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 μM 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-α (TNF-α) and monocyte chemoattractant protein-1 (MCP-1), and it significantly reduced the expression of intercellular adhesion molecule-1, vascular cell adhesion molecule-1, TNF-α 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 asialo-glycoprotein 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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doi: 10.1111/jcmm.12943
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-acetylmuramic acid (the major form of sialic acid in mammalians) [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-acetylmuramic 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-acetylmuramic acid, quercetin, 3-(4,5-dimethyl-2-thiazoyl)-2,5-diphenyl-2-tetrazolium bromide (MTT), lipopolysaccharide (LPS), 2′,7′-dichlorofluorescin diacetate (DCFH-DA), fluorosecin-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-α (TNF-α) 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 chemotactant protein-1 (MCP-1), rabbit polyclonal antibody against ATP-binding cassette transporter (ABC) G1, mouse monoclonal antibody against ABCA1 and rabbit polyclonal antibody against monocyte chemoattractant protein-1 (MCP-1), mouse monoclonal antibody against ABCA1 and rat 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-α 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-α-D-galacto-2-nonulopyranoside) (4a)

Strong cation-exchange resin (Dowex-50W-X2) was added to a stirred solution of N-acetylmuramic 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 Ac2O 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, NaHCO3 and brine. The organic layer was dried over Na2SO4 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 CH2Cl2 (5.0 ml) at 20°C. After stirring for 12 hr at room temperature, the mixture was diluted with cold CH2Cl2 and subsequently washed with H2O, NaHCO3 and brine. The organic layer was dried over Na2SO4 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.

3,3′,4′,5-tetra-O-acetyl quercetin 7-O-(5-acetamido-4,7,8,9-tetra-O-acetyl-3,5-dideoxy-b-D-glycero-a-D-galacto-2-nonulopyranosonate) (8a)

K2CO3 was slowly added to a stirred mixture of 6 (300 mg, 0.59 mmol) and imidazole (8 mg, 0.12 mmol) in N,N-dimethyl-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 Na2SO4. The crude product was purified by column chromatography on silica gel to give 7 as a white solid.

Quercetin 7-O-(5-acetamido-3,5-dideoxyb-D-glycero-a-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 CH2Cl2 (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+ resin and then filtered. The organic phase was concentrated to give a residue, which was purified by a Sephadex LH-20 gel column (MeOH-H2O) to produce 9 (quercetin 7-O-sialic acid, QA) as a yellow powder.

Nuclear magnetic resonance (NMR) analysis

1H-NMR and 13C-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$_3$, and chemical shifts were expressed in ppm using acetone as internal standard at 2.225 ppm for $^1$H and 31.07 ppm for $^{13}$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$_4$ 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**

HUVECs or macrophages were seeded in a 96-well plate at a density of $1 \times 10^4$ cells per well. Cells were incubated with increasing concentrations of QA (0–75 μM), hydrogen peroxide (H$_2$O$_2$, 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$_2$O$_2$ 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$_2$O$_2$ 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, DCPIP-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$_2$ 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$_2$O$_2$ 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$_4$ 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 FITC 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$_4$ treatment but without H$_2$O$_2$ 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 μM H₂O₂ (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 H₂O₂ induction.

**Measurement of N-acetylenuraminic acid by LC-MS/MS**

N-acetylenuraminic acid analysis was performed by LC-MS/MS. This system was composed of a Shimazu LC-20AD binary pump, DGU-20A3 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 C18 column (3.5 μm, 2.1 mm i.d. × 100 mm) and a Waters C18 guard column (3.5 μm, 2.1 mm i.d. × 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 μl, 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 → 86.7 for N-acetylenuraminic 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 × 10⁵ cells per well. Six hours later, the culture medium was discarded and cells were gently washed with PBS three times. Then, 600 μl of DMEM containing 1% FBS and 1 μCi/ml [³H]-cholesterol were added to each well and incubated for another 48 hr. The medium containing [³H]-cholesterol was removed, and cells were gently washed with PBS three times. Cells were treated with 500 μl DMEM containing 1% FBS in the presence or absence of 50 μM QA dissolved in DMEM containing 1% FBS for 4 hr. Then, 0.5 ml of DMEM containing 1% FBS and 50 μg/ml LPS were added and incubated for another 3 hr [31]. TNF-α 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, HUVECs 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 μM QA for another 3 hr. TNF-α 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.

**ELISA assay**

HUVECs were seeded in six-well plates at a density of 4.0 × 10⁵ cells per well. After adherence, cells were further incubated in the presence or absence of 50 μM QA dissolved in DMEM containing 1% FBS for 4 hr. Then, 0.5 ml of DMEM containing 1% FBS and 50 μg/ml LPS were added and incubated for another 3 hr [31]. TNF-α or MCP-1 secreted into the medium was measured by an ELISA kit 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 β-actin.

**Data analysis**

All the bioassay results were expressed as mean ± 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-acetylenuraminic 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-α-glycero-α-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. 1H NMR (500 MHz, CDCl3): 1.98 (s, 3 H, OMe), 4.08 (dd, J = 2.9 Hz, 1 H, 8-H), 6.03 (d, J = 2.9 Hz, 1 H, 5″-H), 7.51-7.59 (m, 2 H, 2″-H).

**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 (HUVECs, EA.hy926) and Figure 5A and B (Raw 264.7 macrophages), QA exhibited no significant cytotoxicity compared with the control within the concentration range 0–75 μM. Quercetin concentrations higher than 50 μM 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 μM.

**Anti-oxidant activity**

Both H2O2 and ox-LDL were used to induce cellular oxidative models. To choose appropriate concentrations, the cytotoxicity of H2O2 or ox-LDL was evaluated by the MTT method. As shown in Figure 1C (and D), after 24 hr of exposure, the cytotoxicity of both H2O2 and ox-LDL was concentration-dependent. Cell viability of approximately 40% was set as representative of an oxidative damage model, and hence, 400 μM H2O2 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 H2O2 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 μM H2O2 or 100 mg/l ox-LDL was used in the following experiments. In the protective model, both H2O2 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 H2O2 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 H2O2 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 H2O2 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 H2O2-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.
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 μM H₂O₂ remarkably decreased the level of sialic acid on the cell surface (P < 0.01). Quercetin and especially QA protected sialic acid against H₂O₂-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 H₂O₂-induced desialylation. As shown in Figure 3(E and F), when exposed to 100 μM H₂O₂ 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, H₂O₂-induced desialylation was remarkably suppressed. The protective effect of QA was significantly higher compared with quercetin against H₂O₂-induced HDL desialylation (Fig. 3F, P < 0.05).
Anti-inflammatory activity

The inhibitory effects of QA on LPS-induced (50 μg/ml) TNF-α or MCP-1 production by HUVECs were evaluated by ELISA. Compared with the control, stimulation of HUVECs with LPS resulted in a fivefold increase in TNF-α and threefold increase in MCP-1. In the protective model, 50 μM QA or quercetin significantly attenuated the secretion of TNF-α or MCP-1 (Fig. 4A and B). The protein expression of TNF-α, 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-α, 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-α 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 [3H]-cholesterol efflux from Raw 264.7 macrophages (Fig. 5C and D, P < 0.01). Compared
with quercetin, QA showed a significantly increased effect at improving \([3H]-\text{cholesterol efflux}\) 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
concentration of 50 μM. However, both quercetin and QA showed no effect on the protein expression of SR-BI.

**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...
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 H2O2- 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-acetylgalactosamine, which could scavenge...
equimolar amounts of H\textsubscript{2}O\textsubscript{2} [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\textsubscript{2}O\textsubscript{2}-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\textsubscript{2}O\textsubscript{2}-induced HUVECs desialylation was significantly reduced under the action of QA compared with that of quercetin, which may be explained by the \textit{N}-acetylneuraminic acid (QA) of QA, which may attenuate equimolar amounts of ROS and incorporate into cells just as exogenous \textit{N}-acetylneuraminic acid [40, 41] under the action of sialytransferase. The results also demonstrated that QA exhibited an improved protective effect on H\textsubscript{2}O\textsubscript{2}-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 \textit{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-\textalpha 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 \textkappa 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-BI 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 \textit{N}-acetylneuraminic acid could improve RCT-related protein expression in apoE-deficient mice [49].

\section*{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 physiochemical 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\textsubscript{2}O\textsubscript{2} 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 \textit{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) \textit{N}-acetylneuraminic acid linked to QA may be incorporated into the cell under the action of sialytransferase; and (3) QA may be hydrolysed by neuraminidase, and then, \textit{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 sialytransferase 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-\textalpha and MCP-1 showed no significant difference compared with quercetin. A previous study demonstrated that the combination of quercetin and \textit{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 \textit{N}-acetylneuraminic acid did not accelerate but instead reduced inflammation to some extent in apoE-deficient mice provided a high-fat diet [49].

\section*{Perspective for clinical application of QA}

Based on the protective and therapeutic \textit{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-acetyleneuraminic 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.

### 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.

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