a biomarker of sustained inflammatory response in CVD patients [5, 6]. Presently, studies investigating the correlation between serum total sialic acid and the severity of atherosclerosis have presented conflicting results. It is noteworthy that recent studies have demonstrated that sialic acid could scavenge ROS [13–15] and may be applied as therapeutic option in some diseases [16–18].

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Oxidative stress and inflammation participate in the pathogenesis of CVD, and therefore, attenuating oxidative stress and/or inflammatory reactions may ameliorate CVD. The cardiovascular protective effects of the natural product quercetin, such as its antioxidant [19], anti-inflammatory [20] and possible promotion of cholesterol efflux effects [21], have attracted a great deal of attention. We assumed that the coupling of quercetin and *N*-acetylneuraminic acid (the major form of sialic acid in mammals) [16–18, 22, 23] could not only enhance the cardiovascular protective functions of quercetin but also protect biomolecules against desialylation. In this study, both quercetin and *N*-acetylneuraminic acid as pharmacophores for CVD were coupled to form quercetin 7-*O*-sialic acid (QA) with 5% yield. The cardioprotective action of QA was investigated *in vitro* in endothelial and macrophage cell lines in comparison with quercetin.

## Materials and methods

### Materials

Human umbilical vein endothelial cells (HUVEC, EA.hy926) and Raw 264.7 macrophages were purchased from Shanghai BoYao Biological Technology Co., Ltd (Shanghai, China). *N*-acetylneuraminic acid, quercetin, 3-(4,5-dimethyl-2-thiazolyl)-2,5-diphenyl-2-*H*-tetrazolium bromide (MTT), lipopolysaccharide (LPS), 2',7'-dichlorofluorescein diacetate (DCFH-DA), fluorescein-5-thiosemicarbazide (FTSC) and 4',6-diamidino-2-phenylindole (DAPI) were Sigma-Aldrich products (St. Louis, MO, USA). Dulbecco's modified Eagle's medium (DMEM) and foetal bovine serum (FBS) were from Gibco (BRL, Gaithersburg, MD, USA). Complete protease inhibitor cocktail tablets were purchased from Roche (Schweiz, Germany). RIPA lysis buffer, malondialdehyde (MDA) assay kit and bicinchoninic acid protein quantitative kits were the products of Solarbio (Beijing, China). Mouse monoclonal antibody against tumour necrosis factor- $\alpha$  (TNF- $\alpha$ ) was purchased from Santa Cruz Biotechnology (Santa Cruz, CA, USA). Rat monoclonal antibody against intercellular adhesion molecule-1 (ICAM1), rabbit monoclonal antibody against vascular cell adhesion molecule-1 (VCAM1), rabbit polyclonal antibody against monocyte chemoattractant protein-1 (MCP-1), rabbit polyclonal antibody against ATP-binding cassette transporter (ABC) G1, mouse monoclonal antibody against ABCA1 and rabbit monoclonal antibody against scavenger receptor B type I (SR-BI) were from Abcam (Cambridge, MA, USA). Enhanced chemiluminescence (ECL) kits were purchased from Thermo Scientific Pierce (Rockford, IL, USA). Enzyme-linked immunosorbent assay (ELISA) kits for TNF- $\alpha$  or MCP-1 were BlueGene products (Shanghai, China). Polyvinylidene fluoride (PVDF) membranes were purchased from Millipore (Bedford, MA, USA). Centrifugal filters (Vivaspin 6 ml, molecular weight cut-off, MWCO 300 kDa) were the product of Sartorius (AG, Germany). Double-deionized water was produced using a Milli-Q gradient system from Millipore. All reagents used in this study were of analytical grade.

### Synthesis of quercetin 7-*O*-sialic acid

#### Methyl (5-acetamido-4,7,8,9-tetra-*O*-acetyl-2-chloro-3,5-dideoxy- $\beta$ -glycero- $\beta$ -galacto-2-nonulopyranosid) onate (4)

Strong cation-exchange resin (Dowex-50W-X2) was added to a stirred solution of *N*-acetylneuraminic acid **1** (100 mg, 0.32 mmol) in dry

MeOH. After stirring for 10 hr at room temperature, the mixture was neutralized to pH 7, filtered and concentrated. The residue was dissolved in dry pyridine (8 ml), and Ac<sub>2</sub>O and 4-dimethylaminopyridine were then added. After reacting for 8 hr, the mixture was concentrated, diluted with cold EtOAc and subsequently washed with 1 M HCl, NaHCO<sub>3</sub> and brine. The organic layer was dried over Na<sub>2</sub>SO<sub>4</sub> and concentrated to a residue. AcCl (1.5 ml) and 37% HCl (0.21 ml) were added to a stirred solution of the above residue in CH<sub>2</sub>Cl<sub>2</sub> (5.0 ml) at –20°C. After stirring for 12 hr at room temperature, the mixture was diluted with cold CH<sub>2</sub>Cl<sub>2</sub> and subsequently washed with H<sub>2</sub>O, NaHCO<sub>3</sub> and brine. The organic layer was dried over Na<sub>2</sub>SO<sub>4</sub> and concentrated to give **4** as a foamy solid.

#### 4-(3,5-diacetoxy-7-hydroxy-4-oxo-4H-chromen-2-yl)-1,2-phenylene diacetate (7)

Acetic anhydride (1.25 ml, 13.2 mmol) was added to a solution of quercetin **5** (500 mg, 1.65 mmol) in pyridine (3.5 ml), and the reaction mixture was stirred at room temperature. The reaction was monitored by thin layer chromatography (TLC). After the starting material was consumed, the reaction mixture was concentrated under reduced pressure. The crude compound was purified by column chromatography on silica gel to afford **6** as a white solid.

ToIsh (60 mg) was slowly added to a stirred mixture of **6** (300 mg, 0.59 mmol) and imidazole (8 mg, 0.12 mmol) in *N*-methyl-2-pyrrolidone (3 ml) at 0°C. The reaction mixture was stirred for 1.5 hr at room temperature. The mixture was diluted with EtOAc and washed with 1 M HCl. The organic layer was concentrated under reduced pressure and dried over Na<sub>2</sub>SO<sub>4</sub>. The crude product was purified by column chromatography on silica gel to give **7** as a white solid.

#### 3,3',4',5-tetra-*O*-acetyl quercetin 7-*O*-(5-acetamido-4,7,8,9-tetra-*O*-acetyl-3,5-dideoxy- $\beta$ -*D*-glycero- $\alpha$ -*D*-galacto-2-nonulopyranosonate) (8a)

K<sub>2</sub>CO<sub>3</sub> was slowly added to a stirred mixture of **4** (65 mg, 0.13 mmol) and **7** (50 mg, 0.10 mmol) in *N,N*-dimethylformamide (DMF) (3 ml) (100 mg) at room temperature. The reaction mixture was stirred for 15 hr at room temperature. The mixture was diluted with EtOAc and washed with 1 M HCl. The organic layer was concentrated under reduced pressure and dried over Na<sub>2</sub>SO<sub>4</sub>. The crude product was purified by column chromatography on silica gel to give **8a** as a white solid.

#### Quercetin 7-*O*-(5-acetamido-3,5-dideoxy- $\beta$ -*D*-glycero- $\alpha$ -*D*-galacto-2-nonulopyranosonate) (9)

A solution of NaOMe in methanol in one portion at argon atmosphere was added to a solution of **8a** (30 mg, 0.031 mmol) in CH<sub>2</sub>Cl<sub>2</sub> (3 ml). The reaction was completed, as determined by TLC, after stirring at room temperature for 4 hr. The mixture was neutralized by Dowex-50 H<sup>+</sup> resin and then filtered. The organic phase was concentrated to give a residue, which was purified by a Sephadex LH-20 gel column (MeOH-H<sub>2</sub>O) to produce **9** (quercetin 7-*O*-sialic acid, QA) as a yellow powder.

### Nuclear magnetic resonance (NMR) analysis

<sup>1</sup>H-NMR and <sup>13</sup>C-NMR spectra were recorded at 23°C using a JEOL JNM-ECP 500 MHz spectrometer. Compound **4**, **7**, **8a** and **9** (3–5 mg) were

dissolved in CDCl<sub>3</sub>, and chemical shifts were expressed in ppm using acetone as internal standard at 2.225 ppm for <sup>1</sup>H and 31.07 ppm for <sup>13</sup>C.

## Preparation of lipoproteins

Plasma samples were obtained from healthy volunteers after overnight fasting. Lipoproteins were prepared using sequential ultracentrifugation according to the method described by Havel *et al.*, with some modifications [24]. Briefly, the plasma density was adjusted to 1.006 g/ml for ultracentrifugation at 10°C (128,000 g for 24 hr). The upper layer containing very low-density lipoprotein was recovered, and the rest was adjusted to 1.063 g/ml density for next ultracentrifugation at 128,000 g for 48 hr. The upper layer containing low-density lipoprotein (LDL) was obtained, and the rest was adjusted to 1.21 g/ml density for ultracentrifugation at 128,000 g for another 48 hr to obtain high-density lipoprotein (HDL) in the upper layer. The protein content was determined by the Bradford method, using bovine serum albumin as standard. Isolated lipoproteins were kept under the nitrogen protection at 4°C and used within 2 weeks.

## Oxidation of LDL

Oxidized LDL (ox-LDL) was prepared according to the method published by Yao *et al.* [25]. Briefly, LDL was adjusted to 10 mg/ml and incubated with CuSO<sub>4</sub> solution (10 μM). Oxidation was fulfilled at 37°C for 24 hr, then the reaction was stopped by addition of 500 μM EDTA. Ox-LDL was dialysed at 4°C against 0.01 M phosphate buffer saline (PBS, pH = 7.4), filtered through a 0.22-μm filter and stored in nitrogen at 4°C. Ox-LDL had a relative mobility index of 2.0–2.5 in 2% agarose gel compared with that of native LDL. Ox-LDL was freshly prepared every 2 weeks and stored at 4°C.

## Cell culture and treatment

HUVEC EA.hy926 or Raw 264.7 macrophages were seeded in a 25-cm<sup>2</sup> flask and then cultured in DMEM supplemented with 10% FBS, 100 U/ml penicillin and 100 μg/ml streptomycin. Cells were grown in a humidified 5% CO<sub>2</sub> incubator at 37°C [26]. To assess the cardiovascular protective and therapeutic effects of QA, 'the protective model' and 'the therapeutic model' were established as described below.

In the protective model, HUVECs were cultivated in six-well plates and cultivated in the presence or absence of 50 μM QA for 4 hr and then exposed to 100 μM H<sub>2</sub>O<sub>2</sub> or 100 mg/l ox-LDL for 24 hr. In the therapeutic model, HUVECs were exposed to 100 μM H<sub>2</sub>O<sub>2</sub> or 100 mg/l ox-LDL for 24 hr, and then, the cells were further treated with 50 μM QA for another 12 hr.

## Cell viability

HUVECs or macrophages were seeded in a 96-well plate at a density of 1 × 10<sup>4</sup> cells per well. Cells were incubated with increasing concentrations of QA (0–75 μM), hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>, 0–400 μM) [20], or ox-LDL (0–300 mg/l) [25] for 24 hr. The number of viable cells was evaluated by the MTT method [27]. Briefly, after the incubation period, the culture medium from each well was removed and fresh medium with

20 μl of 5 mg/ml MTT was added. Cells were incubated for another 2 hr until the formation of formazan crystals. After washing cells with PBS for three times, formazan crystals were solubilized with 150 μl of DMSO, and the optical density at 570 nm was recorded using a multifunctional microplate reader Infinite M200 Pro (Tecan, Switzerland). Controls were defined as groups without drug treatment and H<sub>2</sub>O<sub>2</sub> or ox-LDL induction. Cell viability in the control group was set at 1, and cell viability in the other groups was determined as a fold of the control.

## Anti-oxidant activity

### Assessment of oxidative stress marker

The level of the lipid oxidation product MDA in the culture medium was assessed by estimating thiobarbituric acid reactive substances using MDA kits according to the manufacturer's instructions (Beijing Solarbio Science & Technology Co., Ltd., Beijing, China). Controls were defined as the groups without drug treatment and H<sub>2</sub>O<sub>2</sub> or ox-LDL induction.

### Intracellular ROS measurement

To assess intracellular ROS, cells grown on glass slides in six-well plates were washed with PBS for three times after treatments. Then, DCFH-DA (30 μM), a fluorogenic dye that measures hydroxyl, peroxyl and other ROS activities within the cell, was added [19]. The glass slides in six-well plates were light-protected and incubated in a humidified 5% CO<sub>2</sub> incubator at 37°C for 30 min. Fluorescence was measured by an Olympus BX51 microscope (Tokyo, Japan, absorption/emission wavelength at 485/520 nm), and the mean fluorescence intensity was calculated with the Image-Pro Plus software (Version 6.0; Media Cybernetics, Silver Spring, MD, USA). Controls were defined as groups without drug treatment and H<sub>2</sub>O<sub>2</sub> or ox-LDL induction. The fluorescence intensity in the control group was set at 1, and the fluorescence intensity in other groups was determined as a fold of the control.

### In situ quantitative analysis of sialic acid

HUVECs were seeded on glass slides in six-well plates. After treatments, cells were gently washed with PBS three times. Then, 1.5 ml of a 1 mM NaIO<sub>4</sub> solution was added to each well and maintained at 4°C for 20 min. The selective periodate oxidation of sialic acid was quenched with 1.5 ml of 1 mM glycerol and washed twice with cold PBS. Cells were subjected to ligation with FTSC in PBS buffer (100 μM, pH = 7.0) for 40 min. [28], and then, the nucleus was stained with DAPI according to the manufacturer's instruction. Finally, cells were visualized using an Olympus BX51 microscope (Olympus, Tokyo, Japan), and images were recorded with a JVC 3-CCD camera (Olympus) and analysed using the Image-Pro Plus software (version 6.0; Media Cybernetics, LP). Controls were defined as the groups with NaIO<sub>4</sub> treatment but without H<sub>2</sub>O<sub>2</sub> induction and drug treatment. The fluorescence intensity in the control group was set at 1, and the fluorescence intensity in the other groups was determined as a fold of the control.

### Desialylation of lipoproteins

The protein concentration of lipoproteins (LDL or HDL) was adjusted to 1.0 mg/ml in the presence or absence of 50 μM QA for protection. The

mixture was exposed to 100  $\mu\text{M}$   $\text{H}_2\text{O}_2$  (except for the blank control) and incubated at 37°C for 24 hr in 1.5-ml polyethylene tubes. Then, the mixture from each tube was loaded into a centrifugal filter (MWCO, 300 kDa; Sartorius), the filtrate was discarded and lipoproteins were recovered. Sialic acid from lipoprotein samples was released by acetic acid (pH = 2) at 80°C for 2 hr, and then neutralized with ammonia [29]. The mixture was subjected to ultrafiltration (MWCO, 300 kDa), and the filtrate was collected and stored at 4°C for liquid chromatography-tandem mass spectrometry (LC-MS/MS) analysis. Controls were defined as normal lipoproteins without drug treatment and  $\text{H}_2\text{O}_2$  induction.

## Measurement of *N*-acetylneuraminic acid by LC-MS/MS

*N*-acetylneuraminic acid analysis was performed by LC-MS/MS. This system was composed of a Shimadzu LC-20AD binary pump, DGU-20A<sub>3</sub> degasser, SIL-20AC autosampler and a triple quadrupole mass spectrometer 4000 Q TRAP. High-purity nitrogen for mass spectrometry was produced by the nitrogen generator ABN2ZA (Peak Scientific Instruments LTD, Scotland, UK). Chromatographic separations were carried out with a linear elution using a Waters Symmetry<sup>®</sup> C18 column (3.5  $\mu\text{m}$ , 2.1 mm i.d.  $\times$  100 mm) and a Waters C18 guard column (3.5  $\mu\text{m}$ , 2.1 mm i.d.  $\times$  10 mm). The mobile phase was composed of 2 mM ammonium acetate and 0.1% acetic acid in 5% methanol. The injection volume was 5  $\mu\text{l}$ , and the flow rate was 0.4 ml/min. The mass spectrometer was operated in negative ion mode with an ionspray voltage of  $-4500$  V at 500°C. The mass spectrometer was supplied by auxiliary gas at 55 psi, nebulizer gas at 55 psi, curtain gas at 10 psi and collision gas at medium. The precursor to product ion transition of  $m/z$  308.1  $\rightarrow$  86.7 for *N*-acetylneuraminic acid (collision energy  $-18.0$  eV) was used for selective reaction monitoring [29]. Quantification was performed with the Analyst Software version 1.6 (AB SCIEX, Foster, CA, USA).

## The cholesterol efflux assay

This experiment was carried out as suggested by Low *et al.* with some modifications [30]. Briefly, Raw 264.7 macrophages were plated into 24-well plates at a final density of  $1 \times 10^5$  cells per well. Six hours later, the culture medium was discarded and cells were gently washed with PBS three times. Then, 600  $\mu\text{l}$  of DMEM containing 1% FBS and 1  $\mu\text{Ci/ml}$  [<sup>3</sup>H]-cholesterol were added to each well and incubated for another 48 hr. The medium containing [<sup>3</sup>H]-cholesterol was removed, and cells were gently washed with PBS three times. Cells were treated with 500  $\mu\text{l}$  DMEM containing 1% FBS in the presence or absence of 50  $\mu\text{M}$  QA for 4 hr, and then 100  $\mu\text{l}$  of acceptor medium (HDL final concentration of 20  $\mu\text{g/ml}$  or apolipoprotein A-1 final concentration of 10  $\mu\text{g/ml}$ ) was added and incubated for another 6 hr. The culture medium was collected into 1.5-ml microfuge tubes and was centrifuged at 18,000 g for 10 min at room temperature to remove cellular debris. Cells were treated with 1 ml of hexane/isopropanol (3:2, v/v) for 30 min at room temperature. The extract was transferred to 1.5-ml microfuge tubes and centrifuged at 14,000 rpm for 10 min at room temperature to remove cellular debris. After centrifugation, 200  $\mu\text{l}$  of medium or cell extract were transferred into a 5.0-ml scintillation vial, and 4.0 ml of HIONIC a FLUOR<sup>™</sup> complete LSC-cocktail (PerkinElmer, Inc., Waltham, MA, USA) was added and mixed well. Controls were defined as groups

with a balance of [<sup>3</sup>H]-cholesterol without drug and acceptor treatment. The scintillation vials were counterered in a Tri-Carb 2810 TR liquid scintillation analyzer (PerkinElmer, Waltham, MA, USA). The rate of cholesterol efflux was expressed as proportion of [<sup>3</sup>H]-cholesterol moved from the cells to the acceptor.

## ELISA assay

HUVECs were seeded in six-well plates at a density of  $4.0 \times 10^5$  cells per well. After adherence, cells were further incubated in the presence or absence of 50  $\mu\text{M}$  QA dissolved in DMEM containing 1% FBS for 4 hr. Then, 0.5 ml of DMEM containing 1% FBS and 50  $\mu\text{g/ml}$  LPS were added and incubated for another 3 hr [31]. TNF- $\alpha$  or MCP-1 secreted into the medium was measured by an ELISA kit according to the manufacturer's instructions. To investigate the therapeutic effect of QA, HUVEC were exposed to LPS for 3 hr, and then, the medium was discarded and cells were further cultivated in the presence or absence of 50  $\mu\text{M}$  QA for another 3 hr. TNF- $\alpha$  or MCP-1 secreted into the medium was measured by ELISA, as described above. Controls were defined as the groups without drug treatment and LPS induction.

## Protein isolation, electrophoresis and Western blotting

Total proteins were extracted from treated and non-treated cells using RIPA lysis buffer supplemented with complete protease inhibitor according to the manufacturer's instructions. Equal amounts of protein were subjected to 12% or 10% SDS-PAGE and transferred onto PVDF membranes by electroblotting. After blocking in Tris-buffered saline (TBS) containing 0.1% Tween 20 and 5% non-fat dry milk for 2 hr at room temperature, the membranes were incubated with primary antibodies overnight at 4°C. After three time washes with TBS containing 0.1% Tween 20, membranes were incubated with horseradish peroxidase-conjugated secondary antibodies for 2 hr at room temperature. Immunoblots were revealed by ECL reaction and visualized using a high-performance chemiluminescence film. Densitometry analysis was conducted using the Image-Pro Plus software version 6.0 (Media Cybernetics Corp, Bethesda, MD, USA) and normalized by the housekeeping protein  $\beta$ -actin.

## Data analysis

All the bioassay results were expressed as mean  $\pm$  standard deviation (S.D.) for at least three independent experiments. Statistical analysis was performed using the SPSS 13.0 software by Student–Newman–Keuls multiple comparison tests. Differences were considered to be significant if  $P < 0.05$ .

## Results

This study aimed to investigate whether the coupling of *N*-acetylneuraminic acid and quercetin could enhance the cardiovascular protective effects of quercetin. The potential protective and therapeutic effects of the novel compound QA were evaluated *in vitro* in various



cellular models by focusing on oxidative stress, inflammation, cholesterol efflux and molecular desialylation.

## Synthesis of quercetin 7-O-sialic acid

Synthesis of methyl (5-acetamido-4,7,8,9-tetra-*O*-acetyl-2-chloro-3,5-dideoxy- $\beta$ -*D*-galacto-2-nonulopyranosid) onate (compound 4) was carried out by the route outlined in Scheme 1(A). The starting material was *N*-acetylneuraminic acid **1** (100 mg), after three steps' modification, compound **4** (122 mg, 75% for three steps) was obtained as a foamy solid.  $^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ): 1.98 (s, 3 H, NHAc), 2.07, 2.09, 2.13, 2.15 (s each, 3 H each, 4 OAc), 2.34 (t,  $J = 13.5$  Hz, 1 H, H-3a), 2.82 (dd,  $J = 4.5, 13.5$  Hz, 1 H, H-3e), 3.91 (s, 3 H, OMe), 4.08 (dd,  $J = 5.7, 12.5$  Hz, 1 H, H-9a), 4.24 (q,  $J = 10.1$ , 1 H, H-5), 4.35 (dd,  $J = 2.4, 10.9$  Hz, 1 H, H-6), 4.47 (dd,  $J = 2.7, 12.3$  Hz, 1 H, H-9b), 5.21 (m, 1 H, H-8), 5.38 (d,  $J = 10.3$  Hz, 1 H, NH), 5.47 (m, 1 H, H-4), 5.53 (dd,  $J = 2.4, 7.3$  Hz, 1 H, H-7).

Synthesis of 4-(3,5-diacetoxy-7-hydroxy-4-oxo-4H-chromen-2-yl)-1,2-phenylene diacetate (compound 7) was carried out according to the route outlined in Scheme 1(B). The starting material was quercetin **5** (500 mg); after the reaction of acetylation, 7-deacetylation and purification, the white solid compound **7** (160 mg, 65%) was obtained.  $^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  2.26-2.31 (m, 9 H, 3  $\times$   $\text{CH}_3$ ), 2.33 (s, 3 H,  $\text{CH}_3$ ), 6.45 (d,  $J = 2.4$  Hz, 1 H, 6-H), 6.69 (d,  $J = 2.4$  Hz, 1 H, 8-H), 7.29 (d,  $J = 9.3$  Hz, 1 H, 5'-H), 7.58-7.65 (m, 2 H, 2'-H, 6'-H).

Synthesis of 3,3',4',5'-tetra-*O*-acetyl quercetin 7-O-(5-acetamido-4,7,8,9-tetra-*O*-acetyl-3,5-dideoxy- $\beta$ -*D*-glycero- $\alpha$ -*D*-galacto-2-nonulopyranosonate) (**8a**) can be approached by the route outlined in Scheme 1(C). A mixture of **4** (65 mg) and **7** (50 mg) was used to give **8a** (34 mg, 36%) as a white solid.  $^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  2.01, 2.03, 2.05, 2.10, 2.15, 2.26, 2.29, 2.31, 2.34 (s each, 3 H each, OAc and NAc), 2.65 (dd,  $J = 12.8, 4.6$  Hz, 1H, H-3" eq), 3.69 (s, 3 H,  $\text{COOCH}_3$ ), 3.85 (dd,  $J = 10.7, 1.8$  Hz, 1 H), 4.07 (dd,  $J = 12.1, 5.7$  Hz, 1 H), 4.18 (td,  $J = 11.6, 6.9$  Hz, 1 H), 4.38 (dd,  $J = 12.3, 2.8$  Hz, 1 H), 4.85 (td,  $J = 12.3, 4.6$  Hz, 1 H), 5.23 (d,  $J = 9.7$  Hz, 1 H), 5.29 (dd,  $J = 8.5, 1.4$  Hz, 1 H), 5.36 (m, 1 H), 5.47 (m, 1H), 5.93 (t,  $J = 4.8$  Hz, 1 H), 6.03 (d,  $J = 2.9$  Hz, 1 H), 6.47 (d,  $J = 2.7$  Hz, 1 H, 6-H), 6.63 (d,  $J = 2.7$  Hz, 1 H, 8-H), 7.21 (d,  $J = 9.5$  Hz, 1 H, 5'-H), 7.51-7.59 (m, 2 H, 2'-H, 6'-H);  $^{13}\text{C-NMR}$  (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  171.1, 170.6, 170.3, 170.1, 169.9, 169.6, 169.1, 168.3, 168.2, 162.3, 158.3, 153.3, 151.1, 144.6, 142.6, 133.9, 128.4, 126.7, 124.3, 124.0, 117.0, 110.6, 109.6, 101.6, 76.7, 72.3, 70.6, 69.3, 69.0, 67.8, 67.7, 67.6, 62.6, 62.0, 21.3, 20.9.

Synthesis of the target compound quercetin 7-O-(5-acetamido-3,5-dideoxy- $\beta$ -*D*-glycero- $\alpha$ -*D*-galacto-2-nonulopyranosonate) (**9**, quercetin 7-O-sialic acid) was carried out according to the route outlined in Scheme 1(C). **8a** (30 mg) was used to produce **9** as a yellow powder (10 mg, 51%).  $^1\text{H-NMR}$  (500 MHz,  $\text{CD}_3\text{OD}$ ):  $\delta$  2.31 (s, 3 H, NAc), 2.45 (dd,  $J = 12.3, 4.1$  Hz, 1H, H-3" eq), 3.55 (dd,  $J = 10.1, 2.3$  Hz, 1 H), 3.97 (dd,  $J = 12.3, 5.1$  Hz, 1 H), 4.01 (td,  $J = 11.6, 6.5$  Hz, 1 H), 4.21 (dd,  $J = 12.5, 2.9$  Hz, 1 H), 4.33 (td,  $J = 12.7, 4.5$  Hz, 1 H), 4.65 (dd,  $J = 8.0, 1.9$  Hz, 1 H), 4.78 (d,  $J = 9.3$  Hz, 1 H), 4.93-4.97 (m, 2 H), 5.03 (t,  $J = 4.9$  Hz, 1 H), 5.55 (d,  $J = 2.6$  Hz, 1 H), 6.53 (d,

$J = 2.9$  Hz, 1 H, 6-H), 6.61 (d,  $J = 2.9$  Hz, 1 H, 8-H), 7.23 (d,  $J = 9.5$  Hz, 1 H, 5'-H), 7.53-7.60 (m, 2 H, 2'-H, 6'-H);  $^{13}\text{C-NMR}$  (500 MHz,  $\text{CD}_3\text{OD}$ ):  $\delta$  169.3, 162.1, 157.1, 153.5, 151.0, 144.8, 142.3, 133.9, 128.2, 126.1, 124.3, 124.0, 116.6, 110.3, 109.4, 101.7, 75.1, 71.3, 69.3, 68.0, 67.1, 66.9, 66.5, 66.1, 62.3, 62.1, 21.6, 20.7.

## Cytotoxicity

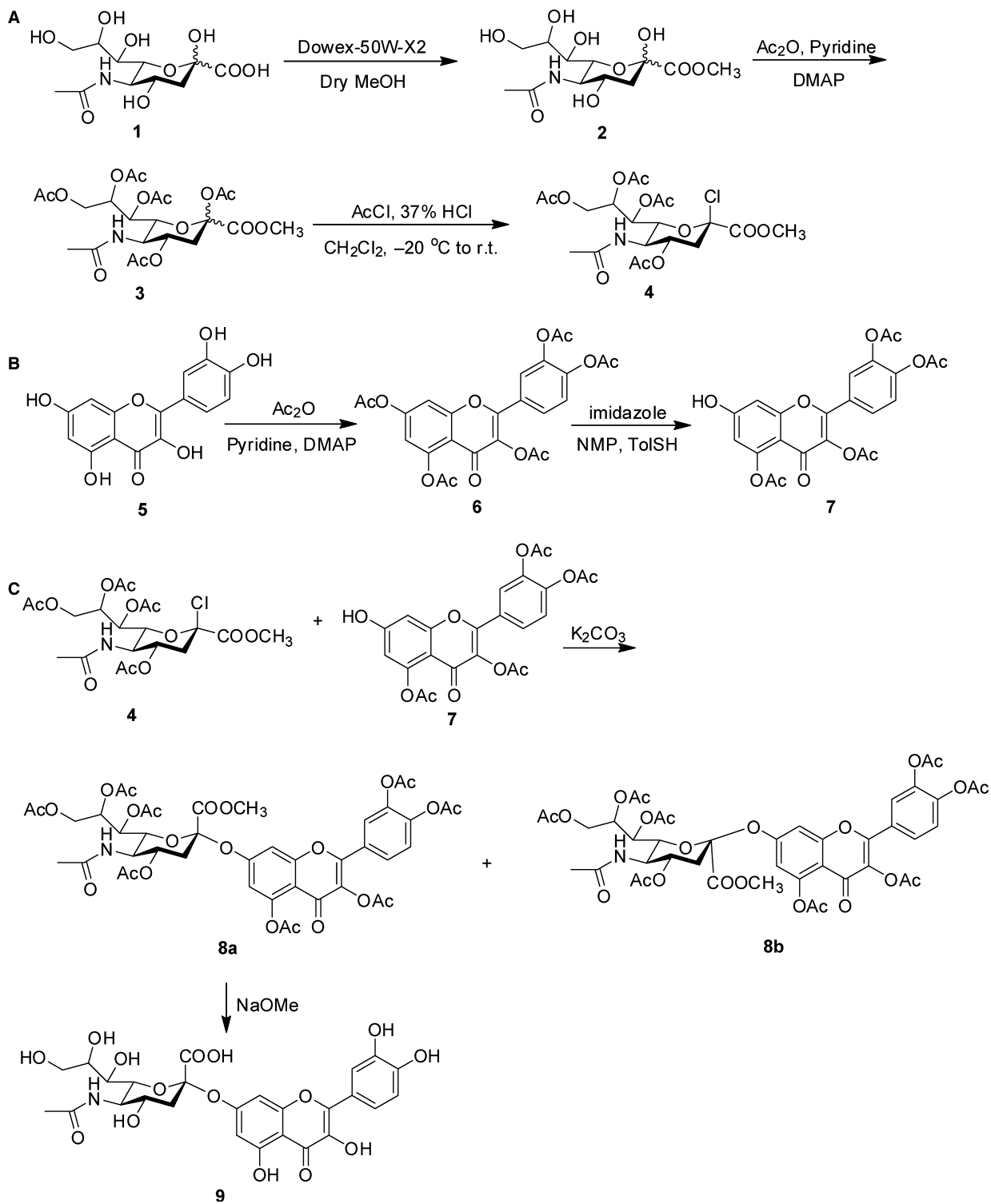
The cytotoxicity of QA and quercetin was determined by the MTT method which provided information on the number of metabolically active cells. As shown in Figure 1A and B (HUVEC, EA.hy926) and Figure 5A and B (Raw 264.7 macrophages), QA exhibited no significant cytotoxicity compared with the control within the concentration range of 0–75  $\mu\text{M}$ . Quercetin concentrations higher than 50  $\mu\text{M}$  were found to be cytotoxic *in vitro*, which is related to increased ROS production due to impairment of anti-oxidant activity [32]. As QA was synthesized based on quercetin, QA may also have pro-oxidant activity at high concentrations. To obtain a maximum effect at a safe dosage [27, 33], the experimental concentration for QA or quercetin was set at 50  $\mu\text{M}$ .

## Anti-oxidant activity

Both  $\text{H}_2\text{O}_2$  and ox-LDL were used to induce cellular oxidative models. To choose appropriate concentrations, the cytotoxicity of  $\text{H}_2\text{O}_2$  or ox-LDL was evaluated by the MTT method. As shown in Figure 1(C and D), after 24 hr of exposure, the cytotoxicity of both  $\text{H}_2\text{O}_2$  and ox-LDL was concentration-dependent. Cell viability of approximately 40% was set as representative of an oxidative damage model, and hence, 400  $\mu\text{M}$   $\text{H}_2\text{O}_2$  or 200 mg/l ox-LDL was used in the following antioxidant assays. The results indicated that pretreatment of cells with either QA or quercetin for 4 hr could dramatically protected HUVECs from oxidation-induced apoptosis by  $\text{H}_2\text{O}_2$  or ox-LDL (Fig. 1E and F). Although the protective effect of QA seemed to be superior to that of quercetin, results showed no significant differences.

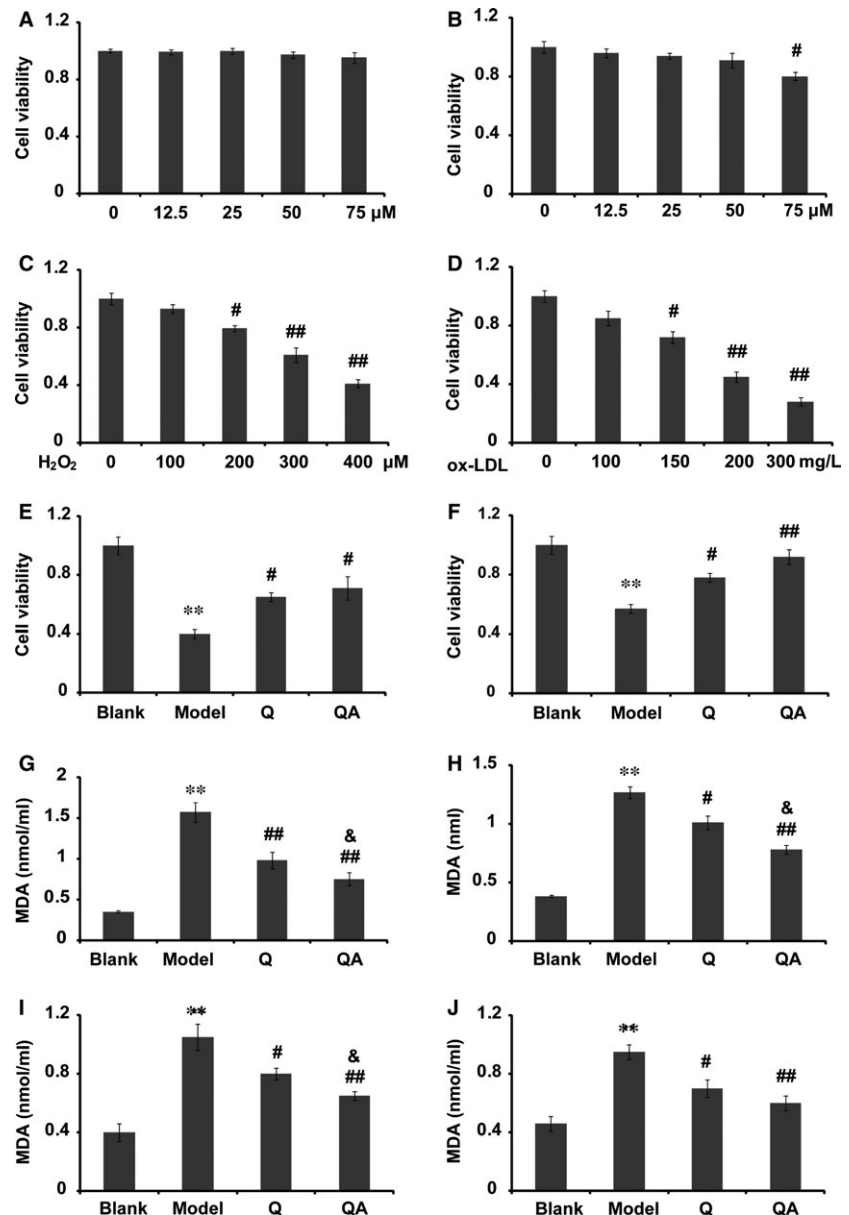
To compare the protective effect of QA and quercetin under mild oxidative stress, 100  $\mu\text{M}$   $\text{H}_2\text{O}_2$  or 100 mg/l ox-LDL was used in the following experiments. In the protective model, both  $\text{H}_2\text{O}_2$  and ox-LDL increased the MDA level in the medium. Compared with quercetin, QA led to a marked decrease in the MDA level induced by either  $\text{H}_2\text{O}_2$  or ox-LDL (Fig. 1G and H,  $P < 0.05$ ). In the therapeutic model, QA exhibited a better therapeutic effect than quercetin on reducing the production of MDA after  $\text{H}_2\text{O}_2$  treatment (Fig. 1I,  $P < 0.05$ ). Although QA could further reduce ox-LDL-induced MDA production compared with quercetin, results showed no significant differences (Fig. 1J).

Intracellular ROS production was evaluated using the fluorogenic probe DCFH-DA. As shown in Figure 2, both ox-LDL and  $\text{H}_2\text{O}_2$  could promote ROS production in cells after 24 hr cocultivation ( $P < 0.01$ ), and quercetin and QA significantly reduced the increased ROS level. In the protective model, QA pretreatment produced significant differences in the  $\text{H}_2\text{O}_2$ -induced oxidation damage model compared with quercetin (Fig. 2B). Further assays on the antioxidant action of QA also demonstrated that QA was better than quercetin at decreasing the level of intracellular ROS (Fig. 2C and D).



**Scheme 1** Reagents and conditions for the synthesis of quercetin 7-O-sialic acid (QA). DMAP, 4-dimethylaminopyridine; NMP, *N*-methyl-2-pyrrolidone.

**Fig. 1** Cytotoxicity and antioxidant effect of quercetin 7-O-sialic acid (QA). (A) Viability of HUVECs in the presence of 0–75  $\mu$ M QA; (B) viability of HUVECs in the presence of 0–75  $\mu$ M quercetin (Q); (C) viability of HUVECs treated with 0–400  $\mu$ M H<sub>2</sub>O<sub>2</sub>; (D) viability of HUVECs treated with 0–300 mg/l ox-LDL; (E) in the protective model, the effect of QA on cell viability in H<sub>2</sub>O<sub>2</sub>-induced apoptosis; (F) in the protective model, the effect of QA on cell viability in ox-LDL-induced apoptosis; (G) in the protective model, the effect of QA on the secretion of MDA in H<sub>2</sub>O<sub>2</sub>-induced oxidation; (H) in the protective model, the effect of QA on the secretion of MDA in ox-LDL-induced oxidation; (I) in the therapeutic model, the effect of QA on the secretion of MDA in H<sub>2</sub>O<sub>2</sub>-induced oxidation; (J) in the therapeutic model, the effect of QA on the secretion of MDA in ox-LDL-induced oxidation. Q, quercetin; QA, quercetin 7-O-sialic acid. Controls were defined as groups without drug treatment and H<sub>2</sub>O<sub>2</sub> or ox-LDL induction. Cell viability in the control group was set at 1, and cell viability in the other groups was determined as a fold of the control. Data are expressed as the mean  $\pm$  S.D. ( $n = 3$ ). \*\* $P < 0.01$  versus blank control; # $P < 0.05$  versus model control and ## $P < 0.01$  versus model; & $P < 0.05$  versus quercetin.

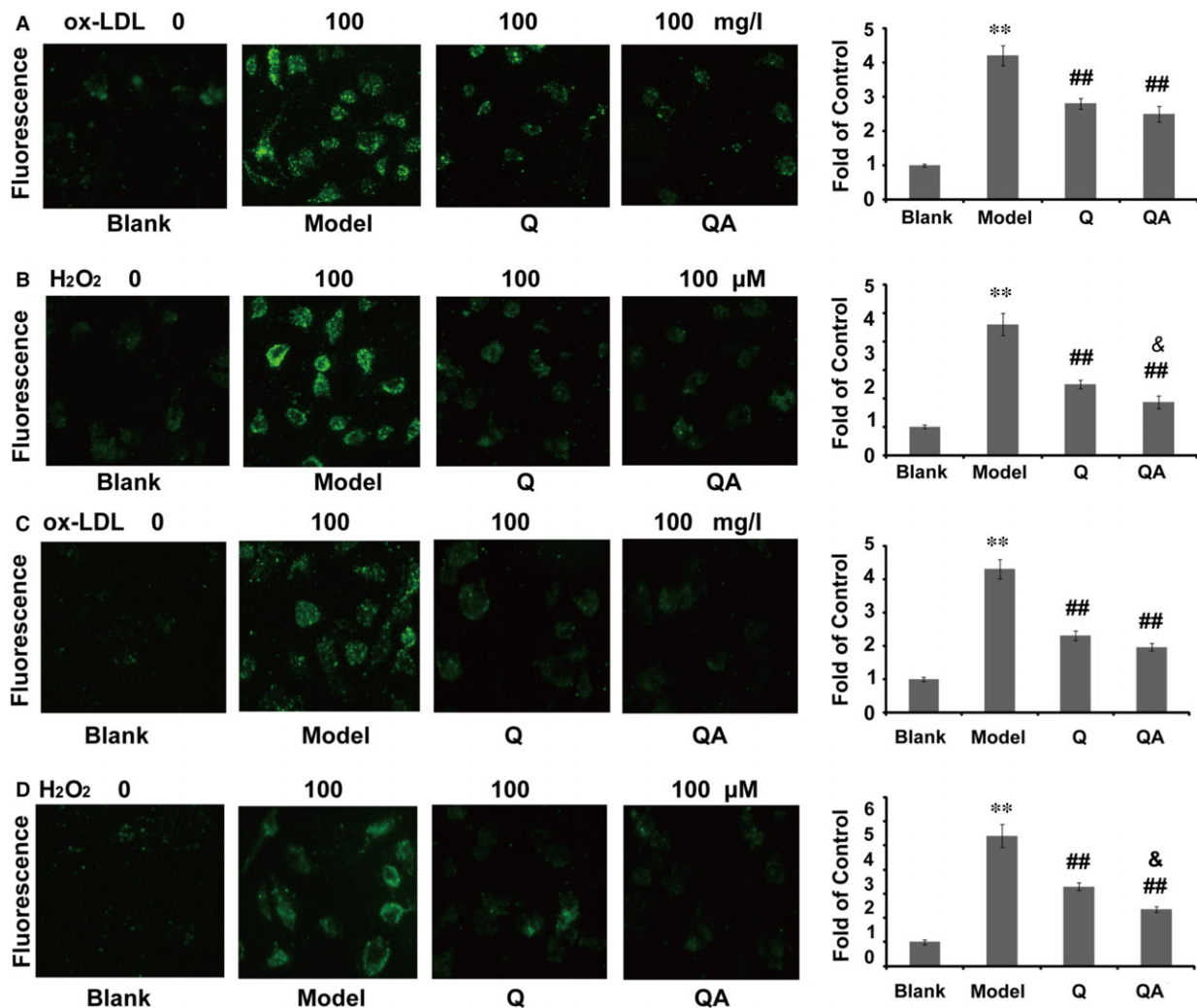


## Desialylation

Sialic acid is found at the non-reducing terminal end of glycoconjugates, and it is widely distributed on the surface of various cells. ROS can induce desialylation and subsequently influence the normal functions of cells. In this study, sialic acid was evaluated *in situ* by the ligation with FTSC [28]. In the protective model, 100  $\mu$ M H<sub>2</sub>O<sub>2</sub> remarkably decreased the level of sialic acid on the cell surface ( $P < 0.01$ ). Quercetin and especially QA protected sialic acid against H<sub>2</sub>O<sub>2</sub>-induced degradation (Fig. 3A and B). Compared to quercetin, QA induced a higher increase in cellular sialylation (Fig. 3B,

$P < 0.05$ ). In the therapeutic model, QA also significantly increased cellular sialylation (Fig. 3C and D), and the effect of QA was significantly higher.

In the further study, we investigated whether QA could protect lipoproteins against H<sub>2</sub>O<sub>2</sub>-induced desialylation. As shown in Figure 3(E and F), when exposed to 100  $\mu$ M H<sub>2</sub>O<sub>2</sub> for 24 hr, sialic acid of either LDL or HDL was significantly decreased ( $P < 0.01$ , Fig. 3C and D) compared with the control. With the protection of quercetin or QA, H<sub>2</sub>O<sub>2</sub>-induced desialylation was remarkably suppressed. The protective effect of QA was significantly higher compared with quercetin against H<sub>2</sub>O<sub>2</sub>-induced HDL desialylation (Fig. 3F,  $P < 0.05$ ).



**Fig. 2** Effect of quercetin 7-O-sialic acid (QA) on H<sub>2</sub>O<sub>2</sub>- or ox-LDL-induced intracellular ROS production. **(A)** In the protective model, the fluorescence image of ROS in ox-LDL-induced HUVECs, and the quantified fluorescence intensity; **(B)** in the protective model, the fluorescence image of ROS in H<sub>2</sub>O<sub>2</sub>-induced HUVECs, and the quantified fluorescence intensity; **(C)** in the therapeutic model, the fluorescence image of ROS in ox-LDL-induced HUVECs, and the quantified fluorescence intensity; **(D)** in the therapeutic model, the fluorescence image of ROS in H<sub>2</sub>O<sub>2</sub>-induced HUVECs, and the quantified fluorescence intensity. Controls were defined as groups without drug treatment and H<sub>2</sub>O<sub>2</sub> or ox-LDL induction. Data are expressed as the mean  $\pm$  S.D. ( $n = 3$ ). \*\* $P < 0.01$  versus blank control; ## $P < 0.01$  versus model, & $P < 0.05$  versus quercetin.

### Anti-inflammatory activity

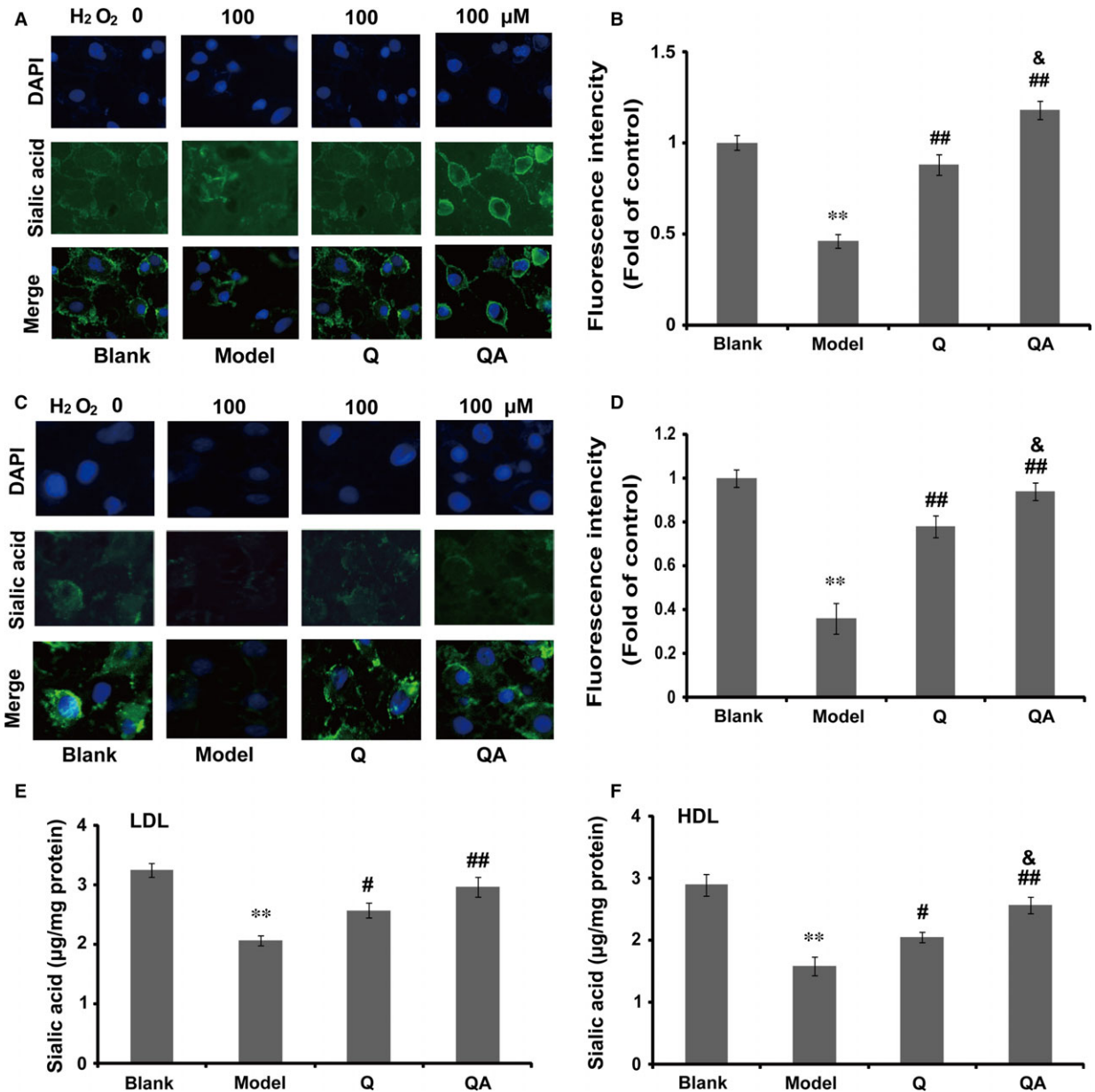
The inhibitory effects of QA on LPS-induced (50  $\mu$ g/ml) TNF- $\alpha$  or MCP-1 production by HUVECs were evaluated by ELISA. Compared with the control, stimulation of HUVECs with LPS resulted in a five-fold increase in TNF- $\alpha$  and threefold increase in MCP-1. In the protective model, 50  $\mu$ M QA or quercetin significantly attenuated the secretion of TNF- $\alpha$  or MCP-1 (Fig. 4A and B). The protein expression of TNF- $\alpha$ , MCP-1, ICAM-1 and VCAM-1 in HUVECs was semi-quantified by Western blotting. As shown in Figure 4(C–F), LPS induced a 1.5- to 2-fold increase in these proteins. QA significantly reduced the expressions of TNF- $\alpha$ , ICAM-1, VCAM-1 and MCP-1

(Fig. 4C). QA showed remarkably protective effects on the LPS-induced VCAM-1 expression compared with quercetin (Fig. 4E,  $P < 0.05$ ). In the therapeutic model, both quercetin and QA significantly decreased the secretion of TNF- $\alpha$  and MCP-1 (Fig. 4G and H). However, the effect of QA was not significantly different from that of quercetin.

### Cholesterol efflux

Both quercetin and QA significantly improved [<sup>3</sup>H]-cholesterol efflux from Raw 264.7 macrophages (Fig. 5C and D,  $P < 0.01$ ). Compared

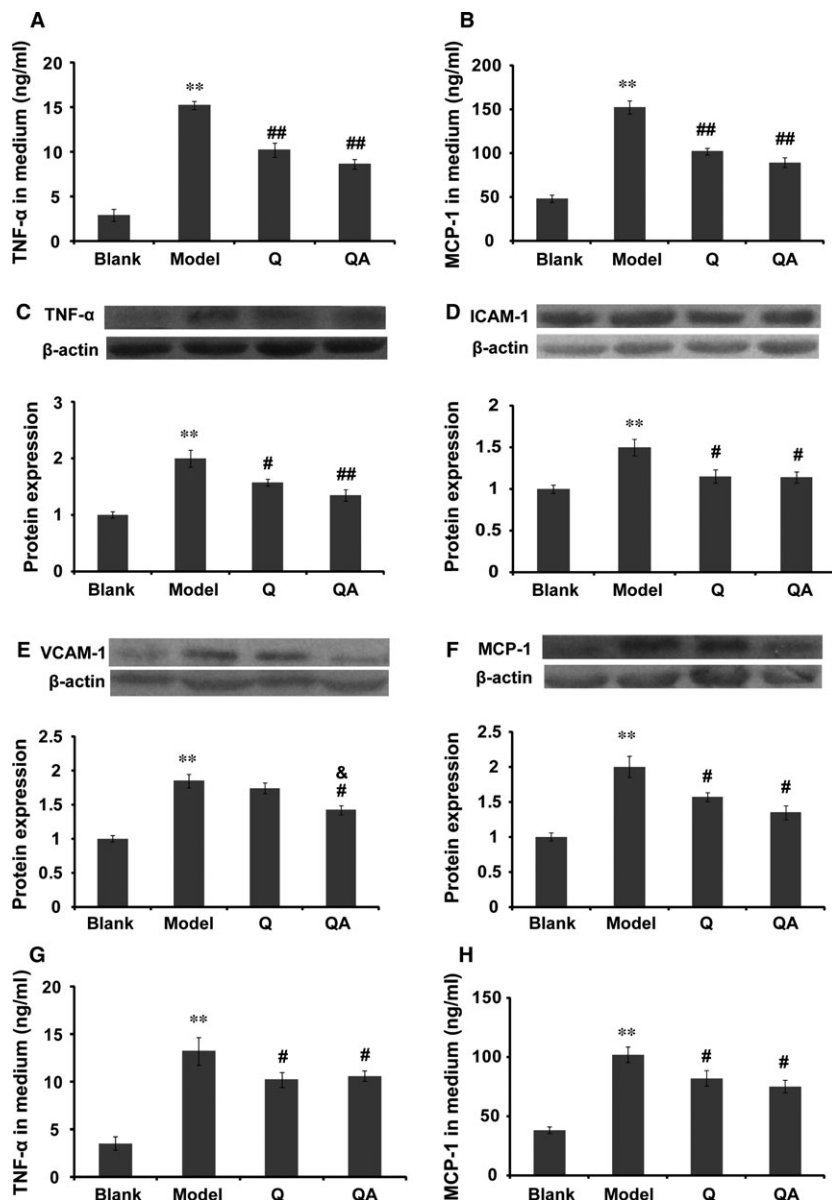




**Fig. 3** Effect of quercetin 7-O-sialic acid (QA) on H<sub>2</sub>O<sub>2</sub>-induced desialylation. (A) In the protective model, the fluorescence image of sialic acid in H<sub>2</sub>O<sub>2</sub>-induced HUVECs; (B) in the protective model, the quantified fluorescence intensity of sialic acid in H<sub>2</sub>O<sub>2</sub>-induced HUVECs; (C) in the therapeutic model, the fluorescence image of sialic acid in H<sub>2</sub>O<sub>2</sub>-induced HUVECs; (D) in the therapeutic model, the quantified fluorescence intensity of sialic acid in H<sub>2</sub>O<sub>2</sub>-induced HUVECs; (E) the protective effect of QA on H<sub>2</sub>O<sub>2</sub>-induced desialylation of LDL; (F) the protective effect of QA on H<sub>2</sub>O<sub>2</sub>-induced desialylation of HDL. In A–D, controls were defined as groups with NaIO<sub>4</sub> treatment without H<sub>2</sub>O<sub>2</sub> induction and drug treatment; in E and F, controls were defined as normal lipoproteins without drug treatment and H<sub>2</sub>O<sub>2</sub> induction. Data are expressed as the mean ± S.D. (n = 3). \*\*P < 0.01 versus blank control; #P < 0.05 versus model and ##P < 0.01 versus model; &P < 0.05 versus quercetin.

with quercetin, QA showed a significantly increased effect at improving [<sup>3</sup>H]-cholesterol efflux from macrophages to apolipoprotein A-1. ABCG1 and ABCA1 are important cholesterol transporters that mediate cholesterol efflux from peripheral cells to HDL and apolipoprotein

A-1, respectively. As shown in Figure 5(E and F), both QA and quercetin improved the protein expression of ABCG1 and ABCA1 in Raw 264.7 cells, especially that of ABCA1. The results showed that QA significantly promoted ABCA1 expression compared with quercetin at a



**Fig. 4** Anti-inflammatory effect of quercetin 7-O-sialic acid (QA) on LPS-challenged HUVECs. (A) In the protective model, TNF- $\alpha$  released by HUVECs; (B) in the protective model, MCP-1 released by HUVECs; (C) TNF- $\alpha$  expression in the presence or absence of quercetin or QA; (D) ICAM-1 expression in the presence or absence of quercetin or QA; (E) VCAM-1 expression in the presence or absence of quercetin or QA; (F) MCP-1 expression in the presence or absence of quercetin or QA; (G) in the therapeutic model, TNF- $\alpha$  secreted into medium; (H) in the therapeutic model, MCP-1 secreted into medium. Controls were defined as groups without drug treatment and LPS induction. Data are expressed as the mean  $\pm$  S.D. ( $n = 3$ ). \*\* $P < 0.01$  versus blank control; # $P < 0.05$  versus model and ## $P < 0.01$  versus model; & $P < 0.05$  versus quercetin.

concentration of 50  $\mu$ M. However, both quercetin and QA showed no effect on the protein expression of SR-B1.

## Discussion

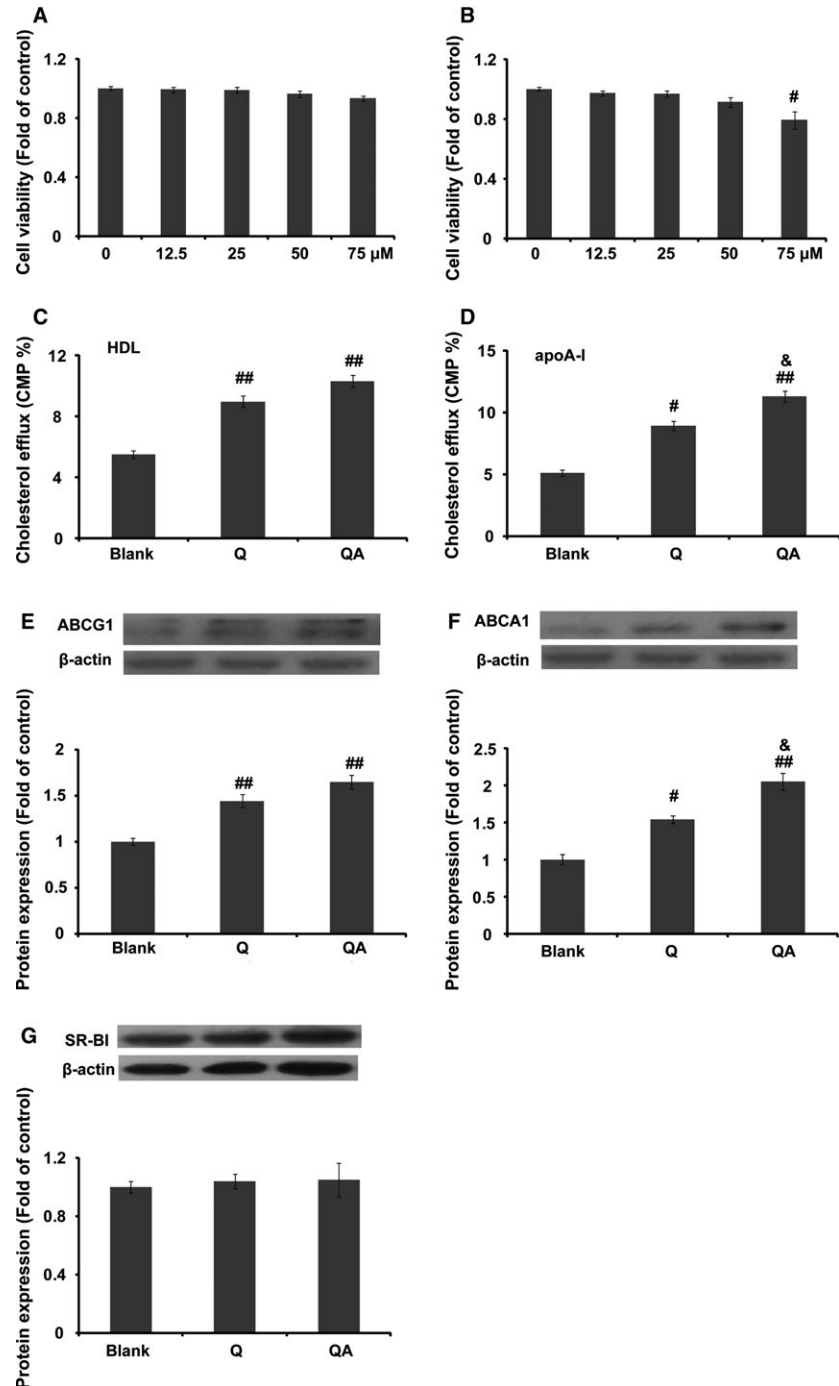
Oxidative stress and inflammation are two key factors involved in CVD onset and progression [34, 35]. Theoretically, attenuating oxidative stress and/or inflammatory reactions may ameliorate CVD. In this study, QA was synthesized aiming to put together the cardiovascular protective effect of quercetin and *N*-acetylneuraminic acid. The biological efficacy of QA was evaluated *in vitro* in various cellular models. We reported here for the first time that: (1) the ligation of *N*-

acetylneuraminic acid to quercetin decreased to some extent the cytotoxicity of quercetin, (2) QA attenuated significantly ROS production and inflammation in both 'the protective model' and 'the therapeutic model', (3) QA was proved to be more active in protecting molecules against desialylation than quercetin, (4) QA significantly improved cholesterol efflux compared with quercetin, mainly by up-regulation of ABCA1.

## QA is superior to quercetin in preventing CVD

ROS regulates a vast array of intracellular proteins and signalling pathways [36, 37] and therefore plays important roles in maintaining

**Fig. 5** The action of quercetin 7-O-sialic acid (QA) on cholesterol efflux. **(A)** Viability of Raw 264.7 macrophages in the presence of 0–75  $\mu$ M QA; **(B)** viability of Raw 264.7 macrophages in the presence of 0–75  $\mu$ M quercetin; **(C)** percentage of [ $^3$ H]-cholesterol from Raw 264.7 macrophages to HDL; **(D)** percentage of [ $^3$ H]-cholesterol from Raw 264.7 macrophages to apolipoprotein A-1; **(E)** ABCG1 expression in the presence or absence of quercetin or QA; **(F)** ABCA1 expression in the presence or absence of quercetin or QA; **(G)** SR-BI expression in the presence or absence of quercetin or QA. Controls were defined as groups with a balance of [ $^3$ H]-cholesterol and without drug and acceptor treatment. Data are expressed as mean  $\pm$  S.D. ( $n = 3$ ).  $^{\#}P < 0.05$  versus blank;  $^{\#\#}P < 0.01$  versus blank;  $^{\&}P < 0.05$  versus quercetin.



normal cardiovascular functions [38]. Endothelial dysfunction caused by oxidative stress is an independent predictor of CVD. The *in vitro* study demonstrated that QA showed better activity than quercetin in protecting HUVECs against H<sub>2</sub>O<sub>2</sub>- or ox-LDL-induced cell apoptosis, and the underlying mechanism of this protection may be due to

reduced intracellular ROS production, as measured using DCFH-DA. Therefore, QA could, at least in part, suppress lipid oxidation and subsequently decreased MDA production in HUVECs by inhibiting ROS production. The increased antioxidant action of QA may be due to the presence of N-acetylneuraminic acid, which could scavenge

equimolar amounts of H<sub>2</sub>O<sub>2</sub> [13] or other ROS [14]. The oxidation of lipids, such as ox-LDL, is an initial event in the development of atherosclerosis. Therefore, the inhibitory effect of QA on lipid oxidation may decrease susceptibility to CVD. Additionally, the results of H<sub>2</sub>O<sub>2</sub>-induced apoptosis of HUVECs and the protective effect of quercetin were similar to a previous report [39].

Desialylation is a possible primary step of atherogenic modification [10]. In this study, we demonstrated that the effect of QA on H<sub>2</sub>O<sub>2</sub>-induced HUVECs desialylation was significantly reduced under the action of QA compared with that of quercetin, which may be explained by the *N*-acetylneuraminic acid of QA, which may attenuate equimolar amounts of ROS and incorporate into cells just as exogenous *N*-acetylneuraminic acid [40, 41] under the action of sialyltransferase. The results also demonstrated that QA exhibited an improved protective effect on H<sub>2</sub>O<sub>2</sub>-induced desialylation of LDL and HDL. Previous publications have demonstrated that desialylation, the reduction in the negative charge provided by sialic acid, could increase potential aggregation between lipoproteins and/or adherence of lipoprotein to HUVECs, or even decrease the lifespan of macromolecules and stimulate the accumulation of cholesterol in cells [42, 43], thereby increasing the CVD potential. According to the results obtained by us, QA may be explored as a sialic acid protector due to its antioxidant effects and/or as a donor of exogenous *N*-acetylneuraminic acid, thereby exerting its potential cardiovascular protective effects.

It is well established that inflammation participates throughout the progression of CVD [35]. It is known that both MCP-1 and VCAM-1 help blood monocytes to adhere to endothelial cells and transmigrate into the subendothelial space, which is an initial event in atherogenesis [44]. In addition, ICAM-1 could facilitate the invasion of neutrophils into the arterial wall, which is also a key event of CVD [45]. In the protective model, QA could remarkably quench the production of MCP-1 and the pro-inflammatory factor TNF- $\alpha$  and attenuated the protein expression of ICAM-1 and VCAM-1 compared with quercetin. Taken together, QA showed a better ability to reduce inflammation in HUVECs compared with quercetin. Previous research demonstrated that the anti-inflammatory mechanisms of quercetin may be due to its ability to down-regulate nuclear factor  $\kappa$ B [27], CD80 [14] and its ROS inhibitory effect. We hypothesized that QA may exert anti-inflammatory effects through the same pathways as quercetin.

Cholesterol homeostasis is critical for cell function and metabolism [46]. It has been documented that cholesterol accumulation in macrophages is one of the risk factors for atherosclerosis [47]. ABCA1 and ABCG1 are two key transporters mediating cholesterol efflux from macrophages to apolipoprotein A-1 and HDL, respectively. In this study, we demonstrated for the first time that QA could promote cholesterol efflux from Raw 264.7 macrophages to its acceptor HDL or apolipoprotein A-1. The underlying mechanisms were related to the activation of ABC transporters. However, protein expression of SR-B1 was not affected by the presence of QA or quercetin. Previous studies have indicated that flavonoids may activate ABCA1 by up-regulation of peroxisome proliferator-activated receptor  $\gamma$  and liver X receptor  $\alpha$  [21]; another research study showed that quercetin enhances ABCA1 expression through a p38-dependent pathway in

macrophages [48]. Our previous data indicated that both quercetin and exogenous *N*-acetylneuraminic acid could improve RCT-related protein expression in apoE-deficient mice [49].

## QA is better than quercetin in CVD therapy

Oxidative stress can accelerate the development of CVD through multiple signalling pathways [38]. ROS generated in the vascular wall cells could change the physicochemical properties of endothelial system. An impaired endothelium permits increased permeability to macromolecules such as ox-LDL, and thereby exacerbates CVD. In this study, QA could decrease the production of the lipid oxidation product MDA in HUVECs pretreated with H<sub>2</sub>O<sub>2</sub> or ox-LDL compared with quercetin. This action may be attributed to the increased inhibitory effect of QA on ROS production and other ROS-related signalling pathways.

Desialylation occurs in some molecules during the progression of CVD, which could reduce the negative charge carried by glycoconjugates, and subsequently increase the adherence of inflammatory cells or molecules to the endothelium. The results obtained in 'the therapeutic model' demonstrated that QA significantly increased the *N*-acetylneuraminic acid level compared with quercetin. The underlying mechanisms may be associated to: (1) the higher antioxidant activity of QA compared with quercetin, which could reduce ROS-induced desialylation, (2) *N*-acetylneuraminic acid linked to QA may be incorporated into the cell under the action of sialyltransferase; and (3) QA may be hydrolysed by neuraminidase, and then, *N*-acetylneuraminic acid and quercetin will exert synergic effects in their free form, as we reported in a previous study [49]. As reviewed by Gokmen *et al.*, both sialyltransferase and neuraminidase activities are increased in CVD patients [5], and therefore, the superiority of QA over quercetin becomes more prominent. QA may work as a substrate of the above enzymes and subsequently protect endogenous substrate against desialylation, and decomposed QA under the action of neuraminidase may then exert synergic effects.

Chronic inflammation is the major cause of the deterioration and complications of CVD. Anti-inflammatory drugs may partially reverse the severity of CVD. In this study, QA was demonstrated to reduce high concentrations of LPS-induced inflammation in HUVECs, but the secretion of TNF- $\alpha$  and MCP-1 showed no significant difference compared with quercetin. A previous study demonstrated that the combination of quercetin and *N*-acetylneuraminic acid had a minor influence on the inflammatory state compared with quercetin in apoE-deficient mice [49]. Although serum total sialic acid has been demonstrated to be a marker of chronic inflammation, exogenous supplement of *N*-acetylneuraminic acid did not accelerate but instead reduced inflammation to some extent in apoE-deficient mice provided a high-fat diet [49].

## Perspective for clinical application of QA

Based on the protective and therapeutic *in vitro* models, QA improved the original pharmacological functions of quercetin, such

as its anti-oxidant, anti-inflammation, cholesterol efflux promotion, and especially protection of molecules against desialylation effects. Additionally, QA may also maintain or even elevate other activities of quercetin, such as inhibition of platelet aggregation and reduction of blood pressure, all of which are beneficial for the prevention or treatment of CVD. Although quercetin has been reported to have preventive and therapeutic effects for CVD, its poor solubility and bioavailability has limited its clinical application. The ligation of *N*-acetylneuraminic acid to quercetin is improving the solubility of quercetin due to the addition of hydroxyls and especially carboxyls, which may increase the possibility of using QA for clinical applications. Additionally, lipid reduction is one of the most important strategies for the treatment of CVD with hyperlipidaemia. A previous study by our group indicated that a combination of quercetin and *N*-acetylneuraminic acid or *N*-acetylneuraminic acid alone could significantly reduce triglycerides and cholesterol in apoE-deficient mice to which a high-fat diet was provided [49]. The *in vitro* results of this study showed QA's attractive ability to improve cholesterol efflux. We presume that the lipid reducing effect of QA may be comparable to that of regular lipid-regulatory drugs, such as statins.

However, there are several limitations in this study. (1) Although the toxicity of QA seemed to be lower than that of quercetin, the cytotoxicity assessment using cellular models could not reflect the factual situation *in vivo*. Therefore, pharmacokinetic studies of QA are required to exclude whole-organ toxicity and to analyse whole-organism effects and the effective dose. (2) Anti-inflammatory effects of QA should be further studied using primary monocytes/macrophages in addition to the Raw cell line, which are critically involved in inflammation by producing ROS, NO and pro-inflammatory cytokines. (3) The effectiveness of QA needs to be studied in the context of conventional drugs used for treating CVD.

## References

1. **Taggart M.** Vascular function in health and disease review series. *J Cell Mol Med.* 2010; 14: 1017.
2. **Seidemann SB, Lighthouse JK, Greif DM.** Development and pathologies of the arterial wall. *Cell Mol Life Sci.* 2014; 71: 1977–99.
3. **Strilić B, Eglinger J, Krieg M, et al.** Electrostatic cell-surface repulsion initiates lumen formation in developing blood vessels. *Curr Biol.* 2010; 20: 2003–9.
4. **Keppeler OT, Hinderlich S, Langner J, et al.** UDP-GlcNAc 2-epimerase: a regulator of cell surface sialylation. *Science.* 1999; 284: 1372–6.
5. **Gokmen SS, Kilicli G, Ozcelik F, et al.** Association between serum total and lipid-bound sialic acid concentration and the severity of coronary atherosclerosis. *J Lab Clin Med.* 2002; 140: 110–8.
6. **Gopaul KP, Crook MA.** Sialic acid: a novel marker of cardiovascular disease? *Clin Biochem.* 2006; 39: 667–81.
7. **Heistad DD.** Oxidative stress and vascular disease: 2005 Duff lecture. *Arterioscler Thromb Vasc Biol.* 2006; 26: 689–95.
8. **Goswami K, Koner BC.** Level of sialic acid residues in platelet proteins in diabetes, aging, and Hodgkin's lymphoma: a potential role of free radicals in desialylation. *Biochem Biophys Res Commun.* 2002; 297: 502–5.
9. **Tanaka K, Tokumaru S, Kojo S.** Possible involvement of radical reactions in desialylation of LDL. *FEBS Lett.* 1997; 413: 202–4.
10. **Tertov VV, Kaplun VV, Sobenin IA, et al.** Low-density lipoprotein modification occurring in human plasma possible mechanism of *in vivo* lipoprotein desialylation as a primary step of atherogenic modification. *Atherosclerosis.* 1998; 138: 183–95.
11. **Eguchi H, Ikeda Y, Ookawara T, et al.** Modification of oligosaccharides by reactive oxygen species decreases sialyl Lewis x-mediated cell adhesion. *Glycobiology.* 2005; 15: 1094–101.
12. **Weiss P, Ashwell G.** The asialoglycoprotein receptor: properties and modulation by ligand. *Prog Clin Biol Res.* 1989; 300: 169–84.
13. **Iijima R, Takahashi H, Namme R, et al.** Novel biological function of sialic acid (*N*-Acetylneuraminic acid) as a hydrogen peroxide scavenger. *FEBS Lett.* 2004; 561: 163–6.
14. **Ogasawara Y, Namai T, Yoshino F, et al.** Sialic acid is an essential moiety of mucin as a hydroxyl radical scavenger. *FEBS Lett.* 2007; 581: 2473–7.

## Conclusion

In conclusion, the novel compound QA exhibited better capacity than quercetin for anti-oxidation, anti-inflammation, cholesterol efflux promotion and protection of biomolecules from desialylation in cellular modes relevant for CVD, and therefore, it could be a potential compound for the prevention or treatment of CVD.

## Acknowledgements

This work was supported by the Natural Science Foundation of China (31300639), Shandong Provincial Natural Science Fund (ZR2013HQ014), Taishan Scholars Foundation of Shandong Province (ts201511057) and Doctoral Science Foundation of Taishan Medical University (2234).

## Author contributions

H Tian and NN Yang were responsible for cell culture and sialic acid staining and image capture. QC Liu was responsible for the synthesis of quercetin 7-O-sialic acid. SC Qin and CL Zong participated in the experiments design and data interpretation. Y Zhang and ST Yao gave some useful advice during experimental performance and provided several antibodies. RZ Yu and T Guan assisted the Western blot experiments. SD Guo was responsible for the funding, study design, interpretation and manuscript preparation.

## Conflict of interest

The authors declare that there are no conflicts of interest in the manuscript.



15. **Serdar Z, Yesilbursa D, Dirican M, et al.** Sialic acid and oxidizability of lipid and proteins and antioxidant status in patients with coronary artery disease. *Cell Biochem Funct.* 2007; 25: 655–64.
16. **Malicdan MCV, Noguchi S, Hayashi YK, et al.** Prophylactic treatment with sialic acid metabolites precludes the development of the myopathic phenotype in the DMRV-Hibm mouse model. *Nat Med.* 2009; 15: 390–696.
17. **Nishino I, Noguchi S.** Sialic acid supplementation therapy for distal myopathy with rimmed vacuoles. *Brain Nerve.* 2012; 64: 255–61.
18. **Malicdan MCV, Noguchi S, Nishino I.** Perspectives on distal myopathy with rimmed vacuoles or hereditary inclusion body myopathy: contributions from an animal model. Lack of sialic acid, a central determinant in sugar chains, causes myopathy? *Acta Myol.* 2007; 26: 171–5.
19. **Yi L, Chen CY, Jin X, et al.** Differential suppression of intracellular reactive oxygen species-mediated signaling pathway in vascular endothelial cells by several subclasses of flavonoids. *Biochimie.* 2012; 94: 2035–44.
20. **Kleemann R, Verschuren L, Morrison M, et al.** Anti-inflammatory, anti-proliferative and anti-atherosclerotic effects of quercetin in human *in vitro* and *in vivo* models. *Atherosclerosis.* 2011; 218: 44–52.
21. **Lee SM, Moon J, Cho Y, et al.** Quercetin up-regulates expressions of peroxisome proliferator-activated receptor  $\gamma$ , liver X receptor  $\alpha$ , and ATP binding cassette transporter A1 genes and increases cholesterol efflux in human macrophage cell line. *Nutr Res.* 2013; 33: 136–43.
22. **Varki A.** Biological roles of oligosaccharides: all of the theories are correct. *Glycobiology.* 1993; 3: 97–130.
23. **Aksenov DV, Medvedeva LA, Skalbe TA, et al.** Deglycosylation of apo B-containing lipoproteins increase their ability to aggregate and to promote intracellular cholesterol accumulation *in vitro*. *Arch Physiol Biochem.* 2008; 114: 349–56.
24. **Havel RJ, Eder HA, Bragdon JH.** Distribution and chemical composition of ultracentrifugally separated lipoproteins in human serum. *J Clin Invest.* 1955; 34: 1345–53.
25. **Yao ST, Sang H, Song GH, et al.** Quercetin protects macrophages from oxidized low-density lipoprotein-induced apoptosis by inhibiting the endoplasmic reticulum stress-C/EBP homologous protein pathway. *Exp Bio Med.* 2012; 237: 822–31.
26. **Guo SD, Yu Y, Zhang N, et al.** Higher level of plasma bioactive molecule sphingosine-1-phosphate in women in associated with estrogen. *Biochim Biophys Acta.* 2014; 1841: 836–46.
27. **Panicker SR, Sreenivas P, Babu MS, et al.** Quercetin attenuates monocyte chemoattractant protein-1 gene expression in glucose primed aortic endothelial cells through NF- $\kappa$ B and AP-1. *Pharmacol Res.* 2010; 62: 328–36.
28. **Zhang Y, Yuan JB, Song JJ, et al.** An efficient method for selectively imaging and quantifying *in situ* the expression of sialylated glycoproteins on living cells. *Glycobiology.* 2013; 23: 643–53.
29. **Guo SD, Hui S, Yang NN, et al.** Measurement of sialic acid from lipoproteins and human plasma by liquid chromatography-tandem mass spectrometry. *Chin J Chromatogr.* 2014; 32: 1197–200.
30. **Low H, Hoang A, Sviridov D.** Cholesterol efflux assay. *J Vis Exp.* 2012; 61: 1–5.
31. **Muto E, Dell'Agli M, Sangiovanni E, et al.** Olive oil phenolic extract regulates interleukin-8 expression by transcriptional and posttranscriptional mechanisms in Caco-2 cells. *Mol Nutr Food Res.* 2015; 59: 1217–21.
32. **Chang YF, Chi CW, Wang JJ.** Reactive oxygen species production is involved in quercetin-induced apoptosis in human hepatoma cells. *Nutr Cancer.* 2006; 55: 201–9.
33. **Boesch-Saadatmandi C, Pospissil RT, Graeser AC, et al.** Effect of quercetin on paraoxonase 2 levels in Raw 264.7 macrophages and in human monocytes-role of quercetin metabolism. *Int J Mol Sci.* 2009; 10: 4168–77.
34. **Harrison D, Griendling KK, Landmesser U, et al.** Role of oxidative stress in atherosclerosis. *Am J Cardiol.* 2003; 91: 7A–11A.
35. **Pearson TA, Mensah GA, Wayne Alexander R, et al.** Markers of inflammation and cardiovascular disease: application to clinical and public health practice: a statement for healthcare professionals from the centers for disease control and prevention and the American heart association. *Circulation.* 2003; 107: 499–511.
36. **Finkel T.** Signal transduction by reactive oxygen species. *J Cell Biol.* 2011; 194: 7–15.
37. **Kim GH, Ryan JJ, Archer SL.** Antioxidant & redox signaling. April. 2013; 18: 1920–36.
38. **Madamanchi NR, Runge MS.** Redox signaling in cardiovascular health and disease. *Free Radic. Res.* 2014; 48: 3–11.
39. **Yang D, Liu X, Liu M, et al.** Protective effects of quercetin and taraxasterol against H2O2-induced human umbilical vein endothelial cell injury in vitrol. *Exp. Ther. Med.* 2015; 10: 1253–60.
40. **Noguchi S, Keira Y, Murayama K, et al.** Reduction of UDP-N-acetylglucosamine 2-Epimerase/N-acetylmannosamine kinase activity and sialylation in distal myopathy with rimmed vacuoles. *J Bio Chem.* 2004; 279: 11402–7.
41. **Bardor M, Nguyen DH, Diaz S, et al.** Mechanism of uptake and incorporation of the non-human sialic acid N-glycolylneuraminic acid into human cells. *J Bio Chem.* 2005; 280: 4228–37.
42. **Marmillot P, Rao MN, Liu QH, et al.** Desialylation of human apolipoprotein E decreases its binding to human high-density lipoprotein and its ability to deliver esterified cholesterol to the liver. *Metabolism.* 1999; 48: 1184–92.
43. **Khoo JC, Miller E, Mcloughlin P, et al.** Enhanced macrophage uptake of low density lipoprotein after self-aggregation. *Arteriosclerosis.* 1988; 8: 348–58.
44. **Iiyama K, Hajra L, Iiyama M, et al.** Patterns of vascular cell adhesion molecule 1 and intercellular adhesion molecule-1 expression in rabbit and mouse atherosclerotic lesions and at sites predisposed to lesion formation. *Circ Res.* 1999; 85: 199–207.
45. **Van Leeuwen M, Gijbels MJ, Duijvestijn A, et al.** Accumulation of myeloperoxidase-positive neutrophils in atherosclerotic lesions in LDLR<sup>-/-</sup> mice. *Arterioscler Thromb Vasc Biol.* 2008; 28: 84–9.
46. **Goedeke L, Fernández-Hernando C.** Regulation of cholesterol homeostasis. *Cell Mol Life Sci.* 2012; 69: 915–30.
47. **Maxfield FR, Tabas I.** Role of cholesterol and lipid organization in disease. *Nature.* 2005; 438: 612–21.
48. **Chang YC, Lee TS, Chiang AN.** Quercetin enhances ABCA1 expression and cholesterol efflux through a p38-dependent pathway in macrophages. *J Lipid Res.* 2012; 53: 1840–50.
49. **Guo SD, Tian H, Dong RR, et al.** Exogenous supplement of N-acetylneuraminic acid ameliorates atherosclerosis in apolipoprotein E-deficient mice. *Atherosclerosis.* 2016; 251: 183–91.