REVIEW ARTICLE

Research progress on the mechanisms of traditional Chinese medicine in the treatment of atherosclerosis based on multi-omics approaches

Xiaobin Weng[1,*], Jian Chen[2], Mingyuan Zhang[2]

[1]Jiangsu Vocational College of Finance and Economics, Huai'an, Jiangsu 223003, China. [2]Henan University of Chinese Medicine, Zhengzhou, Henan, China.

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Atherosclerosis (AS) is a chronic inflammatory disorder driven by dysregulated lipid metabolism, vascular inflammation, and progressive remodeling of the arterial wall, and remains a major contributor to cardiovascular morbidity and mortality worldwide. Although conventional single-target pharmacological therapies have improved clinical outcomes, their efficacy is often constrained by adverse effects, treatment resistance, and limited capacity to reverse the underlying pathological processes. Traditional Chinese medicine (TCM), particularly multi-component herbal formulations, may exert coordinated therapeutic effects through multi-target and multi-pathway regulatory networks. By simultaneously modulating endothelial dysfunction, oxidative stress, inflammatory responses, and lipid metabolism, TCM offers a system-level strategy for the treatment of AS. However, the molecular basis of these coordinated effects remains incompletely defined, limiting the broader acceptance and integration of TCM into contemporary cardiovascular research. Multi-omics technologies including genomics, transcriptomics, proteomics, metabolomics, and lipidomics provide a powerful framework for resolving the mechanistic complexity of TCM interventions. This review summarized recent advances in the application of integrated multi-omics approaches to investigate the pharmacological actions of TCM in AS and highlighted how multidimensional datasets could be used to identify key regulatory targets, signaling pathways, and biomarkers, thereby clarifying TCM-mediated effects on lipid homeostasis, inflammation, endothelial function, and plaque stability. The study further discussed the strengths, limitations, and future directions of multi-omics strategies in TCM-AS research. This review provided a mechanistic framework for understanding the complex pharmacology of TCM, supporting the discovery of therapeutic targets and promoting the modernization and precision application of TCM in coronary artery disease and related vascular disorders.

Keywords: atherosclerosis; multi-omics; mechanism; cardiovascular diseases.

[*]**Corresponding author:** Xiaobin Weng, Jiangsu Vocational College of Finance and Economics, Huai'an, Jiangsu 223003, China. Email: binbinbinbinweng@126.com.

Introduction

Atherosclerosis (AS) is a chronic, progressive, and proliferative disease of the arterial wall. It is characterized primarily by the deposition of blood-derived components, particularly lipids, within the intima, together with smooth muscle cell proliferation and collagen fiber accumulation. These changes promote the formation of lipid-rich necrotic atheromatous lesions and progressive stiffening of the vascular wall. Consequently, the vessel wall becomes thickened, hardened, and less elastic with progressive luminal narrowing and impaired

blood flow. Depending on the vascular territory involved, these pathological changes can lead to dysfunction of the corresponding target organs or tissues. AS is a complex pathophysiological process involving endothelial injury, lipid deposition, inflammatory activation, and fibrous cap formation. In the early stage, endothelial cells are injured by risk factors such as hypertension, hypercholesterolemia, and smoking, resulting in endothelial dysfunction and increased vascular permeability, which allows lipids including low-density lipoprotein (LDL) to enter the subendothelial space. Lipid accumulation and oxidation within the subendothelial compartment provide the pathological basis for atherosclerotic plaque formation. Over time, deposited lipids recruit immune cells, particularly macrophages, to the injured vascular site. These macrophages engulf oxidized LDL and release inflammatory mediators, thereby amplifying local inflammation and promoting plaque instability. Ultimately, plaques may cause luminal stenosis or rupture, triggering acute cardiovascular events such as myocardial infarction and stroke. Traditional Chinese medicine (TCM) has distinct advantages in the treatment of AS. In recent years, advances in multi-omics technologies have provided new tools for elucidating the mechanisms underlying TCM-mediated pharmacological effects.

Progress in research on the pathogenesis of atherosclerosis

The major potential mechanisms regarding the occurrence and progression of AS include the lipid infiltration hypothesis, thrombosis and platelet aggregation hypothesis, injury–response hypothesis, endothelial dysfunction hypothesis, inflammation hypothesis, genetic–environmental interaction hypothesis, monoclonal hypothesis, and oxidative stress hypothesis. Additional mechanisms may involve neural and endocrine alterations. After decades of research, the most widely accepted theories of AS pathogenesis include lipid infiltration, thrombosis and platelet aggregation, endothelial injury response, and smooth muscle cell proliferation [1]. Drugs developed based on these mechanisms include rosuvastatin and other statins, aspirin and other non-steroidal anti-inflammatory drugs, ezetimibe and related cholesterol absorption inhibitors, fibrates, novel lipid-lowering agents such as PCSK9 inhibitors, and the ATP-citrate lyase inhibitor bempedoic acid [2]. The TCM understanding of AS differs from that of Western medicine. In TCM theory, AS is regarded as a systemic disorder associated mainly with disharmony of Qi and blood, imbalance of Yin and Yang, and dysfunction of the Zang-fu organs. The occurrence of AS is thought to result from interactions among blood stasis, phlegm-dampness, and heat-toxin, which contribute to vascular intimal injury, inflammatory responses, and lipid deposition. Accordingly, AS is commonly classified within the categories of blood stasis, phlegm-dampness, and vessel obstruction syndromes. Treatment therefore often focuses on promoting blood circulation to remove stasis and strengthening the spleen to resolve phlegm. Commonly used clinical preparations include Xinnaokang, Naoxinshu, Chuanxiong and ligustrazine preparations, *Salvia miltiorrhiza* and tanshinone preparations, Guanmaining, and Ginkgo biloba preparations [3]. Studies have shown that TCM has advantages in regulating blood lipids, improving microcirculation, suppressing inflammation, and protecting endothelial cells. These concepts complement modern medical understanding of AS and underscore its complexity and multifactorial nature.

(1) Vascular endothelial dysfunction

AS is an important consequence of pathological changes caused by vascular endothelial dysfunction. Endothelial cells are essential for maintaining vascular integrity and function. With aging, endothelial cells gradually undergo senescence and functional decline, leading to reduced production and bioavailability of nitric oxide (NO). This change impairs vasodilatory function, promotes increased blood pressure, and accelerates vascular aging [4]. In addition, alterations in senescent organelles and increased

secretion of senescence-associated secretory phenotype (SASP) factors further contribute to AS progression [5]. Inflammation is a central driver of endothelial dysfunction. Chronic oxidative stress and persistent inflammation injure endothelial cells and impair their function. Studies have shown that aging-related reductions in the cofactor tetrahydrobiopterin further aggravate endothelial impairment and contribute to vascular remodeling and atherogenesis. Inflammatory factors also activate the NF-κB pathway, promote cytokine expression, and intensify inflammatory responses. This sequence contributes substantially to AS pathogenesis [6]. Therefore, strategies aimed at restoring endothelial function and suppressing inflammation are critical for AS prevention and treatment.

(2) Inflammatory response

Chronic inflammation is a key process in AS development. AS is a chronic inflammatory disease characterized by lipid deposition and endothelial injury. Chronic low-grade inflammation is central to its pathogenesis, and inflammatory mediators including IL-1β, TNF-α, and MCP-1 contribute directly to AS formation. These pro-inflammatory cytokines enhance adhesion between endothelial cells and leukocytes and promote monocyte infiltration, thereby accelerating atherosclerotic progression. In addition, activation of the nuclear factor-κB (NF-κB) signaling pathway occurs across multiple stages of AS and contributes to disease development by regulating downstream inflammatory factors [7]. Pro-inflammatory cytokines are particularly important in the occurrence and progression of AS. Activation of IL-1β not only promotes leukocyte adhesion and chemotaxis in endothelial cells but also stimulates smooth muscle cell proliferation, thereby creating a positive feedback loop that amplifies inflammation. The NLRP3 inflammasome is also an important pro-inflammatory mediator in AS, and its activation may promote plaque instability through the release of pro-inflammatory cytokines [8]. In TCM research, interventions targeting chronic inflammation have received increasing attention. Recent studies suggest that components derived from Chinese herbal medicines can activate TRPV1/TRPA1 and modulate the TLR/NLRP3 pathway, thereby reducing pro-inflammatory cytokine production and attenuating inflammatory responses. Certain active components of Chinese herbal medicines may improve the inflammatory status of patients with AS by inhibiting reactive oxygen species (ROS) generation and cholesterol crystal formation, supporting the application of TCM in AS treatment [9]. Chronic low-grade inflammation occupies a central position in the pathological mechanisms of AS, and pro-inflammatory cytokines are major contributors to this process. TCM-based interventions may help reduce inflammation and improve AS-related pathological changes.

(3) Oxidative stress

Oxidative stress refers to a state in which ROS production exceeds antioxidant defense capacity, resulting in cellular injury and functional impairment. In AS, oxidative stress is an important pathological mechanism. Studies have shown that long-term oxidative stress damages vascular endothelial cells and promotes AS development. Oxidative stress not only impairs endothelial cell function but also induces smooth muscle cell proliferation, inflammatory responses, and plaque formation. In addition, aging-related oxidative stress contributes to vascular endothelial remodeling and ultimately promotes AS [10]. Under oxidative stress, cells develop SASP, which further promotes plaque formation and instability. TCM has shown considerable potential in counteracting oxidative stress through multiple mechanisms. It can inhibit oxidative stress and inflammatory responses by regulating several signaling pathways including TLR4/MyD88/NF-κB, NLRP3/Caspase-1, and MAPK/ERK1, thereby slowing vascular aging and AS progression. Experimental studies have shown that Xuefu Zhuyu Decoction can improve endothelial function by increasing serum NO levels, thereby counteracting AS development. Related studies

have further shown that Xuefu Zhuyu Decoction can inhibit AS, and that its mechanism is associated with the expression of key molecules involved in anti-inflammatory and antioxidant effects [11]. In addition, aqueous extracts of mulberry have been shown to inhibit hypercholesterolemia-induced arterial intimal hyperplasia, an effect associated with downregulation of the NF-κB signaling pathway. These findings further support the efficacy of Chinese herbal medicines in combating oxidative stress. Oxidative stress contributes substantially to AS development. TCM may alleviate oxidative stress through multiple pathways, particularly through antioxidant mechanisms, thereby providing strategies for prevention and treatment. Current AS research is largely based on the above scientific hypotheses, and many studies have focused on abnormal lipid and cholesterol metabolism and inflammatory signaling pathways within the arterial microenvironment. Reducing the expression of inflammation- and apoptosis-related signaling proteins such as those in the NF-κB and mitogen-activated protein kinase (MAPK) pathways and improving endothelial injury caused by lipid deposition in the arterial microenvironment have become major research priorities [12]. Natural compounds such as kaempferol, naringin, quercetin, and baicalein can regulate inflammatory signaling pathways and exert anti-atherosclerotic effects. The hallmark of TCM is the synergistic action of multiple components on multiple targets. Conventional research paradigms based on component–target–pathway–tissue–organ frameworks remain limited in explaining the mechanisms of classical anti-atherosclerotic formulas. By integrating two or more omics layers including genomics, transcriptomics, proteomics, metabolomics, and microbiomics, multi-omics provides a system-level perspective for examining the interactions and functional mechanisms linking human disease with the diverse constituents of herbal compound prescriptions. From the dimensions of genes, transcripts, proteins, and metabolites, multi-omics approaches can explain at a holistic level why Chinese herbal medicines exert pharmacological effects. These approaches therefore provide support for elucidating the "black box" of effective TCM treatment and represent an important means of promoting the modernization of TCM.

Mechanisms of TCM in the treatment of atherosclerosis

(1) Improvement of vascular endothelial function

TCM has shown notable efficacy in improving vascular endothelial function, particularly in the treatment of AS. Studies have demonstrated that components of TCM can protect endothelial cell function and promote endothelial growth and repair, thereby improving overall vascular function. Simiao Yong'an Decoction, which consists of *Lonicera japonica*, *Scrophularia ningpoensis*, *Angelica sinensis*, and *Glycyrrhiza uralensis*, has been shown to accelerate the growth cycle of human umbilical vein endothelial cells and reduce the levels of endothelin-1 (ET-1) and angiotensin-converting enzyme, thereby facilitating the repair of damaged endothelial cells [13]. Endothelial cell senescence and apoptosis are important contributors to AS development. TCM may improve vascular function by regulating endothelial senescence and apoptosis. Studies have shown that appropriate endothelial autophagy can inhibit endothelial cell senescence and inflammatory responses, thereby slowing AS progression [14]. Under TCM intervention, senescent endothelial cells may be effectively cleared, enhancing endothelial regeneration and repair capacity, improving vascular function and reducing the risk of AS. By ameliorating endothelial dysfunction and regulating senescence and apoptosis, TCM provides distinctive mechanisms for AS management. These coordinated effects not only improve the physiological status of endothelial cells but also may help reduce the incidence of cardiovascular disease, supporting the integration of TCM into modern medical practice.

(2) Anti-inflammatory effects

TCM exerts anti-inflammatory effects through multiple pathways. Studies indicate that TCM can modulate systemic inflammation by regulating the balance of cytokines and inflammatory mediators. Recent studies have shown that Wumei Pill can reduce inflammatory injury and inhibit inflammatory progression by suppressing the expression of pro-inflammatory cytokines including tumor necrosis factor-α (TNF-α) and interleukin-6 (IL-6) [15]. In addition, TCM can suppress inflammatory responses by modulating inflammatory signaling pathways. TNF-α is not only a pro-inflammatory cytokine but also an activator of multiple signal transduction pathways that induce the expression of additional cytokines and thereby amplify inflammation [16]. By regulating these signaling pathways, TCM can inhibit TNF-α release and alleviate TNF-α induced inflammation. Through the regulation of inflammatory mediators and cytokine balance, TCM also shows potential for reducing AS progression. Because AS is closely associated with inflammation, Chinese herbal formulas such as the Vascular Anti-aging Formula may reduce aging-related inflammatory markers including TNF-α and IL-6, thereby improving vascular inflammatory status and slowing AS progression. TCM inhibits inflammatory responses through multiple mechanisms and regulates the balance of inflammatory mediators and cytokines. These effects support its value in anti-inflammatory intervention and in reducing AS progression, providing a theoretical basis and practical direction for clinical application and further research.

(3) Antioxidant effects

The antioxidant capacity of various TCM constituents has important implications for AS prevention and treatment. AS is closely linked to oxidative stress. When sustained, oxidative stress damages endothelial cells, promotes structural vascular remodeling, and accelerates lesion formation. Physiological and pathological cascades involving ROS and reactive nitrogen species are major triggers of oxidative stress. When their production exceeds the scavenging capacity of the antioxidant system, cellular injury and disease progression occur [17]. Certain TCM compounds can upregulate endogenous antioxidant enzymes including superoxide dismutase, glutathione peroxidase and catalase, thereby enhance free radical clearance and attenuate oxidative injury. In parallel, TCM may restore endothelial function by recalibrating the balance between NO and endothelin, protecting the vascular lining and limiting disease progression. By correcting oxidative imbalance, these components may mitigate atherosclerotic pathology. Several herbal prescriptions have also been shown to inhibit oxidative stress and reduce inflammatory mediator release, thereby counteracting AS development. Thus, the antioxidant effects of TCM provide approaches for AS prevention and treatment.

Application of multi-omics research in the treatment of atherosclerosis with TCM

Multi-omics is an important research strategy in biological science. It focuses on the composition, interactions, and dynamic changes of biological system components including genes, RNA, proteins, metabolites, and microorganisms under different conditions. By integrating multiple omics datasets, multi-omics research can reveal molecular regulatory mechanisms under physiological and pathological states, thereby providing approaches for disease diagnosis, treatment, and prevention. Multi-omics mainly include genomics, transcriptomics, proteomics, metabolomics, and other interdisciplinary analytical approaches closely related to individual growth, development, and metabolism. In basic research on AS, the most frequently used omics approaches include genomics, transcriptomics, proteomics, lipidomics, and metabolomics, all of which are closely associated with disease development.

(1) Genomics research: Effects of Chinese herbal medicines on differential gene expression

The human genome project and advances in bioinformatics have brought genetic risk factors for AS to the forefront of research. DNA

methylation has been shown to regulate AS by influencing senescence, hyperhomocysteinemia, oxidative stress, endothelial dysfunction, vascular smooth muscle cell proliferation and migration, and macrophage-associated inflammatory responses. In addition, microRNAs (miRNAs) are involved in AS pathogenesis through their effects on lipid metabolism and immune regulation. In the treatment of AS with TCM, genomic studies indicate that herbal active components can significantly affect the differential expression of disease-related genes. Because TCM is multi-component in nature, it may achieve therapeutic effects by coordinating the simultaneous regulation of multiple genes. Chinese herbal components can modulate genes associated with inflammation, metabolism, and apoptosis by influencing specific signaling pathways, thereby improving the pathological state of AS. These studies suggest that combining genomics with network pharmacology can more comprehensively elucidate the mechanisms of Chinese herbal components and provide a theoretical basis for individualized treatment strategies. Furthermore, advances in genomics have made it possible to identify key genes associated with AS and have facilitated further exploration of how traditional Chinese medicine components exert therapeutic effects by modulating these genes.

(2) Transcriptomics research: Regulation of cellular signaling pathways by Chinese herbal medicines

Transcriptomics also contributes to the study of TCM treatment for AS. Through high-throughput sequencing, researchers can analyze the effects of Chinese herbal medicines on intracellular transcriptional profiles and elucidate their regulatory effects on cellular signaling pathways. Several Chinese herbal components have been found to regulate signaling pathways such as NF-κB and MAPK, which are closely associated with inflammatory responses and cell proliferation. Studies have shown that, by modulating these key signaling pathways, Chinese herbal medicines can reduce inflammatory responses in AS and promote vascular endothelial cell repair and regeneration, thereby improving vascular function [18]. In addition, transcriptomic analyses have helped identify target genes of Chinese herbal medicines, providing important clues for further mechanistic studies [19].

(3) Proteomics research: Effects of Chinese herbal medicines on protein expression

Proteomics provides an updated perspective for deciphering the pharmacological actions of TCM in AS. By analyzing the effects of Chinese herbal medicines on intracellular protein expression, researchers can identify key AS-related proteins and their regulatory mechanisms. Several bioactive compounds isolated from Chinese medicinal plants can upregulate antioxidant enzymes and anti-inflammatory factors, thereby alleviating oxidative stress and inflammatory responses within arteries and promoting angiogenesis [20]. Proteomic studies have also revealed potential roles of TCM in modulating lipid metabolism and apoptosis, providing evidence for its application in AS therapy. Emerging evidence supports the preventive and therapeutic roles of TCM in AS. Aqueous extracts of mulberry have been shown to inhibit high-cholesterol-diet-induced arterial intimal hyperplasia in rabbits and reduce the expression of smooth muscle actin and matrix metalloproteinase-2 in vascular smooth muscle cells, thereby suppressing AS progression. This finding provides additional evidence supporting the application of TCM in AS therapy. Moreover, increasing attention has been paid to the modulation of AS-related proteins by TCM. Studies have shown that TCM can simultaneously regulate multiple proteins through multiple pathways, thereby intervening in AS. By coordinating key effectors in the p38 MAPK, ERK1/2, and JNK signaling networks, TCM affects processes such as proliferation, migration, and apoptosis. Proteomics is the systematic study of all proteins expressed by a specific genome including analyses of protein composition, abundance, modifications, and interactions. Using this technology, researchers can identify differences in protein expression induced by different Chinese herbal medicines under various

conditions. Proteomic techniques have also been used to explore the material basis of the cold and heat properties of Chinese herbal medicines. These studies have found that heat-natured herbs can significantly improve pathological changes associated with cold syndromes, whereas cold-natured herbs can markedly reduce hepatic energy consumption. These findings help clarify the diverse therapeutic mechanisms of TCM.

(4) Metabolomics research: Effects of Chinese herbal medicines on metabolites

Recent studies have shown that TCM can substantially reprogram metabolomic profiles, thereby regulating the occurrence and progression of AS. Chinese herbal preparations such as Shexiang Tongxin Dropping Pills have been shown to improve atherosclerotic lesions by regulating lipid metabolism, exerting anti-fibrotic effects, and alleviating inflammation and oxidative stress. Metabolomics can reveal differences in metabolic characteristics across disease states. In AS research, comparing metabolic features of the same syndrome across different diseases can help identify syndrome-related metabolites, thereby supporting the TCM theory of "different diseases sharing the same syndrome". Studies have found that metabolites such as glycine, urea, tryptophan, and alanine are shared in patients with postoperative liver–kidney Yin deficiency syndrome following colorectal cancer and liver cancer. This discovery provides a basis for explaining and applying metabolomics within the framework of TCM theory. The application of metabolomics not only supports the scientific validity of TCM theory but also provides a new perspective for studying the compatibility mechanisms of Chinese herbal compound formulas. Through metabolomic research, it is possible to systematically analyze the interactions among formula components and their effects on metabolic pathways. Metabolomic studies have shown that certain Chinese herbal components can exert antidepressant and regulatory effects by modulating specific metabolites in renal tissues [21]. This finding reveals the multi-target effects of TCM and highlights the importance of holistic and dynamic perspectives in modern TCM research. By altering metabolomic signatures, TCM contributes to AS prevention and treatment. Metabolomic data also provide support for the theoretical basis of TCM. Further research in this field will help clarify the scientific foundation of TCM and promote its application and development in modern medicine.

(5) Lipidomics research: Biological roles of lipid molecules in disease types and their impact on metabolic pathways

Blood lipids are regulated by a multi-target and multi-pathway metabolic system. Identifying metabolic biomarkers and controlling or reducing vascular injury caused by abnormal blood lipids represent direct targeted approaches for AS prevention and treatment. The multi-pathway regulatory system of blood lipids was illustrated in Figure 1. Elevated low-density lipoprotein cholesterol (LDL-C) and reduced high-density lipoprotein cholesterol (HDL-C) are closely associated with AS development [22]. Studies have shown that oxidized LDL-C plays a key role in atherogenesis. Oxidized LDL can induce macrophage infiltration and foam cell formation, thereby promoting inflammatory responses and lipid deposition in the arterial wall. Modern pharmacological studies have shown that Gualou or Trichosanthes fruit can reduce serum total cholesterol and β-lipoproteins, thereby inhibiting vascular lipid deposition. *Eupolyphaga sinensis* has been shown to reduce serum total cholesterol, triglycerides, LDL-C, and hepatic lipid content in hyperlipidemic rabbits, while increasing HDL-C levels. Lipidomic studies of TCM treatment for AS have shown that Qi-tonifying and blood-stasis-resolving formulas including those containing Hirudo and *Astragalus membranaceus* mainly improve AS symptoms by maintaining the stability of disordered glycerophospholipid and glyceride metabolism.

(6) Emerging multi-omics technologies: Multi-omics drives the shift in AS research from macroscopic phenotypes to precise molecular regulatory networks

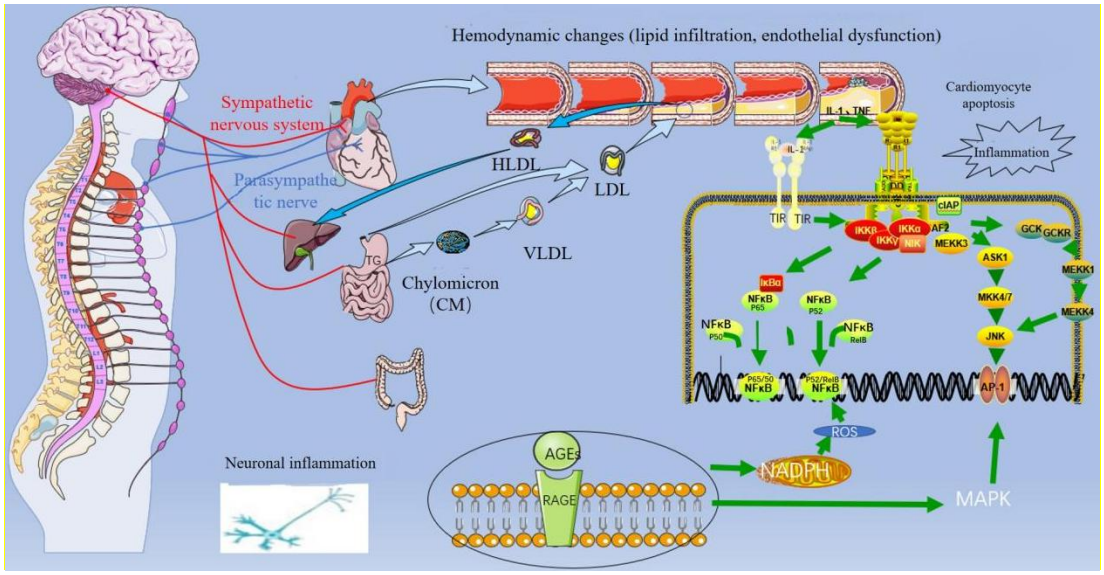

Figure 1. Multi-target and multi-pathway metabolic regulatory system of blood lipids.

Advances in high-throughput biotechnology and systems biology have introduced emerging multi-omics tools that can systematically delineate the complex mechanisms by which TCM treats AS. In particular, single-cell omics, spatial omics and multi-omics integration analysis have enabled TCM research to move from traditional holistic pharmacodynamic observation towards high-resolution, multi-level elucidation of molecular mechanisms [23, 24]. Metabolomic studies indicate that the main anti-AS active components in TCM include flavonoids such as baicalin, quercetin, and puerarin [25, 26]; alkaloids such as berberine, ligustrazine, and tetrandrine [27]; saponins such as ginsenosides, Panax notoginseng saponins, and astragaloside IV [28]; polysaccharides such as *Ganoderma lucidum* polysaccharides, *Astragalus* polysaccharides, and *Angelica sinensis* polysaccharides [29]; and other classes including phenolic acids such as salvianolic acid B, terpenoids such as celastrol, and quinones. These compounds mainly improve AS by regulating lipid metabolism and exerting anti-inflammatory effects. Single-cell transcriptomics and proteomics technologies can reveal the functional remodeling of key cell subsets including vascular endothelial cells, macrophages, and smooth muscle cells after TCM intervention at cellular resolution [30]. These approaches provide precise evidence for deciphering the anti-inflammatory, lipid-modulating, and plaque-stabilizing effects of TCM. Spatial omics technologies acquire molecular information while preserving the spatial architecture of atherosclerotic plaques [31], thereby helping to clarify the differential regulatory effects of TCM across distinct plaque microenvironments [32]. In parallel, multi-omics integration combined with artificial intelligence and network pharmacology methods can systematically construct a “TCM component – target – pathway – phenotype” regulatory network, revealing the intrinsic principles underlying the synergistic actions of multiple components and multiple targets in TCM [33]. Future research that integrates multi-omics data, standardized bioinformatics analysis, and functional experimental validation is expected to promote TCM-based AS research towards greater precision, mechanistic clarity, and clinical translation.

Conclusions

AS is a common cardiovascular disease and a major global health burden. In recent years, TCM has received increasing attention as a therapeutic option for AS. Its unique conceptual framework and therapeutic approaches offer opportunities for mechanistic research. TCM demonstrates potential in the prevention and treatment of AS, particularly regarding the regulation of lipid metabolism, anti-inflammatory effects, protection of endothelial cells, and modulation of immune function. With the continuous advancement of multi-omics research, the mechanisms underlying the treatment of AS with TCM are becoming increasingly clear. Through the integrated analysis of genomics, proteomics, and metabolomics data, researchers can more effectively identify the targets and pathways modulated by TCM components, thereby providing robust evidence for their clinical application. These studies have deepened the scientific understanding of TCM and provided a theoretical basis for its modernization and internationalization.

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