Biological Activities of 2,3,5,4′-Tetrahydroxystilbene-2-O-β-D-Glucoside in Antiaging and Antiaging-Related Disease Treatments

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1, Introduction

Aging is inevitable; it is a progressive, irreversible process that every human will experience in his life. The aging population of the international community brings increasing medical expenses and health care costs. Therefore, prevention and early treatment of aging-related diseases can be effective means of relieving society’s burden and living a better life for individuals. There are many theory researches of aging mechanisms. The most famous one is the oxidative stress theory. Free radicals and peroxides attack all components of cells, including proteins, lipids, RNA, and DNA. Oxidative damage occurs in various aging-associated disease pathologies, especially the cardiovascular diseases and neurological diseases. Theoretically, antioxidant supplementation should be able to reduce the risk of aging-related diseases. The Mediterranean diet with red wine, fruits, vegetables, and other plant foods has been shown to have cardiovascular protection against oxidative damage. At present, the extraction of biological antioxidants from plants is becoming one of the hot topics in the field of medical chemistry.

*Polygonum multiflorum* Thunb. (何首乌, *he-shou-wu*) (Figures 1(a) and 1(b)) is a traditional Chinese medicinal plant. As early as 973 A.D., it was incorporated into *Kaibao Bencao*, an encyclopedia of medical plants edited under an imperial edict of Song Taizu, the first emperor of the Song Dynasty. The plant is processed to produce *radix Polygoni Multiflori* preparata (Figure 1(c)), traditionally taken to increase vitality, improve the health of blood and blood vessels, blacken hair, strengthen bones, nourish the liver and kidney, and prolong life. Currently, *Polygonum multiflorum* Thunb. is listed in the *Chinese Pharmacopoeia*, and *radix Polygoni Multiflori* preparata is widely used for clinically treating of arteriosclerosis, hyperlipidemia, hypercholesterolemia, and diabetes. It is also used in many Chinese medicinal supplements to improve general health.

2,3,5,4′-Tetrahydroxystilbene-2-O-β-D-glucoside (THSG) (Figure 1(d)) is the main component of *Polygonum multiflorum* Thunb., which is used as a standard compound for appraising *Polygonum multiflorum* Thunb. in the *Chinese Pharmacopoeia* [1]. THSG belongs to polyhydroxystilbene group. The structure of THSG is similar to that of resveratrol (3,4′,5-Trihydroxy-trans-stilbene), which is quite well known for its numerous biological activities especially in cardiovascular protection. As a resveratrol analog with glucoside, THSG has been proved to possess strong antioxidant and free radical scavenging activities even much stronger than resveratrol in superoxide anion radical scavenging, hydroxyl...
radical scavenging, and DPPH radical scavenging [2]. It is because THSG has a 2-O-Glu group in chemical structure, in which C_5-OH and C_4-OH are more active to H-abstraction [3]. Furthermore, 2-O-Glu group can stabilize the phenoxy radical and they are easy to be hydrolyzed in extreme pH environments (in the gastrointestinal environment).

Contemporary pharmacological studies have demonstrated that THSG exhibits numerous biological functions in antiaging and antiaging-related disease treatments. In this review, we focus on THSG, discussing its biological effects and molecular mechanisms.

2. Delaying the Senescence Effect

A few years ago, we found that THSG can delay vascular senescence and markedly enhance blood flow in spontaneously hypertensive rats (SHRs), but it does not affect blood pressure or body weight [4]. The data revealed that senescence-associated β-galactosidase (SA-β-gal) staining, γH2AX phosphorylation, and p53 acetylation are suppressed by THSG in the aortic arches of SHRs. THSG promotes deacetylation of p53, a transcription factor associated with aging. THSG also induces endothelial nitric oxide synthase (eNOS) expression in the aortas and urinary mononitrogen oxide (NO_x) production. In vitro, THSG activates SIRT1 activity, stimulates eNOS promoter reporter gene activity, and ameliorates H_2O_2-induced human umbilical vein endothelial cell (HUVEC) senescence [4]. Our unpublished data show that in vivo THSG is more effective in delaying vascular senescence than resveratrol.

A recent study revealed that THSG prolongs the lifespan of senescence-accelerated prone mouse (SAMP8) by 17% and notably improves their memory. THSG also increases neural klotho protein level and reduces levels of the neural insulin, the insulin receptors, insulin-like growth factor-1 (IGF-1), and IGF-1 receptor in the brain of SAMP8 [5]. In a subsequent report, this research group again demonstrated that THSG improves memory, reduces levels of reactive oxygen species (ROS), nitric oxide (NO), and IGF-1, and increases protein levels of superoxide dismutase (SOD) and klotho in serum. Furthermore, THSG upregulates klotho protein expression in cerebrum, heart, kidney, testis, and epididymis tissues of D-galactose induced aging mice [6].
A German study reported that THSG exerted a DAF-16-independent antiaging effect in a Caenorhabditis elegans model [7]. THSG prolongs the mean, median, and maximum adult lifespans of C. elegans by 23.5%, 29.4%, and 7.2%, respectively, and increases the resistance of C. elegans to lethal thermal stress, comparable to the effects of resveratrol. THSG also exerts a higher antioxidative capacity in nematode compared with resveratrol and reduces the levels of the aging pigment lipofuscin.

3. Cardiovascular Protection

3.1. Atherosclerosis and Lipid Metabolism. An experimental investigation using New Zealand rabbits demonstrated that THSG reduces atherosclerotic plaque accumulation caused by a high cholesterol diet, and lower plasma cholesterol, low-density lipoprotein (LDL) cholesterol, very-low-density lipoprotein (VLDL) cholesterol, and triglyceride levels [8]. Moreover, THSG decreases secretion protein levels of the intercellular adhesion molecule-1 (ICAM-1) and the vascular endothelial growth factor (VEGF) in the U937 foam cell cultured medium [8]. Subsequent studies have reported that in rat aortic walls in high-cholesterol-fed rats THSG improves the serum lipid profile and suppresses serum C-reactive protein (CRP), IL-6 and TNF-α levels, and matrix metalloproteinase-2 (MMP-2), MMP-9 mRNA, and protein expressions [9]. THSG also restores the mRNA and protein expression of eNOS in the rat aorta and improves acetylcholine-induced endothelium-dependent relaxation [10]. THSG exhibited antioxidant properties and protected against apoptosis in a lysophosphatidylcholine- (LPC-) induced endothelial cell injury model [11]. THSG suppresses intracellular ROS and malondialdehyde (MDA) and restores SOD and glutathione peroxidase (GSH-Px) levels. THSG apparently reversed the loss of mitochondrial membrane potential, the activation of caspase-3 and poly(ADP-ribose) polymerase 1 (PARP-1), the decrease of Bcl-2, the upregulation of Bax, and the release of cytochrome C in LPC-stimulated HUVECs [11].

Ten years ago, a Japanese group found that THSG does not affect the food intake, growth, or blood pressure of SHRs, consistent with our data [4, 12], but significantly reduces free fatty acid content in serum. THSG significantly reduces cholesterol and neutral lipid content in the VLDL fraction and neutral lipid content in the high-density lipoprotein (HDL) fraction in the blood, as well as neutral lipid content in the liver [12]. Another study reported that THSG administration to rats for 1 week can effectively control serum levels of total cholesterol and LDL cholesterol. The expression of LDL receptors in the liver was significantly upregulated in a high-fat-fed rat model [13]. Furthermore, in vitro experiments revealed a downregulation effect of THSG on 3-hydroxy-3-methylglutaryl-coenzyme A (HMG-CoA) reductase and an upregulation effect on cholesterol 7 alpha-hydroxylase (CYP7A) in human steatosis L02 cells. THSG enhanced downregulation activities in TC, LDL cholesterol, and VLDL contents and increased activity in HDL cholesterol [14].

3.2. Vascular Remodeling and Fibrosis. In vitro, THSG prevents the proliferation of vascular smooth muscle cells (VSMCs) and blocks the G1/S phase progression of the cell cycle in platelet-derived growth factor-BB- (PDGF-BB-) or angiotensin II-induced VSMCs [15, 16]. THSG inhibits the phosphorylation of Rb and extracellular signal-regulated kinase 1/2 (ERK1/2); it also inhibits the expressions of cyclin D1, cyclin-dependent kinase-4 (CDK4), CDK2, cyclin E, the proliferating cell nuclear antigen (PCNA) in PDGF-BB-induced VSMCs [15], phosphorylated ERK1/2, MEK1/2, Src, c-fos, c-jun, and c-myc mRNA in angiotensin II-induced VSMCs [16]. In vivo, THSG inhibits neointimal hyperplasia in a rat carotid arterial balloon injury model [17], and the ratio of intima-to-media was significantly reduced, and the expressions of PCNA, α-smooth muscle actin (α-SMA), and PDGF-BB were suppressed. Moreover, signaling pathways associated with smooth muscle cell proliferation, migration, and inflammation were inhibited, in addition to the activation of AKT, ERK1/2, and nuclear factor κB (NF-κB) and the expressions of c-myc, c-fos, c-jun, MMP-2, MMP-9, and collagens I and III [17]. Our recent study reported that orally administering THSG for 14 weeks significantly inhibited vascular remodeling and fibrosis in SHRs with increasing blood flow and with constant blood pressure [18]. THSG reduces intima-media thickness in the aortic arch of SHRs, increases the vascular diastolic rate in response to acetylcholine, and reduces remodeling and fibrosis-related mRNA expression, such as that of genes ACTA2, CCL3, COLIA2, COL3A1, TIMP1, WISP2, IGFBPI, ECE1, KLF5, MYL1, BMP4, FNI, and the plasminogen activator inhibitor-1 (PAI-1). THSG inhibits the acetylation of Smad3 and prevents Smad3 binding to the PAI-1 proximal promoter in SHR aortas [18].

3.3. Heart. THSG improves cardiac ischemia-reperfusion, cardiac remodeling, and cardiac stem cells. The infarct size, ST segment recovery, and incidence of arrhythmia in the THSG postconditioning group are all significantly improved compared with the control group [19]. THSG has also been shown to promote myocardial biogenesis and induce the expression of erythropoietin (EPO) in nonhematopoietic cells, including primary cardiomyocytes, and enhance EPO–EPO receptor autocrine activity. THSG robustly increases the endurance performance activity of healthy and doxorubicin-induced cardiomyopathic mice in ischemic disorders, stimulates myocardial mitochondrial biogenesis, and improves cardiac function [20].

In cardiac remodeling, THSG can attenuate pressure overload-induced cardiac pathological changes. Such pathological changes include increases in heart weight/body weight and left ventricular weight/body weight ratios, increased myocyte cross-sectional areas and left ventricular posterior wall, hypertrophic ventricular septum, and accumulation of myocardial interstitial perivascular collagen, as well as elevated cardiac hydroxyproline content [21]. Furthermore, THSG significantly reduces myocardium angiotensin II, enhances the activities of SOD and GSH-Px in serum and myocardial tissue, and inhibits the protein expression of transforming growth factor beta 1 (TGF-β1) and the phosphorylation of ERK1/2 and p38 MAP kinase in myocardial
tissue [22]. However, THSG treatment increases the percentage of the S-phase in sorted c-kit(+) rat cardiac stem cells and promotes expressions of PCNA, VEGF, the T-box transcription factor, hyperpolarization-activated cyclic nucleotide-gated 2 (HCN2), HCN4, the α myosin heavy chain, β myosin heavy chain mRNA, stem cell antigen 1, cardiac troponin-I, GATA-4, Nkx2.5, and connexin 43 protein [22].

3.4. Platelets. In vitro, THSG treatment inhibits adenosine diphosphate- (ADP-) or thrombin-induced platelet aggregation dose-dependently. THSG does not affect intracellular calcium ion dynamics at rest; however, in the ADP or thrombin stimulation, THSG reduces dose-dependently the rise in intracellular calcium flow [23]. Another study demonstrated that THSG prevents dose-dependently collagen-induced platelet aggregation and ATP secretion [24]. THSG also inhibits platelet P-selectin expression, glycoprotein IIb-IIIa binding, and platelet spreading on immobilized fibrinogen, as well as Fc receptor FcγRIIA, Akt (Ser473), and GSK3β (Ser9) phosphorylations [24].

4. Neuroprotective Effects

4.1. Learning and Memory. In β-amyloid peptide-induced dementia mice, ischemia-reperfusion gerbils, and D-galactose induced dementia mouse models, oral administration of THSG for dementia prevention or treatment improves learning and memory function in Morris water maze tests. THSG significantly decreases MDA level and monoamine oxidase B activity in the Morris water maze tests. THSG significantly decreases the percentage of apoptotic hippocampal neurons, and facilitates high-frequency stimulation-induced hippocampal long-term potentiation (LTP) in a bell-shaped manner. The facilitation of LTP induction by THSG required calcium/calmodulin-dependent protein kinase II and ERK activation [28]. In vivo, THSG treatment also restores memory impairment, as assessed using the passive avoidance test, in models for sleep-deprived mice, amyloid-β-injected aging mice, and kainic acid-injected brain-damage mice. Concurrently, THSG induces expressions of erythropoietin, PPAR-γ coactivator 1α (PGC-1α), and hemoglobin in astrocytes and PC12 neuronal-like cells and in the hippocampus of mice [29].

4.2. Neuroinflammation. Neuroinflammation is closely implicated in the pathogenesis of neurological diseases. Thus, the inhibition of microglial inflammation may have potential therapeutic significance for neurological diseases. Researchers have used a microglia BV2 cell line as a model to investigate the antineuroinflammatory effects of THSG, finding that THSG reduced the LPS-induced microglia-derived release of proinflammatory factors such as TNF-α, IL-1β, IL-6, and NO and attenuated LPS-induced nicotinamide adenine dinucleotide phosphate oxidase activation and subsequent ROS production [30, 31]. THSG failed to suppress IκB-α degradation, NF-κB phosphorylation and nuclear translocation, and ERK1/2, JNK, and p38 phosphorylation. However, THSG markedly reduced the binding of NF-κB to its DNA element in the iNOS promoter [31]. Moreover, THSG stimulates the secretion of the glial cell-line derived neurotrophic factor and the secretion of brain-derived neurotrophic factor and NGF in cultured rat primary astroglial cells, by activating the ERK1/2 pathway [32].

4.3. Alzheimer and Parkinson Diseases. In chronic aluminum exposure or amyloid-β(1–42)-injected rat models, THSG protects dopaminergic neurons from degradation in substantia nigra tyrosine hydroxylase-positive cells, enhances striatal dopaminergic transporter protein levels, and increases striatal Akt and GSK3β phosphorylation and the upregulation of the Bcl-2/BAD ratio. Furthermore, in the pole test, THSG reduces the times required to turn the body and climbing down to the floor [36]. In vitro, THSG protects PC12 cells and SH-SY5Y cells against MPP+-induced neurotoxicity. The antiapoptotic effects of THSG were probably mediated through the inhibition of ROS generation and modulation of JNK activation [37, 38], involving activation of PI3K-Akt pathway [39].

4.4. Cerebral Ischemia. Previous studies have shown that THSG significantly decreases the percentage of apoptotic cells in injured rat brain tissue induced by ischemia reperfusion, promotes Bcl-2, and inhibits Bax protein expression in brain tissue [40]. THSG also promotes changes in animal nerve behavior; improves neurological function scores; increases the expression of NGF, growth-associated protein 43, and PKA catalytic subunit proteins; and presents a positive correlation between neurological function scores and determined protein expression [41]. In the middle cerebral artery occlusion (MCAO) models, THSG significantly reduces the brain infarct volume and the number of apoptosis cells in the cerebral cortex according to a TUNEL assay [42]. Furthermore, the authors used an in vitro ischemic model of oxygen-glucose deprivation followed by reperfusion (OGD-R), revealing that THSG reverses intracellular ROS generation and mitochondrial membrane potential dissipation and inhibits c-Jun N-terminal kinase (JNK) and Bcl-2 family-related apoptotic signaling pathway. Concurrently, THSG prevents the expression of iNOS induced by OGD-R through the activation of SIRT1 and inhibition of NF-κB [42].
5. Diabetes and Other Diseases

5.1. Diabetes. The beneficial effects of THSG in alleviating diabetic complications are reflected in diabetic nephropathy and gastrointestinal disorders. Treatment with THSG reduces the increase in total cholesterol and triglyceride levels of diabetic rats [43]. Treatment with THSG also significantly reduces blood urea nitrogen, creatinine, 24 hours urinary protein levels, the ratio of kidney weight/body weight, and MDA and markedly increases the activities of SOD and GSH-Px in diabetic rats. Furthermore, THSG inhibits diabetic complications are reflected in diabetic nephropathy [43]. For disorders of gastrointestinal function in diabetes, long-term preventive treatment with THSG reduces delayed gastric emptying and increases intestinal transit, impaired nonadrenergic-noncholinergic relaxations, and deficiency of neuronal NO synthase expression in streptozotocin-induced diabetic mice. Moreover, THSG prevented significant decreases in PPAR-γ and SIRT1 expression in diabetic ileum [44].

5.2. Bone Mineral Density. Recently, a study reported that THSG promotes bone mineral density and bone strength in the femoral bones of rats and enhances the bone mineral weight and bone mineral size in the iliac and humeral section after 90 days of administration [45]. Another report described in greater detail how in vitro THSG significantly enhances the cell survival, alkaline phosphatase (ALP) activity, and calcium deposition in H₂O₂-injured osteoblastic MC3T3-E1 cells. THSG enhances mRNA expressions of ALP, collagen 1, and osteocalcin but weakens the receptor activator of nuclear factor-κB ligand and IL-6, as well as intracellular ROS and MDA production [46].

5.3. Hair Growth. A report indicated that a THSG fed group had significantly more hair growth compared with the control group, and that THSG accelerated the growth rate of early hair in C57BL/6J mice. In vitro, THSG also promoted hair growth in the cultured tentacles follicles of mice, with longer hair than that in the control group after 8 days [47]. Another report indicated that in vitro THSG increased the proliferation of dermal papilla cells of mice compared with the control group [48]. In addition, THSG promoted tyrosinase activity and melanin biosynthesis dose-dependently [49, 50].

6. Summary

Although THSG has been found to exhibit many medicinal properties, because no systematic study has investigated its regulatory mechanisms and proteomics or genomics data, its functional targets remain unclear. Nevertheless, we summed up the signal transduction pathways that are regulated by THSG, shown in Figure 2, which presents multipathway multitarget characteristics that block and activate different signaling and gene expression. In all the animal experiments in this study, the rats and mice were the main models (Table 1). However, the experiments involving the genetic model and the specific gene knockout model were used less. Most experimental drug dosages of THSG are between 20 and 120 mg/kg, with some individual extreme doses of 300 mg/kg or more. In most studies, THSG has been administered daily by oral gavage, but in some cases it has been delivered intraperitoneal injection. The pharmacologic activity of THSH in low concentration in cellular studies is summarized in this review (Table 2). Dosages of THSG in vitro are normally between 0.1 and 100 μmol/L, whilst in some dosages the concentration will reach a maximum of 300 μmol/L. Then the high concentration of THSG may play a role in toxicological effects instead of activation effects. Because of this, clinical value may be restricted. From the perspective of drug effects, THSG achieves favorable results in delaying senescence and in treating...
| Classification | Diseases | Animals | Sex | Induction | Treatment | Duration | Dosage | Administration | Evaluation | Reference number |
|----------------|----------|---------|-----|-----------|-----------|----------|--------|----------------|------------|-----------------|
| Antiaging | Antiaging | SHR rats | Male | Genotype | Posttreatment | 14 weeks | 50 mg/kg | Oral gavage daily | SA-β-gal stain; blood flow assay; p53 and phospho-H2AX determination | [4] |
| | Senescence | SAMP8 mice | Male | Genotype | Posttreatment | 30 days | 2, 20, or 50 µM | Water ad libitum | SA-β-gal stain; Morris water maze assay; lifespan assays | [5] |
| | Senescence | Kunming mice | Male | D-galactose | Posttreatment | 4 weeks | 42, 84, or 168 mg/kg | Oral gavage daily | Klotho expression in cerebrum, heart, kidney, testis, and epididymis tissues | [6] |
| | Longevity | C. elegans | Male/female | Genotype | Posttreatment | 10 hours | 50 or 100 µM | Culture liquid | Dermal layer thickness determination | [7] |
| | Dermal thinning | Kunming mice | Male | Natural aging | Posttreatment | 8 weeks | 18 mg/kg | Oral gavage daily | Dermal layer thickness determination | [5] |
| | Atherosclerosis | NZW rabbits | Male | High cholesterol diet | Posttreatment | 12 weeks | 25, 50, or 100 mg/kg | Oral gavage daily | Atherosclerotic plaque area; plasma cholesterol; LDL cholesterol; VLDL cholesterol; plasma triglyceride. | [8] |
| | Vascular dysfunction | SD rats | Male | Atherogenic-Diet | Posttreatment | 12 weeks | 30, 60, or 120 mg/kg | Oral gavage daily | Atherosclerotic plaque area; plasma cholesterol; LDL cholesterol; VLDL cholesterol; plasma triglyceride. | [9,10] |
| | | Wistar rats | Male | Occluding left anterior descending coronary artery | Pretreatment | 10 min before reperfusion | 75 mg/kg | Intravenous injection | ST segment recovery; myocardial infarct size | [16] |
| | | C57BL/6J mice | Male | Doxorubicin-induced cardiomyopathy | Posttreatment | 1 week | 10, 30, or 90 mg/kg | Ad libitum | Myocardial mitochondrial biogenesis, improving cardiac function; EPO expression | [17] |
| | Myocardial ischemia | SD rats | Male | Carotid arterial balloon injury | Posttreatment | 2 weeks | 30, 60, or 120 mg/kg | Oral gavage daily | Carotid neointimal formation; PCNA, a-SMA, PDGF-BB gene expression; VSMCs proliferation and migration. | [14] |
| | Cardiovascular organ remodeling | SHR rats | Male | Genotype | Posttreatment | 14 weeks | 50 mg/kg | Oral gavage daily | Intima-media thickness in the aorta, remodeling-related mRNa expressions, and effect on Smad3 deacetylating Heart weight and left ventricular weight indexes, MMPs, TIMPs, collagen, TGF-β1 protein, ERK1/2, JNK, and p38 activation | [15] |
| | Cardiovascular organ remodeling | SD rats | Male | Pressure-overloaded rats induced by abdominal aortic banding | Posttreatment | 30 days | 30, 60, or 120 mg/kg | Oral gavage daily | Intima-media thickness in the aorta, remodeling-related mRNa expressions, and effect on Smad3 deacetylating Heart weight and left ventricular weight indexes, MMPs, TIMPs, collagen, TGF-β1 protein, ERK1/2, JNK, and p38 activation | [18] |
### Table 1: Continued.

| Classification                  | Diseases                                      | Animals | Sex   | Induction                      | Treatment | Duration | Dosage | Administration | Evaluation                                                                                     | Reference number |
|--------------------------------|-----------------------------------------------|---------|-------|--------------------------------|-----------|----------|--------|----------------|---------------------------------------------------------------------------------------------|------------------|
| Lipid metabolism              | Serum cholesterol                             | SHR rats| Male  | Genotype                       | Posttreatment | 4 weeks  | 0.15% THSG in rodent chow | Ad libitum         | Cholesterol and neutral lipid content VLDL and HDL fraction Serum TC, TG, LDL- and HDL-cholesterol levels, and LDL receptor mRNA expression | [20]             |
|                               | Serum cholesterol                             | SD rats | Male  | 20% lard, 10% cholesterol, and 0.2% propylthiouracil | Posttreatment | 1 week   | 90,180 mg/kg | Oral gavage daily | Serum TC, TG, LDL- and HDL-cholesterol levels, and LDL receptor mRNA expression | [21]             |
|                               | β-amyloid peptide- or D-galactose-induced dementia | BALB/c mice | Female | Intracranial injection of 3 μL β-amyloid1–40 or subcutaneous injection of 50 mg/kg D-galactose for 60 days | Posttreatment | 60 days | 33, 100, or 300 mg/kg | Oral gavage daily | Morris water maze assay; passive avoidance test; MAO-B activity in the cerebral cortex; NGF and NT-3 expression in hippocampal CA1 region | [25, 26]         |
|                               | Ischemia-reperfusion                          | Gerbils | Male  | Ischemia-reperfusion            | Posttreatment | 7 days   | 1.5, 3, or 6 mg/kg | Intrapertoneal injection | Morris water maze test |                                                                  | [27]             |
|                               | Stress; aging; brain damage                   | C57BL/6J mice | Male  | Amyloid β- injected; kainic acid-injected brain damage | Posttreatment | 3 days; 17 days and 24 days; 2 weeks | 50, 100, or 200 mg/kg | Ad libitum | Passive avoidance task; erythropoietin, PGC-1α, and haemoglobin expression | [29]             |
| Alzheimer's disease           | SD rats                                       | Male    | Chronic aluminum exposure | Posttreatment | 1, 3, or 5 months | 4 g/kg | Oral gavage daily | Passive avoidance task or Morris water maze tests; APP |                                                                    | [33]             |
| Alzheimer's disease           | SD rats                                       | Male    | Amyloid-β(1–42)- injected | Posttreatment | 4 weeks | 25 mg/kg | Oral gavage daily | Passive avoidance task or Morris water maze tests; APP |                                                                    | [34]             |
| Alzheimer's disease           | APP Tg mice                                   | Male    | APPV717I Tg mice | Posttreatment | 6 months | 120 or 240 µmol/kg/d | Oral gavage daily | α-synuclein expression and aggregation in the hippocampus; Pole test; tyrosine hydroxylase-positive neurons in the substantia nigral compacts | [35]             |
| Parkinson's disease           | C57BL/6 mice                                  | Male    | MPP +-induced damage | Posttreatment | 14 days | 20 or 40 mg/kg | Oral gavage daily | Passive avoidance task or Morris water maze tests; APP |                                                                    | [36]             |
| Classification | Diseases | Animals | Sex | Induction | Treatment | Duration | Dosage | Administration | Evaluation | Reference number |
|---------------|----------|---------|-----|-----------|-----------|----------|-------|----------------|------------|------------------|
| Cerebral ischemia | Cerebral ischemia | SD rats | Male | Middle cerebral artery occlusion | Posttreatment | 7 days prior to surgery | 30, 60, or 120 mg/kg | Oral gavage daily | Percentage of apoptotic cells in injured rat brain tissue; Bcl-2 and Bax protein expression in brain tissue | [40] |
| Cerebral ischemia | Cerebral ischemia | SD rats | Male | Middle cerebral artery occlusion | Posttreatment | 7 days prior to surgery | 60 or 120 mg/kg | Oral gavage daily | Animal’s nerve behavior and neurological function score; expression of NGF, GAP-43, and PKA catalytic subunit proteins. The brain infarct volume and the number of positive cells | [41] |
| Cerebral ischemia | Cerebral ischemia | Mice | Male | Middle cerebral artery occlusion | Posttreatment | At the onset of reperfusion | 15 or 40 mg/kg | Intraperitoneal administration | | [42] |
| Diabetes | Diabetic nephropathy | SD rats | Male | 60 mg/kg streptozotocin intraperitoneal injection | Posttreatment | 8 weeks | 10 or 20 mg/kg | Treatment with TSG | Blood urea nitrogen, creatinine, 24 h urinary protein, ratio of kidney weight/body weight, SOD and GSH-Px activities, and TGF-β1 and COX-2 expression. | [43] |
| Diabetes | Diabetic gastrointestinal dysmotility | Kunming mice | Male | 150 mg/kg streptozotocin intraperitoneal injection | Posttreatment | 8 weeks | 10, 30, or 60 mg/kg | Oral gavage daily | Gastric emptying, intestinal transit, and NANC relaxations | [44] |
| Bone | Bone mineral density and bone strength | SD rats | Male and female | Natural development (110 ± 10 g) | Posttreatment | 90 days | 150, 300, or 600 mg/kg | Oral gavage daily | Bone mineral density and bone strength; bone mineral weight and bone mineral size | [45] |
| Hair | Hair growth | C57BL/6j mice | Female | Natural development (20–26 g) | Posttreatment | 9,18 days | 50,100, or 150 mg/kg | Oral gavage daily | Hair follicles and capillary growth | [47] |
| Classification          | Model                                      | Cell types                          | Induction                  | THSG concentration | Potential targets or/and pathway                                                                 | Reference number |
|-------------------------|--------------------------------------------|--------------------------------------|----------------------------|---------------------|-----------------------------------------------------------------------------------------------|------------------|
| Antioxidation           | ROS accumulation                           | 3T3 cells; MCF-7                     | Doxorubicin on MCF-7       | 60, 120, 180, and 240 µmol/L | SOD; ROS; MitoSOX                                                                                      | [52]             |
|                         | Apoptosis; ROS accumulation                | Human umbilical vein endothelial cells (HUVECs) | Lysophosphatidylcholine (LPC) | 0.1, 1, and 10 µmol/L | Caspase-3, Bcl-2, PARP-1, Bax, cytochrome C, SOD, glutathione peroxidase, and MDA                        | [14]             |
| Cardiovascular protection| VSMCs migration                            | Vascular smooth muscle cells (VSMCs) | Tumor necrosis factor α (TNF-α) | 0.1–100 µmol/L | Vimentin, TGFβ1, TGFβR1, and Smad2/3                                                              | [53]             |
|                         | Endothelial dysfunction                    | HUVECs                              | TNF-α                      | 1, 10, 25, 50, and 100 µmol/L | Vimentin, TGFβ1 signaling, TGFβ1, phosphorylation of Smad2 and Smad3, and nuclear translocation of Smad4 | [54]             |
|                         |                                          |                                      |                            |                     | Apoptosis pathway; ROS generation; mitochondrial membrane potential loss; intracellular [Ca²⁺]   | [55]             |
|                         | Cardioprotection                           | Primary rat cardiomyocytes           | Doxorubicin                | 10–300 µmol/L       | Vimentin, ICAM-1, VCAM-1, TGFβ1, phosphorylation of Smad2 and Smad3, and nuclear translocation of Smad4 | [56]             |
|                         | Endothelial dysfunction                    | HUVECs                              | Oxidized low-density lipoprotein (oxLDL) | 1, 10, 25, 50, and 100 µmol/L | Apoptosis pathway; ROS generation; mitochondrial membrane potential loss; intracellular ROS; Src; MEK2; ERF1/2-ERF1/2 signal pathway | [57]             |
|                         | VSMCs proliferation                        | VSMCs                               | Angiotensin II (Ang II)    | 1, 10, 25, 50, and 100 µmol/L | ROS-extracellular signal-regulated kinase 1/2 pathway; ERK1/2 activation; MMP-2; MMP-9, MEK      | [16]             |
|                         | Cardiac fibroblast proliferation           | Primary rat cardiac fibroblast       | Ang II; hydrogen peroxide  | 3–100 µmol/L; 30 µmol/L | ICAM-1; VCAM-1                                                                                     | [58]             |
|                         | Endothelial dysfunction                    | 937 cells                           | Ox-LDL                    | 30, 60, and 120 µg/L | NO-cGMP/PKG pathway                                                                                 | [59]             |
|                         | VSMCs proliferation                        | VSMCs                               | Platelet-derived growth factor (PDGF)-BB | 0.1, 1, 10, and 100 µmol/L | ERK1/2                                                                                              | [15]             |
|                         | VSMCs proliferation; oxidation of lipoprotein | VSMCs                           | PDGF-BB                   | 1–50 µmol/L         | Oxidation of lipoprotein, proliferation, and decrease of NO content                                | [60]             |
|                         | Inflammation                              | Porcine coronary arterial smooth cells (CASMCs) | LDL, VLDL, ox-LDL, and ox-VLDL | 0.1–100 µmol/L | COX-2                                                                                              | [61]             |
|                         | Endothelial dysfunction                    | RAW 264.7 macrophage cells           | Lipopolysaccharide (LPS)   | 1, 10, and 100 µmol/L | Vascular endothelial growth factor (VEGF)                                                            | [62]             |
|                         | Cardiovascular protection                  | ECV 304                             | LPC                       | 10 µmol/L          | Vascular endothelial growth factor (VEGF)                                                            | [63]             |
|                         | Cardiac stem cells (CSCs) proliferation    | Rat CSCs                            | —                         | 1, 10, and 100 µmol/L | Vascular endothelial growth factor (VEGF)                                                            | [64]             |
|                         | Normal cells                               | Primary hepatocytes; primary cardiomyocytes; C2C12 myoblasts | —                          | 0.5, 6, 25, and 100 µmol/L | EPO-EPOR; mitochondrial activity and Hb production                                                  | [20]             |
**Classification** | **Model** | **Cell types** | **Induction** | **THSG concentration** | **Potential targets or/and pathway** | **Reference number**
--- | --- | --- | --- | --- | --- | ---
**Lipid metabolism** | Steatosis hepatic L02 cell | Steatosis hepatic L02 cell | — | 50,100, and 300 μmol/L | HMG-CoA reductase; DGAT1; CYP7A; lipolysis | [12]
Learning and memory | — | Astrocytes; PC12 cells | — | 0.4, 2, and 10 μg/mL | Erythropoietin; PPAR-y coactivator 1α (PGC-1α); haemoglobin-β | [29]
Neurotoxicity | Rat hippocampal neurons | Staurosporine | 200 μmol/L | PI3K/Akt signaling; mitochondrial apoptotic pathways | [63]
Neuroinflammation | Mouse microglial BV2 cell lines | LPS | 20–80 μmol/L | NF-κB signaling pathway; ROS production and NADPH oxidase activation | [30]
| Human dopaminergic SH-SY5Y cells | 1-Methyl-4-phenylpyridinium (MPP+) | 3.125, 6.25, 12.5, 25, and 50 μmol/L | ROS; mitochondrial membrane potential; the ratio of Bax to Bcl-2; caspase-3; apoptosis | [38]
Cell model of Parkinson's disease | — | PC12 cells | — | 1.5 μmol/L | MEK and ERK signaling pathways; calcium, CaMKII | [28]
| PC12 cells | MPP+ | 0.1, 1, and 10 μmol/L | PI3K/Akt signaling pathway; apoptotic | [39]
| PC12 cells | MPP+ | 1.5, and 10 μmol/L | ROS generation; JNK | [37]
**Parkinson's disease** | — | PC12 cells | MPP+ | ALP; OCN; COL-I; RNAKL; IL-6; MDA; calcium | [46]
**Bone** | Oxidative stress | MC3T3-E1 cells | Hydrogen peroxide | 0.1, 1, and 10 μmol/L | [46]
**Platelet** | Platelet aggregation, secretion | Platelets | Collagen; thrombin; U46619; ADP | 10, and 50 μmol/L | Platelet Fc γ RIIa, Akt (Ser473), and GSK3β (Ser9) phosphorylation. | [24]
**Pigmentation** | Induction of pigmentation | B16F1 melanoma cells | — | 10 μg/L | Microphthalmia-associated transcription factor (MITF); cAMP response element (CRE) binding protein (CREB) activation; p38 MAPK pathway | [50]
| Induction of pigmentation | B16 melanoma cells | — | 0.1–12.5 μg/mL | Murine tyrosinase | [49]
Oxidative Medicine and Cellular Longevity

aging-related diseases, especially in the cardiovascular and nervous system. Some studies have shown that THSG may be more effective than resveratrol in delaying senescence. Nevertheless, more research is necessary to explain the mechanism of THSG.

Abbreviations

| Abbreviation | Definition |
|--------------|------------|
| ADP          | Adenosine diphosphate |
| ALP          | Alkaline phosphatase |
| Ang II       | Angiotensin II |
| APP          | Amyloid precursor protein |
| BDNF         | Brain-derived neurotrophic factor |
| CaMKII       | Calcium/calmodulin-dependent protein kinase II |
| CASMC        | Coronary arterial smooth cell |
| CDK          | Cyclin-dependent kinases |
| COX-2        | Cyclooxygenase-2 |
| CRP          | C-reactive protein |
| CYP7A        | Cholesterol 7 alpha-hydroxylase |
| CSC          | Cardiac stem cells |
| DAF-16       | A homologous protein of Forkhead box protein O in C. elegans |
| DAT          | Dopaminergic transporter |
| eNOS         | Endothelial NO synthase |
| EPO          | Erythropoietin |
| ERK1/2       | Extracellular signal-regulated kinase 1/2 |
| GAP-43       | Growth associated protein 43 |
| GDNF         | Glial cell-line derived neurotrophic factor |
| GP Ib-IIIa/PAC-1 | Glycoprotein IIb/IIIa |
| GSH-Px       | Glutathione peroxidase |
| HCN2         | Hyperpolarization-activated cyclic nucleotide-gated 2 |
| HDL          | High-density lipoprotein |
| γH2AX        | Histone H2AX phosphorylated on serine 139 |
| HMG-CoA       | 3-Hydroxy-3-methylglutaryl-coenzyme A |
| HUVECs       | Human umbilical vein endothelial cells |
| ICAM-1       | Intercellular adhesion molecule-1 |
| IGF-1        | Insulin-like growth factor-1 |
| iNOS         | Inducible NO synthase |
| JNK          | c-Jun N-terminal kinase |
| LDL          | Low-density lipoprotein |
| LTP          | Long-term potentiation |
| LPC          | Lysophosphatidylcholine |
| LPS          | Lipopolysaccharide |
| MAO-B        | Monoamine oxidase B |
| MCAO         | Cerebral artery occlusion |
| MDA          | Malondialdehyde |
| MMP          | Matrix metalloproteinase |
| MPO          | Myeloperoxidase |
| MPP+         | 1-Methyl-4-phenylpyridinium ion |
| MPTP         | Ethyl-4-phenyl-1,2,3,6-tetrahydropyridine |
| NADPH        | Nicotinamide adenine dinucleotide phosphate |
| NANC relaxation | Nonadrenergic-noncholinergic relaxation |
| NF-kappaB     | Nuclear factor \( \kappa B \) |
| NGF          | Nerve growth factor |
| nNOS         | Neuronal NO synthase |
| NO           | Nitric oxide |
| NO2⋅         | Nitric oxide and nitrogen dioxide (NO and NO2) |
| NT-3         | Neurotrophic factor-3 |
| OGD-R        | Oxygen-glucose deprivation followed by reperfusion |
| PAI-1        | Plasminogen activator inhibitor-1 |
| PARP-1       | Poly(ADP-ribose) polymerase 1 |
| PCNA         | Proliferating cell nuclear antigen |
| PDGF-BB      | Platelet-derived growth factor-BB |
| PGC-1α       | PPAR-γ coactivator \( \lambda \) |
| PLC          | Lysophosphatidylcholine |
| PPAR-γ       | Peroxisome proliferator activated receptor gamma |
| RANKL        | Receptor activator of nuclear factor-\( \kappa \)B ligand |
| ROS          | Reactive oxygen species |
| SA-β-gal     | Senescence-associated \( \beta \)-galactosidase |
| SAMP8        | Senescence-accelerated prone mouse |
| α-SMA        | \( \alpha \)-smooth muscle actin |
| SOD          | Superoxide dismutase |
| Tbk5         | T-box transcription factor |
| THSG         | 2,3,5,4′-Tetrahydroxystilbene-2-O-\( \beta \)-D-glucoside |
| TGF-βI       | Transforming growth factor beta 1 |
| TNF-\( \alpha \)  | Tumor necrosis factor \( \alpha \) |
| TUNEL assay  | Terminal deoxynucleotidyl transferase mediated dUTP nick end labeling assay |
| VCAM-1       | Vascular cell adhesion molecule 1 |
| VEGF         | Vascular endothelial growth factor |
| VLDL         | Very-low-density lipoprotein |
| VSMCs        | Vascular smooth muscle cells |

Competing Interests

The authors declare that they have no competing interests.

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