Research Article

Chitoheptaose Promotes Heart Rehabilitation in a Rat Myocarditis Model by Improving Antioxidant, Anti-Inflammatory, and Antiapoptotic Properties

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Background. Myocarditis is one of the important causes of dilated cardiomyopathy, cardiac morbidity, and mortality worldwide. Chitosan oligosaccharides (COS) may have anti-inflammatory and cardioprotective effects on myocarditis. However, the exact molecular mechanism for the effects of functional COS on myocarditis remains unclear. Methods. Anti-inflammatory activities of COS (chitobiose, chitotriose, chitotetraose, chitopentaose, chitoheptaose, and chitoctaose) were measured in lipopolysaccharide- (LPS-) stimulated RAW264.7 cells. A rat model with myocarditis was established and treated with chitopentaose, chitohexaose, chitoheptaose, and chitoctaose. Serum COS were measured by using high-performance liquid chromatography (HPLC) in all rats. Myocarditis injury, the levels of reactive oxygen species (ROS), reactive nitrogen species (RNS), inflammatory factors, and apoptotic factors were also measured. Pearson’s correlation coefficient test was used to explore the relationship between the levels of ROS/RNS and cardiac parameters. Results. Among all chitosan oligosaccharides, the COS > degrees of polymerization (DP) > 4 showed anti-inflammatory activities (the activity order was chitopentaose < chitohexaose < chitoheptaose < chitoctaose) by reducing the levels of interleukin- (IL-) 1β, IL-17A, and interferon- (IFN-) γ and increasing the level of IL-10. However, the serum level of chitoctaose was low whereas it showed significant therapeutic effects on myocarditis by improving cardiac parameters (left ventricular internal dimension in end diastole (LVIDd) and left ventricular internal diameter in end systole (LVIDs)). The levels of ROS/RNS had a strong relationship with cardiac parameters. Conclusions. Chitoheptaose plays a myriad of cardioprotective roles in the myocarditis model via its antioxidant, anti-inflammatory, and antiapoptotic activities.

1. Introduction

Myocarditis is an inflammation of the myocardium, which is one of the important causes of dilated cardiomyopathy [1] and cardiac morbidity and mortality worldwide [2]. The pro-inflammatory factors include the following: high-level interleukin- (IL-) 1β is associated with high myocarditis risk [3] and IL-1 receptor antagonist (IL-1ra) can prevent cardiac dysfunction [4]. Myocarditis involves many myocardial inflammatory diseases, such as acute myocarditis, chronic myocarditis, and inflammatory cardiomyopathies, and inflammatory diseases with cardiomyopathies [5]. Oxidative stress is also an important risk in the pathogenesis of myocarditis [6]. Inflammatory and oxidative stress can affect the left ventricular internal diameter in end diastole (LVIDd) and left ventricular internal diameter in end systole (LVIDs) [7].
The volume of the ejection fraction (EF) is often measured clinically to assess cardiac mechanics and function and significantly reduced in the progression of myocarditis [8]. The value of fractional shortening (FS) is widely used to assess left ventricular dysfunction and often decreases after myocarditis [9]. On the other hand, preserved EF [10] is associated with predominant inflammation and oxidant stress.

IL-17A is a CD4+ T cell-derived proinflammatory cytokine and plays an important role in the pathogenesis of myocarditis [11]. Interferon-γ (IFN-γ) is an important immune regulator in normal immunity and involved in the regulation of most immune and inflammatory responses. IL-10 is a type 2 cytokine, which inhibits proinflammatory cytokine formation. Lowering the IFN-γ level and increasing the IL-10 level will reduce the progression of myocarditis [12].

Reactive oxygen species (ROS) [13] and reactive nitrogen species (RNS) [14] are normally produced highly in myocarditis. Antioxidants can ameliorate cardiac apoptosis and dysfunction in an animal model with autoimmune myocarditis [15, 16]. From the above information, antioxidant and anti-inflammatory therapy has become a very important approach in preventing myocarditis progress.

Chitosan oligosaccharides (COS) are homo- or hetero-oligomers of N-acetylglucosamine and D-glucosamine and active and have more physiological functions than chitosan with solubility in water. COS exert cardiac protective effects on the patients with coronary heart disease (CHD) by improving antioxidant capacity [17]. COS also possess anti-inflammatory properties by activating mitogen-activated protein kinase (MAPK) signaling [18]. However, the effects of COS on myocarditis and which oligosaccharide of COS plays a more important functional role still remain unclear. Normally, long-chain oligosaccharides (degrees of polymerization (DP) > 5) may have an excellent function than short-chain ones [19]. The effects of COS with different DP on myocarditis were explored in a rat model.

2. Materials and Methods

2.1. Reagents. The standards of COS (chitobiose, chitotriose, chitotetraose, chitopentaose, chitoheptaose, and chitoctaose) were purchased from Qingdao BZ Oligo Biotech Co., Ltd. (Qingdao, China). Lipopolysaccharide (LPS, #L2880) was from Sigma (Sigma, Louis, MO, USA). RAW264.7 cells (an appropriate model of macrophages) were from Shanghai Institute of Cell Biology, CAS (Shanghai, China), and cultured in RPMI 1640 medium supplemented with 10% fetal bovine serum (Hyclone, Logan, UT, USA), 100 U/mL penicillin, and 100 mg/mL streptomycin at 37°C and 5% CO2.

2.2. Measurement of COS Anti-Inflammatory Activity. According to previous reports, RAW264.7 cells were seeded in 96-well plates at a density of 1 × 10^4 cells/well and incubated in the above medium with 100 μM different DP of COS (chitobiose, chitotriose, chitotetraose, chitopentaose, chitoheptaose, chitoheptaose, and chitoctaose) for 24 h and stimulated with LPS (200 ng/mL, 6 h). RAW264.7 cells were washed 3 times with cold PBS and centrifuged at 1,000 g for 10 min at 4°C. The cell pellet thus obtained was resuspended in 0.5 mL Tris buffer (20 mM, pH 7.5, 1 μg/mL chymostatin, 2 μg/mL of pepstatin A, 100 μM phenylmethylsulfonyl fluoride, and 5 μg/mL aprotinin). The cells were lysed by two freeze-thaw cycles [20]. The supernatants were collected via centrifugation at 15,000 g for 10 min at 4°C. The inflammatory production was measured by using the kits (mouse IL-1β ELISA Kit, ab100704; mouse IL-10 ELISA Kit, ab108870; mouse IL-17A ELISA Kit, ab100702; and mouse IFN-γ ELISA Kit, ab100689; Abcam, USA).

2.3. Establishment of the Experimental Autoimmune Myocarditis (EAM) Model. Before the present experiment, all procedures were approved by the animal research ethics committee of China-Japan Union Hospital of Jilin University (approval no. 2017CCZYY03017). Forty-eight 8-week-old specific pathogen-free (SPF) rats (200–220 g) were purchased from the animal center of Jilin University. Porcine cardiac myosin (PCM, Sigma Aldrich, M0531) was dissolved in 0.10 mol/L PBS solution (10 g/L). The solution was mixed with complete Freund’s adjuvant (CFA, Sigma Aldrich, F5881) in an equal volume of 1:1 to make it a homogeneous emulsion. On the first day and the eighth day, 200 μL of myosin (1 mg) was injected subcutaneously into the bilateral inguinal and axillary sites of the 40 rats. The control group (n = 8) was immunized with myosin-free PBS and CFA emulsion. From day 1, all rats were housed at a temperature of 23 ± 1°C in a 12 h/12 h daylight/dark cycle and allowed indicated food and water ad libitum.

2.4. Animal Grouping. After the establishment of an EAM model, the mice were orally treated with 100 μM different DP of COS (chitopentaose, chitoheptaose, chitoheptaose, and chitoctaose in saline solution) daily for one month. Forty-eight rats were evenly divided into the CG group (control), MG group (EAM model), PG group (chitopentaose-treated EAM model), HexG group (chitoheptaose-treated EAM model), HepG group (chitoheptaose-treated EAM model), and OG group (chitoctaose-treated EAM model) (Figure S1). The mice were treated with equal-volume saline solution in the CG and MG groups.

2.5. Echocardiography Analysis of Cardiac Parameters. After one-month intervention, all rats were anesthetized by intraperitoneal injection of 10% chloral (300 mg/kg). After depletion of the chest, echocardiography was performed on the left side of the supine position, and the experiments were performed in triplicate. Cardiac parameters were measured by echocardiography, including the left ventricular internal diameter in end diastole (LVIDd), left ventricular internal diameter in end systole (LVIDs), and ejection fraction (EF). Fractional shortening (FS) was calculated as ([LVIDd − LVIDs]/LVIDd) × 100.

2.6. HPLC Analysis of Serum COS. Theoretically, the larger size oligosaccharide will be more difficult to be absorbed into blood vessels. Therefore, it is necessary to measure the serum level of different DP of COS. After one-month COS
intervention, serum levels of COS were measured in all rats (Figure S1). One mL of blood was sampled from each rat tail in anticoagulant-free tubes and kept at room temperature for 1h before the serum was isolated (centrifugation at 1,500 g for 10 min at 22°C). Serum levels of COS were analyzed by using HPLC (Varian 920-LC, HPLC-DAD/UV system, Varian, Inc., Palo Alto, CA, USA) [21] according to COS standards (chitopentaose, chitoheptaose, and chitooctaose). The column was Metacarb 87H (300 x 7m m) and the flow rate was set at 0.6 mL/min, and the temperature was 80°C. A sample of 20 μL was injected into the HPLC.

2.7. Measurement of Serum Inflammatory Cytokines. After one-month COS intervention, serum inflammatory cytokines were measured (Figure S1) by using the kits (rat IL-1β ELISA Kit, ab100768; rat IL-10 ELISA Kit, ab214566; rat IL-17A ELISA Kit, ab119536; and rat IFN-γ ELISA Kit, ab239425; Abcam, USA).

2.8. Oxidative Stress Measurement. After one-month COS intervention, the oxidative stress levels were measured (Figure S1) by using reactive oxygen species (ROS) and reactive nitrogen species (RNS) via DCF DA and/or DAF-FM DA fluorescence. Cardiac tissues were digested into a single cell by trypsin. The single cells were resuspended in RPMI 1640 medium (Gibco) and adjusted to 1 x 10^6 cells/mL. After one-month COS intervention, the oxidative stress levels were measured (Figure S1) by using reactive oxygen species (ROS) and reactive nitrogen species (RNS) via DCF DA and/or DAF-FM DA fluorescence.

2.9. Analysis of Myocardial Histopathology. After one-month COS intervention, myocardial histopathology was analyzed (Figure S1). The rat chest was opened to expose the anterior cardiac region, and the heart was separated and removed. After being repeatedly washed with cold PBS on ice, the heart was cut longitudinally into two parts along the coronal plane, half of which was fixed in 10% formaldehyde solution for HE staining and immunohistochemistry, and the other part was stored at -80°C for subsequent analysis of the mRNA and protein expression of caspase 3, BAX, and BCL-2 (Figure S1). The myocardial tissue fixed in 10% formaldehyde solution was dehydrated with gradient ethanol and treated with xylene I/II,respectively, and then dipped in benzene/wax I/wax II and embedded in solid paraaffin. The tissue of each group of rats was subjected to hematoxylin-eosin (HE) staining and myocarditis injury, and inflammatory status was observed. H&E stain was scored to assess infiltration based on the following scale: 0 = normal myocardium, 1 = mild myocarditis (<5% cross section of infiltration), 2 = moderate myocarditis (5-10% cross section of infiltration), 3 = marked myocarditis (10-25% cross section of infiltration), and 4 = severe myocarditis (>25% cross section of infiltration).

Paraffin sections were baked for 2 h at 65°C; after dewaxing to water, sections were repaired, incubated, and sealed; primary antibodies (anti-BAX 1:1000, Abcam, ab32503; anti-BCL-2 1:1000, Abcam, ab59348; and 1:500 monoclonal rat anti-caspase 3 (sc-7148) and anti-β-actin (sc-47778), Santa Cruz Biotechnology) were incubated at 4°C overnight, and secondary antibodies (1:50,000 goat anti-rabbit HRP (ab6702, Abcam) in 3% BSA in TBS) were incubated at 37°C for 50 min. Meanwhile, the NC group (negative control group without primary antibody) and the PC group (positive control group with β-actin as a primary antibody) were detected in intestinal tissues. Freshly prepared DAB solution was added to develop the color. After the color development was complete and after counterstaining, differentiation, blue return, dehydramination, and drying, the xylene was transparent and the slides were sealed. Immunohistochemistry (IHC) was scored as follows: 0 (negative), 1 (weak brown), 2 (moderate brown), and 3 (strong brown).

2.10. Real-Time Quantitative RT-PCR. Ten mg heart tissue was ground into powder in liquid nitrogen, and RNA was extracted using RNase Mini Kit (Qiagen, Valencia, CA, USA). The RNA was treated with RQ1 RNase-Free DNase and reverse transcribed using the M-MLV reverse transcriptase (TaKaRa, Dalian, China). The following primers were used: caspase 3 (forward primer 5'-ATGCTTACTCTACCGACCCGG-3' and reverse primer 5'-GGTTAACAGCAGTGAGGATGTGCGC-3'), BAX (forward primer 5'-TGGACACAAAGACATGGGAG-3' and reverse primer 5'-AGCAAGTAGAAGAGGGCAACC-3'), BCL-2 (forward primer 5'-TTGGGCGCTTCTTTGAGTTGC-3' and reverse primer 5'-TTCAAGACACGCAGAGAAATC-3'), and β-actin (forward primer 5'-AGGTCATCACTATCGGCAA and reverse primer 5'-ACTCACTCATGGCAGAAG-3') as an internal control. qRT-PCR was performed in 96-well plates using the following parameters: 10 μL 2x SYBR Green PCR master mix, 0.5 μL forward primer (10 μM), 0.5 μL reverse primer (10 μM), 1 μL (10 ng) of diluted cDNA, and 8 μL ddH₂O. The qRT-PCR program was performed on a LightCycler 480 Real-Time PCR system (Roche, Basel, Switzerland): 94°C 20 s; 40 amplification cycles of 94°C 10 s and 60°C 45 s. qRT-PCR data were normalized to β-actin.

2.11. Western Blot. Ten mg heart tissues were ground into a fine powder using a mortar and pestle in liquid nitrogen. The ground powder was placed into the Qiagen TissueLyser II® for lysing (MD, USA). The mixture was centrifuged at 12,000 g for 10 min, and the supernatants were obtained for Western blot analysis. Total proteins were separated by 10% SDS-PAGE and transferred to the polyvinylidene difluoride (PVDF) membrane. The PVDF membrane was blocked with 5% nonfat milk in TBS-T buffer for 2 h, incubated with specific primary antibodies overnight at 4°C, washed with TBS-T, and incubated with peroxidase-conjugated antibodies. Protein bands were observed by using...
2.12. Statistical Analysis. The data were processed by SPSS17.0 software (SPSS Statistics, IBM, Armonk, NY, USA). The measurement data were expressed as mean ± S.D. and analyzed by using the t-test, and the count data were analyzed by the $\chi^2$ test. The Wilcoxon rank-sum test was used to evaluate grade data. One-way (with 1 independent variable) analysis of covariance (ANCOVA) was used to explore the response of the dependent variable among all groups. Pearson’s correlation coefficient test was used to explore the relationship between the levels of ROS/RNS and the values of cardiac parameters. The difference was statistically significant if $p < 0.05$.

3. Results

3.1. Anti-Inflammatory Effects of COS. The inflammatory analysis showed that chitobiose, chitotriose, and chitotetraose had almost no effects on the levels of inflammatory cytokines IL-1$\beta$ (Figure 1(a)), IL-10 (Figure 1(b)), IL-17A (Figure 1(c)), and IFN-$\gamma$ (Figure 1(d), $p > 0.05$) in LPS-stimulated RAW264.7 cells when compared with the control group. Among all chitosan oligosaccharides, the COS with more than degrees of polymerization (DP) 4 (a qualitative anti-inflammatory activity order, chitopentaose < chitoheptaose < chitohexaose < chitooctaose) showed anti-inflammatory activities by reducing the levels of interleukin- (IL-) 1$\beta$, IL-17A, and interferon- (IFN-) $\gamma$, and increasing the level of IL-10.
The results suggest that the anti-inflammatory activity is improved with the increase in the degrees of polymerization of COS.

3.2. HPLC Analysis of Serum COS Levels. HPLC analysis showed that the elution time of chitopentaose, chitohexaose, chitoheptaose, and chitooctaose was 9.3, 10.3, 12.1, and 23.1 min, respectively (Figure 2(a)). No serum COS were detected in the rats from the CG group (Figure 2(b)) and the MG group (Figure 2(c)), respectively. The serum level of chitopentaose was highest and chitooctaose was lowest, and the serum contents of chitopentaose (Figure 2(d)),

Figure 2: HPLC analysis of blood chitosan oligosaccharides. (a) Standard of chitosan oligosaccharides. (b) Control group. (c) Model group. (d) Chitopentaose. (e) Chitohexaose. (f) Chitoheptaose. (g) Chitooctaose.
chitohexaose (Figure 2(e)), chitohptaose (Figure 2(f)), and chitooctaose (Figure 2(g)) were 230, 110, 45, and 18 μchitohexaose (Figure 2(e)), chitoheptaose (Figure 2(f)), and chitooctaose (Figure 2(g)) were 230, 110, 45, and 18 μM in the PG, HexG, HepG, and OG groups, respectively. The results suggest that the COS with high degrees of polymerization become more difficult to be absorbed into blood vessels with the increase in the size of COS.

3.3. Chitoheptaose Improved Cardiac Function Better Than Other COS. After the model establishment, the values of LVIDd (Figure 3(a)) and LVIDs (Figure 3(b)) in the MG group were higher than those in the CG group whereas the percent of EF (Figure 3(c)) in the MG group was lower than that in the CG group. The results suggest the model establishment causes cardiac injury. Meanwhile, chitoheptaose showed significant therapeutic effects by reducing the values of LVIDd (Figure 3(a)) and LVIDs (Figure 3(b)) and increasing the percent of EF (Figure 3(c)) and FS (Figure 3(d)) when compared with other COS (p < 0.05).

3.4. Chitoheptaose Prevented Myocarditis Injury Better Than Other COS. H&E staining of the whole heart showed that the myocardium was thickest and the cells with light blue may be necrotic in the MG group when compared with other groups, and chitoheptaose showed significant inhibitory effects on the thickness of the myocardium and necrosis situation (Figure S2). H&E analysis showed that myocarditis injury was observed with damaged myomuscular fiber and abundant inflammatory cells in the MG group after the model establishment (Figure 4). COS intervention repaired the damage, prevented the injury in the HepG group, and reduced the amounts of inflammatory cells. Chitoheptaose showed significant therapeutic effects by reducing more pathological scores and inflammatory situation when compared with other COS (Figure 4, p < 0.05).

3.5. Chitoheptaose Showed Higher Anti-Inflammatory Effects Than Other COS. After the model establishment, the serum levels of IL-1β (Figure 5(a)), IL-17A (Figure 5(b)), and IFN-γ (Figure 5(c)) in the MG group were more than those in the CG group whereas the level of IL-10 (Figure 5(d)) in the MG group was lower than that in the CG group. The results suggest the model establishment causes inflammatory responses. Meanwhile, chitoheptaose showed significant anti-inflammatory properties by reducing the serum levels of IL-1β (Figure 5(a)), IL-17A (Figure 5(b)), and IFN-γ (Figure 5(c)) and increasing the level of EF (Figure 5(d)) when compared with other COS (p < 0.05).

3.6. Chitoheptaose Showed Higher Antioxidant Effects Than Other COS. After the model establishment, the levels of ROS (Figure 6(a)) and RNS (Figure 6(b)) in the MG group were higher than those in the CG group. The results suggest the model establishment increases the oxidative stress. Meanwhile, chitoheptaose showed significant antioxidant properties by reducing the levels of ROS (Figure 6(a)) and RNS (Figure 6(b)) when compared with other COS (p < 0.05).

3.7. Chitoheptaose Intervention Reduced More the Relative mRNA Level of Apoptotic Factors Than Other COS. After the model establishment, the relative mRNA levels of caspase 3 (Figure 7(a)) and BAX (Figure 7(b)) in the MG group were
Figure 4: H&E analysis of myocarditis injury. (a) Control group (CG). (b) Model group (MG). (c) Chitopentaose-treated group (PG). (d) Chitohexaose-treated group (HexG). (e) Chitoheptaose-treated group (HepG). (f) Chitooctaose-treated group (OG). A p < 0.05 vs. the CG group, B p < 0.05 vs. the MG group, C p < 0.05 vs. the PG group, D p < 0.05 vs. the HexG group, E p < 0.05 vs. the HepG group, and F p < 0.05 vs. the OG group. n = 8 for each group.

Figure 5: ELISA analysis of serum inflammatory factors. (a) Interleukin-1β (IL-1β). (b) IL-17A. (c) Interferon-γ (IFN-γ). (d) IL-10. A p < 0.05 vs. the CG group, B p < 0.05 vs. the MG group, C p < 0.05 vs. the PG group, D p < 0.05 vs. the HexG group, E p < 0.05 vs. the HepG group, and F p < 0.05 vs. the OG group. n = 8 for each group.
higher than those in the CG group whereas the level of BCL-2 (Figure 7(c)) in the MG group was lower than that in the CG group. The results suggest the model establishment causes the apoptotic responses. Meanwhile, chitoheptaose showed higher antiapoptotic properties by reducing the relative mRNA levels of caspase 3 (Figure 7(a)) and BAX (Figure 7(b)) and increasing the level of BCL-2 (Figure 7(c)) when compared with other COS ($p < 0.05$).

3.8. Chitoheptaose Intervention Reduced More the Relative Protein Level of Apoptotic Factors Than Other COS. For Western blot analysis, three samples were measured from each group. Figure 8 shows the Western blot analysis for sample 1 from each group. Supplementary Figure S3 shows the Western blot analysis of samples 2 and 3 from each group. After the model establishment, the relative protein levels of caspase 3 (Figure 8(a)) and BAX (Figure 8(b)) in the MG group were more than those in the CG group whereas the level of BCL-2 (Figure 8(c)) in the MG group was lower than that in the CG group. The results suggest the model establishment causes apoptotic responses. Meanwhile, chitoheptaose showed higher antiapoptotic properties by
reducing the relative protein levels of caspase 3 (Figure 8(a)) and BAX (Figure 8(b)) and increasing the level of BCL-2 (Figure 8(c)) when compared with other COS (\(p < 0.05\)).

3.9. Chitoheptaose Intervention Reduced the Expression of Apoptotic Factors More Than Other COS. IHC analysis showed that the IHC scores were lowest in the NC group and highest in the PC group, suggesting that the method was conducted successfully (Figure 9(a)). After the model establishment, the relative expression of caspase 3 (Figure 9(a)) and BAX (Figure 9(b)) in the MG group was higher than that in the CG group whereas the expression of BCL-2 (Figure 9(c)) in the MG group was lower than that in the CG group. The results suggest the model establishment causes apoptotic responses. Meanwhile, chitoheptaose showed significant antiapoptotic properties by reducing the relative expression of caspase 3 (Figure 9(a)) and BAX (Figure 9(b)) and increasing the level of BCL-2 (Figure 9(c)) in the MG group when compared with other COS (\(p < 0.05\)).

3.10. Oxidative Stress Levels Had a Strong Relationship with Cardiac Parameters. The correlation test showed that with the increase in the level of ROS, the levels of LVIDd (Figure 10(a)) and LVIDs (Figure 10(b)) were increased whereas the percent of EF (Figure 10(c)) and FS (Figure 10(d)) was reduced (\(p < 0.001\)). In a similar situation, with the increase in the level of RNS, the levels of LVIDd (Figure 10(e)) and LVIDs (Figure 10(f)) were increased whereas the percent of EF (Figure 10(g)) and FS (Figure 10(h)) was reduced (\(p < 0.001\)). The results suggest that oxidative stress levels have a strong relationship with cardiac parameters.

4. Discussion

The present findings demonstrated that COS improved cardiac function by increasing the antioxidant and anti-inflammatory capacities and reducing the apoptotic risk in a rat model with myocarditis. COS can exert better physiological function than chitosan with excellent water solubility. Theoretically, the COS with high degrees of polymerization will be with high bioactivity than the low-degree ones. Thus, different COS (chitobiose, chitotriose, chitotetraose, chitopentaose, chitohexaose, chitoheptaose, and chitooctaose) were explored by using the rat model with myocarditis. Just
as we supposed, chitobiose, chitotriose, and chitotetraose almost showed no anti-inflammatory activities on LPS inducing the release of inflammatory cytokines in RAW264.7 cells when compared with the control group. The COS exhibited anti-inflammatory effects when the DP were more than 4. Meanwhile, the anti-inflammatory activity reached the highest level in the chitooctaose group (Figure 1, p < 0.05). The results also suggest that the COS with low degrees of polymerization may have no functional activity with simple structure.

This study showed that cardiac parameters (LVIDd, LVIDs, EF, and FS) were improved significantly in the HepG group compared with the other groups (Figure 3). The results suggest that chitoheptaose shows higher therapeutic effects...
than chitoctaose according to the improvement of cardiac parameters although chitoctaose has higher anti-inflammatory activity than chitoheptaose. The reason may be that chitoctaose is more difficult than chitoheptaose to be absorbed into the blood vessels in the small intestine in the rat models because the former has the longer chain. Just as we proposed, the short-chain COS in serum reached the highest level in the PG group and the long-chain COS in serum reached the lowest level in the OG group (Figure 2).
On the other hand, apoptotic activity is generally following oxidative [22, 23] and inflammatory responses [24, 25]. Therefore, the effects of COS on the apoptotic activity were also investigated here. Just as the antioxidant and anti-inflammatory properties, the COS showed similar antiapoptotic activity in different COS. Chitoheptaose showed higher antiapoptotic properties than other COS (Figures 7–9). The results suggest that oxidative stress, inflammation, and apoptosis may affect each other.

The correlation test showed that the oxidative stress levels (ROS and RNS) had a strong relationship with the cardiac parameters. The results suggest that chitoheptaose may exert its cardioprotective function by affecting oxidative stress. Further work is highly needed to approve the central role for the correction among inflammatory, oxidative stress, and apoptotic activities in the pathogenesis of myocarditis. The results indicated that the COS with DP 7 exerted the highest antioxidant and anti-inflammatory activity in the animal model, which suggested that their activity had a close relationship with the degree of polymerization of COS. Larger oligosaccharides (chitohexaose and chitoheptaose) have the highest capability for scavenging DPPH [26]. Chitoheptaose has higher capability for scavenging ROS and RNS when compared with other COS and effectively scavenges ROS and RNS generated by electron leakage and protects cells against apoptosis induced by ROS and RNS. Chitoheptaose treatment showed the highest protective effects on the EAM model among the COS chitopentaose, chitoheptaose, chitoheptaose, and chitoocctoaose. The effects of chitopentaose and chitoocctoaose were minimal when compared with the EAM model only treated with saline solution (Figure 9). Larger COS become more potent, and the biological activity of COS is size-dependent. Chitoheptaose was most active compound as the COS with the DP > 4. However, much work is needed to explore the exact molecular mechanism.

There were some limitations in the present work. Only 4 cardiac parameters were investigated here, and the interaction of these parameters was too complex to be explored. The relationship between the levels of ROS and RNS and the values of the parameters of cardiac parameters was only analyzed by using Pearson’s correlation coefficient test and not demonstrated by the experiments. Thus, the mechanisms were examined by using an animal model with CHD via related gene overexpression or silence in future work. The effects of the interaction among different COS on heart therapy are very complex, and it is difficult to understand its exact functional molecular mechanism. The deep molecular mechanism should be explored in the subsequent experiment.

Data Availability

All data are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that there are no other nonfinancial competing interests.

Authors’ Contributions

QZ, LY, LZ, and DJ conceived and performed the present experiment and analyzed all final data; LL and HJ provided new techniques, analyzed all data, and wrote the paper; all authors agreed to the final submission of the present paper. Qini Zhao and Liquan Yin contributed equally to this work.

Supplementary Materials

Figure S1: the present study of the flow chart. Rat serum was used for the analysis of serum COS and serum inflammatory cytokines (ELISA analysis). Figure S2: H&E staining of heart disease among different groups. CG: control group; MG: model group; PG: chitopentaose-treated group; HexG: chitoheptaose-treated group. Figure S3: relative protein levels of apoptotic factors among different groups. Figure S4: ICH staining of apoptotic factor expression in heart tissues among different groups. (Supplementary Materials)

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