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Cardioprotective Effects of High-Density Lipoprotein Beyond its Anti-Atherogenic Action

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High-density lipoprotein cholesterol (HDL-C) has been identified as a powerful independent negative predictor of cardiovascular disease. The beneficial effect of HDL is largely attributable to its key role in reverse cholesterol transport, whereby excess cholesterol in the peripheral tissues is transported to the liver, reducing the atherosclerotic burden. However, mounting evidence indicates that HDL also has pleiotropic properties, such as anti-inflammatory, anti-oxidative, and vasodilatory properties, which may contribute in reducing the incidence of heart failure. Actually, previous data from clinical and experimental studies have suggested that HDL exerts cardioprotective effects irrespective of the presence/absence of coronary artery disease. This review summarizes the currently available evidence regarding beneficial effects of HDL on the heart beyond its anti-atherogenic property. Understanding the mechanisms of cardiac protection by HDL will provide new insight into the underlying mechanism and therapeutic strategy for heart failure.

Key words: High-density lipoprotein, Cardioprotective effect, Heart failure, Fatty acid, Endothelial lipase, mTOR signal

Introduction

Heart failure (HF) is the terminal state of all heart diseases and is the leading cause of mortality worldwide. According to the American Heart Association, there are approximately 550,000 new patients with HF each year¹⁾. Although considerable advances have been made in our understanding of HF, the incidence, prevalence, mortality, and financial burden of the disease continue to steadily increase in the aging population. Therefore, elucidating modifiable risk factors for HF will aid in identifying prevention strategies or developing novel therapeutic approaches.

Numerous studies have established an inverse relationship between high-density lipoprotein cholesterol (HDL-C) and risk for atherosclerotic cardiovascular disease in humans²⁻⁵⁾; low HDL-C is considered to be one of the most important coronary risk factors⁶⁾. This beneficial effect of HDL on the cardiovascular system is largely attributable to its key role in reverse cholesterol transport (RCT), whereby excessive cholesterol in

the peripheral tissues is transported to the liver, reducing the atherosclerotic burden. However, a large amount of evidence has revealed that HDL has many anti-atherosclerotic properties represented by anti-inflammatory, anti-oxidative, anti-thrombotic, anti-apoptotic, and vasodilatory properties, and these vasoprotective effects seem to be independent of RCT activity^{7, 8)}. Hence, it may be reasonable to consider that such properties of circulating HDL do not only protect the coronary vessel wall against atherosclerosis but also exert direct beneficial effects on the myocardium, leading to reduction of the incidence of myocardial diseases, including HF.

It has been well known that cigarette smoking has a negative impact on RCT and reduces circulating HDL-C levels, which is involved in the progression of cardiovascular disease^{9, 10)}. Conversely, several studies have suggested that HDL exerts atherosclerosis-independent cardioprotective effects on the pathological status. Horio *et al.* investigated the influence of serum lipids on LV functions in patients with essential hypertension and found that low HDL-C level is an independent pre-

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dictor of LV mass and LV diastolic dysfunction¹¹). An independent association between low HDL-C level and subclinical LV systolic dysfunction has been observed in patients with not only stable angina but also normal coronary angiogram¹², and Kerola *et al.* suggested that HDL is superior to B-type natriuretic peptide as a marker of systolic cardiac dysfunction in an elderly general population¹³. Moreover, NIPPON DATA90, a large cohort study of cardiovascular disease in Japan, addressed the association between HDL-C levels and HF incidence; serum HDL-C levels tended to show an inverse association with HF mortality with borderline significance and a significant inverse association with all-cause mortality¹⁴. In line with this observation, Vredevoe *et al.* reported that HDL-C is a predictor of mortality in patients with idiopathic HF¹⁵. Taken together, HDL exerts direct cardioprotective effects independent of the atheroprotective property, which possibly influences LV function and HF incidence. In the present review, we summarize currently available evidence regarding direct beneficial effects of HDL on the heart beyond the anti-atherogenic property and discuss underlying mechanisms that have been implicated.

1. HDL Provides Fatty Acids as Energy Substrates for the Myocardium

Vast amounts of energy are required for fueling the continuous pumping action of the heart. Under normal circumstances, nearly 70% of the energy substrate used for myocardial contraction is derived from fatty acid (FA) oxidation and the remainder comes from glucose, lactate, and ketone body oxidation¹⁶. Thus, FAs are considered to be the major energy source for the myocardium, which are delivered to cardiomyocytes in three ways: 1) FAs are produced in the local capillary bed by hydrolysis of triglycerides (TGs) contained in circulating TG-rich lipoproteins (TRL), such as chylomicrons and very low-density lipoproteins (VLDL), via actions of lipoprotein lipase (LPL), 2) FAs are produced by hydrolysis of intracellular TG storages, and 3) FAs are derived from circulating free FAs, referred to as non-esterified FA (NEFA), complexed with serum albumin¹⁷. Moreover, phospholipids might be one of the resources of FAs, whereas metabolic regulation in the heart remains to be fully elucidated. In particular, LPL-mediated lipolysis of chylomicrons and VLDL significantly contributes to cardiac energy supply^{18, 19}; therefore, LPL plays a central role in energy homeostasis in the heart¹⁷. LPL is synthesized in cardiomyocytes and then migrates to the luminal surface of vascular endothelial cells where hydrolysis of TRL takes place²⁰. In contrast to esterified FAs derived from TRL, NEFA availability is limited because of its low solubility and

high toxicity. Myocardium uptakes NEFA as an energy source by passive diffusion and several transporters, such as FA-binding protein, FA translocase (FAT/CD36), and FA transport protein¹⁶. Hauton *et al.* investigated myocardial lipid substrate preference by comparing utilization of NEFA, VLDL-TGs, and CM-TGs in rat-isolated perfused hearts and concluded that myocardial utilization of NEFA and CM-TGs is higher than that of VLDL-TGs²¹. Besides LPL-mediated lipolysis, there is an alternative mechanism by which TRL is assimilated into the heart. The VLDL receptor is a member of the LDL receptor gene family, which has high expression in the heart, and is associated with the uptake of apolipoprotein E-containing lipoproteins^{22, 23}. Although cardiomyocytes also express scavenger receptor class B type I (SR-BI), a receptor related to the uptake of cholesterol from HDL^{24, 25}, it remains unknown whether HDL particles are incorporated into the heart via SR-BI.

Cardiomyocytes possess endothelial lipase (EL), which is another member of the TG lipase family. Although basal expression of EL in cardiomyocytes is very low, its expression level is upregulated under pathological conditions, including inflammation, mechanical, and oxidative stress²⁶. EL is considered to bind to cell surface proteoglycans where it can directly interact with lipoproteins²⁷⁻²⁹. EL primarily has phospholipase activity and relatively less TG lipase activity and exhibits preferential substrate specificity for phospholipids on HDL²⁹. Therefore, EL has the potential ability to release FAs from not only TGs contained in TRL but also phospholipids contained in HDL. However, relative contribution of EL-mediated HDL hydrolysis and TRL lipolysis in FA supply to the myocardium needs to be determined in the future.

A large amount of evidence suggests that cardiac energy metabolism is severely impaired in the failing heart^{30, 31}. Namely, the failing heart is commonly described as an energy-starved engine that has run out of fuel³¹. During development of HF, the predominant myocardial energy substrate switches from FAs to glucose because glucose oxidation allows the heart to produce intracellular adenosine triphosphate (ATP) using less oxygen than that needed for FA oxidation³¹⁻³³. However, compromised cardiac energy metabolism may cause and worsen myocardial dysfunction. Total β -oxidation in the heart is increased by 40% in response to acute energy demand³⁴ and increased glucose oxidation alone is reported to be insufficient to meet the cardiac energy requirement under stress conditions^{33, 35}. Augustus *et al.* reported that heart-specific LPL knockout (hLpL0) mice were susceptible to HF because of loss of LPL-mediated TG lipolysis in spite of increased glucose oxidation³⁵. They showed that hearts of hLpL0 mice that underwent abdominal aortic constriction were

unable to adapt acutely to pressure overload, thereby, all banded hLpL0 mice died within 48 h, whereas all banded wild-type mice continued to thrive. Similarly, the lack of peroxisome proliferator-activated receptor (PPAR)-gamma coactivator-1 alpha (PGC-1 α), a regulator of numerous genes involved in FA import and oxidation, accelerates pressure overload-induced HF induced by transverse aortic constriction³⁶. These findings indicate that FAs are indispensable energy substrates even in the failing myocardium.

Kratky *et al.* observed that EL compensates for free FA uptake in LPL-deficient mouse adipose tissue, which indicates that EL provides an alternative pathway for FA uptake when the action of LPL is insufficient³⁷. Expression of EL in the cardiac tissues is increased in the early phase of pressure overload-induced HF, whereas expression of LPL is significantly decreased²⁶. Subsequently, EL deficiency worsens pressure overload-induced HF due to the attenuated energy production from FA oxidation, which suggests that EL-mediated FA supply from HDL is important for the myocardium in the setting of increased energy demand or insufficient LPL action. In addition, various FAs act as ligands for PPAR α ³⁸, which regulates mitochondrial FA oxidation-related genes. Ahmed *et al.* revealed that EL-mediated hydrolysis of HDL activates PPAR α and subsequently upregulates the expression of acyl-CoA-oxidase, a well-established FA oxidation-related gene³⁹. In line with this finding, incubation of EL-overexpressing cardiomyocytes with HDL augmented the expression of FA oxidation-related genes carnitine palmitoyltransferase-1 and medium-chain acyl CoA dehydrogenase which was accompanied by an increase in intracellular ATP²⁶. From these findings, it is considered that EL-mediated FA supply from HDL not only increases energy substrates for the myocardium but also upregulates the expression of PPAR α -mediated FA oxidation-related genes, thereby preserving FA utilization in the failing heart.

2. HDL Protects Cardiomyocytes Against Oxidative Stress

There is a well-established relationship between myocardial reactive oxygen species (ROS) levels and left ventricular contractile dysfunction, which results in HF^{40, 41}. ROS is generated in the ischemic myocardium, particularly after reperfusion, leading to cell death⁴². One of the most important properties of HDL is its ability to reduce oxidative stress caused by excessive ROS formation^{7, 8}. There is evidence that HDL inhibits NAD(P)H oxidase-dependent ROS generation in vascular smooth muscle cells and isolated aortas⁴³. With regard to the myocardium, in an *ex vivo* model of isch-

emia-reperfusion (I/R) injury, Marchesi M *et al.* showed that synthetic HDL, recombinant apo A-I Milano complexed with 1-palmitoyl-2-oleoyl phosphatidylcholine, reduced cardiac muscle lipid hydroperoxide levels by 46% via its antioxidant potential, thereby attenuating post-ischemic LV dysfunction⁴⁴.

We recently reported that HDL treatment improved cardiomyocyte viability under oxidative stress through the phosphatidylinositol 3-kinase (PI3K)/mammalian target of rapamycin (mTOR) signaling pathway⁴⁵. mTOR belongs to the PI3K-related kinase family and critically regulates protein synthesis, cell survival, growth, and proliferation⁴⁶. In addition, several studies have identified mTOR as an important regulator of cardiac adaptation because its overexpression is protective in pressure-overloaded mouse hearts^{47, 48} and its conditional knockout in murine heart causes cardiac dysfunction⁴⁹. We demonstrated that HDL activated downstream effectors of mTOR signaling, which played anti-apoptotic roles under oxidative stress, may contribute to cardioprotection⁴⁵.

3. HDL Exerts Anti-Inflammatory Effects in the Myocardium

HF is known as a disorder characterized in part by immune activation and inflammation⁵⁰. Niebauer *et al.* showed that plasma bacterial endotoxin (lipopolysaccharide, LPS) levels were increased in patients with HF and peripheral edema probably because venous congestion leads to altered gut permeability for endotoxin and translocation of the endotoxin into the systemic circulation⁵¹. Because endotoxin is a very strong stimulator for the release of inflammatory cytokines from circulating immune competent cells⁵², it may cause substantial immune activation in patients with HF. Conversely, lipoproteins have been shown to bind and inactivate endotoxin in proportion to their cholesterol content⁵³. It has been postulated that low plasma cholesterol levels, a surrogate for the totality of lipoproteins, is related to impaired survival in patients with idiopathic HF¹⁵. Similarly, Rauchhaus M *et al.* proposed that high plasma cholesterol levels in chronic HF are beneficial on the basis of the capacity of circulating cholesterol-rich lipoproteins to bind and inactivate endotoxin⁵². Notably, Ulevitch *et al.* reported that HDL suppressed the buoyant density of LPS in human serum more effectively than LDL or VLDL⁵⁴. Similar to this finding, it was reported that the phospholipid bilayer of the HDL surface could bind to lipid-A, an anchor protein of LPS, to neutralize the activity of LPS⁵⁵. In fact, HDL inhibits LPS-induced expression of cytokines in cardiomyocytes (Fig. 1A). In addition, infusion of reconstituted HDL reduces cytokinemia and

improves clinical outcome in rabbit gram-negative bacteremia models⁵⁶). Furthermore, targeted deletion of EL results in an increase in phospholipid and cholesterol content in HDL particles and thereby improves the survival rate of endotoxin shock in a mouse model of LPS-induced septic shock⁵⁷). These findings indicate that HDL can diminish detrimental effects of endotoxemia *in vivo*. Therefore, it is reasonable to assume that HDL protects against HF by attenuating the action of endotoxin in edematous patient with HF.

4. HDL Enhances Myocardial Perfusion Via Nitric Oxide-Mediated Vasodilatory Effects

There is evidence that HDL administration increases myocardial perfusion *in vivo* via nitric oxide (NO)-dependent mechanisms⁵⁸), suggesting that HDL acts as a coronary vasodilator. HDL mediates vasodilation via NO release⁵⁹⁻⁶¹). Nofer *et al.* reported that HDL stimulates NO release in human endothelial cells and induces vasodilation in isolated aortas via intracellular Ca^{2+} mobilization and Akt-mediated endothelial NO synthase (eNOS) phosphorylation⁵⁹). The vasoactive effect of HDL was mimicked by three lysophospholipids contained in HDL: sphingosine-1-phosphate (S1P), sphingosylphosphorylcholine (SPC), and lysosulfatide (LSF). Deficiency of the S1P3 receptor abolished vasodilatory effects of these lysophospholipids, which indicates that HDL functions as a carrier of bioactive lysophospholipids and induces NO-dependent vasodilation via S1P3 receptor. Conversely, Yuhanna *et al.* have shown that HDL activates eNOS via SR-BI through a process that requires apoA-I binding in endothelial cells, resulting in increased NO production⁶⁰). Afterward, it was identified that apoA-I interaction with SR-BI led to Src-mediated PI3K activation and then PI3K activated Akt kinase and mitogen-activated protein kinase pathways, both of which stimulate eNOS activity⁶¹). Collectively, HDL activates eNOS in endothelial cells through dual signaling pathways involved in S1P receptors and SR-BI and causes NO-mediated vasodilation. In the heart, Levkau B *et al.* observed that administration of human HDL enhanced incorporation of the perfusion tracer 99mTc-methoxyisobutylisonitrile into the murine heart *in vivo* by approximately 18%; this increase was completely abolished in mice deficient of endothelial NO synthase⁵⁸). Furthermore, the stimulatory effect of HDL on myocardial perfusion was preserved in S1P3-deficient mice, which implies that SR-BI-mediated, but not S1P3-mediated, eNOS activation in endothelial cells may be mainly related to the stimulatory effect of HDL on myocardial perfusion.

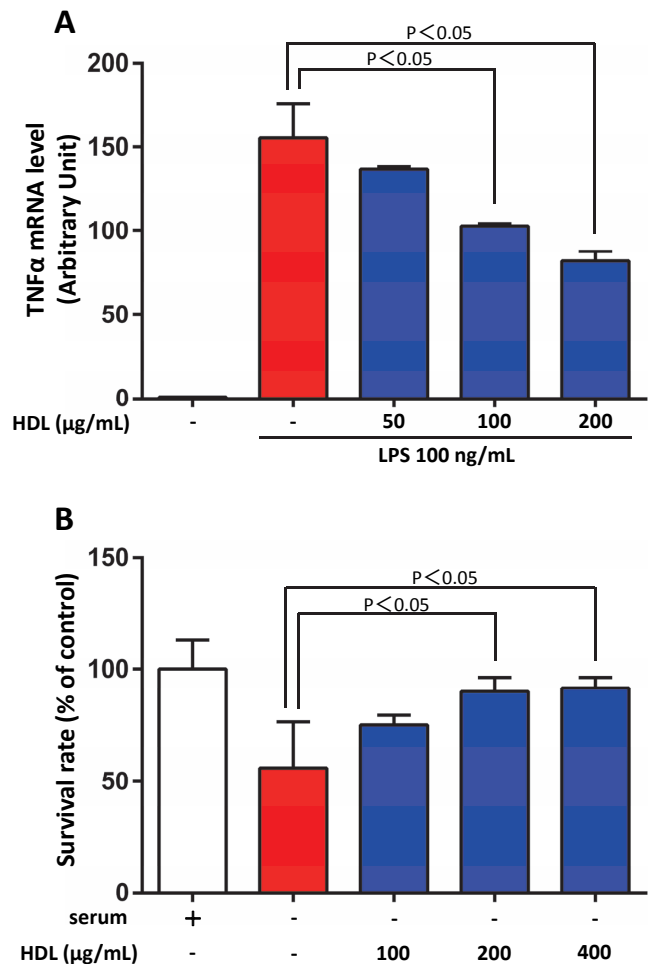


Fig. 1. HDL protected the cardiomyocytes from cell death and inflammatory damages

A) Rat neonatal cardiomyocytes were incubated with lipopolysaccharides (LPS) for 24 h. The mRNA level of TNF- α was evaluated by real-time PCR and calibrated with that of GAPDH. HDL attenuated LPS-induced expression of TNF- α in cardiomyocytes.

B) Rat neonatal cardiomyocytes were incubated in serum-depleted medium with or without HDL for 24 h, and cell viability was assessed by WST-1 assay. HDL protected the cardiomyocytes from serum starvation-induced cell death.

5. HDL Protects Cardiomyocytes by Activating Beneficial Signal Transducers in the Heart

Among HDL constituents that mediate diverse biological effects, S1P is one of the major lipid constituents of HDL; it has gained special attention because it may be responsible for many of the pleiotropic effects of HDL. The major source of S1P is hematopoietic cells (mainly erythrocytes, platelets, and leukocytes), whereas HDL serves as a major carrier of extracellular S1P in the plasma⁶²). Zhang *et al.* showed that HDL-associated S1P is the major determinant of the plasma S1P level and positively correlates with HDL-C and apoli-

poprotein A-I (apo A-I) levels⁶³. S1P is a biologically active sphingolipid metabolite involved in numerous cell activities, including proliferation, differentiation, survival, cytoskeletal rearrangements, cell motility, immunity, and angiogenesis^{64, 65}. These activities are mediated through binding of S1P to its cell surface G protein-coupled receptors, which comprise S1P₁₋₅⁶⁵. Although the expression of S1P₄ and S1P₅ is limited to the immune and nervous system, S1P₁, S1P₂, and S1P₃ are widely expressed in various cell types, including cardiomyocytes and endothelial cells⁶⁶. Tao *et al.* showed that treatment of isolated cardiomyocytes with HDL enhanced cell survival during hypoxia-reoxygenation⁶⁷. They found that HDL activates prosurvival signals, MEK1/2-ERK1/2 and PI3-kinase-Akt, via S1P₁ and S1P₃ receptors on cardiomyocytes, respectively. Conversely, Frias *et al.* demonstrated that HDL and its S1P component protected cardiomyocytes against doxorubicin-induced apoptosis through the S1P₂-ERK1/2-STAT3-mediated pathway⁶⁸. Thelmeier *et al.* reported that HDL and S1P reduced the infarct size by inhibition of inflammatory neutrophil recruitment and cardiomyocyte apoptosis in a mouse model of myocardial I/R⁶⁹. Cardioprotective effects were completely absent in S1P₃-deficient mice and was also canceled by pharmacological eNOS inhibition, indicating that HDL and S1P-mediated cardioprotection is dependent on S1P₃-mediated pathway by NO-dependent mechanisms. They proposed that strategies designed to rapidly elevate HDL levels in general and their S1P content may improve prognosis of the myocardium against ischemia and reperfusion. In addition to S1P, the same group also reported that SPC, another HDL-associated sphingophospholipid, directly protects against myocardial I/R injury *in vivo* via the S1P₃ receptor because of its diverse affinity to different receptor subsets⁷⁰.

Morel S *et al.* reported that HDL or S1P induced PKC-dependent phosphorylation of connexin43 (Cx43), a major myocardial gap junction protein responsible for rapid, synchronous transmission of cardiac action potential⁷¹. They also observed that short-term treatment with HDL or S1P at the onset of reperfusion limited the infarct size induced by I/R insult, in part, by affecting Cx43 gap junction channels in cardiomyocytes. Conversely, the survivor activating factor enhancement (SAFE) pathway, a novel powerful prosurvival signaling pathway that is associated with the activation of the signal transducer and activator of transcription 3 (STAT3) and tumor necrosis factor- α (TNF- α), protects against I/R injuries⁷². Frias MA *et al.* demonstrated that HDL protects against I/R injury by inhibition of mitochondrial mPTP opening, and this effect is mediated via activation of the SAFE pathway by HDL⁷³. This result suggests that HDL influences mi-

tochondrial function in cardiomyocytes.

We found that HDL protects the cardiomyocytes from cell death (Fig. 1B). In addition, we have revealed that HDL treatment improves cardiomyocyte viability under oxidative stress and that the PI3K/mTOR signaling pathway mediates these effects⁴⁵. In this study, we demonstrated that HDL treatment increased phosphorylation of the ribosomal protein S6 kinase (S6K) and BCL2-associated agonist of cell death (BAD) under oxidative stress via PI3K/mTOR. S6K is known as a downstream effector kinase of mTOR signaling and is related to anti-apoptotic signaling through maintenance of BAD phosphorylation. Shende *et al.* reported that mTOR-complex 1 activity was essential for preserving cardiac function. Its deletion impaired cardiac function, leading to dilated cardiomyopathy and high mortality⁷⁴. Correspondingly, they showed that the mTOR-complex 2 was associated with preserving left ventricular contractile function of pressure-overloaded mouse hearts. Cardiac dysfunction due to transverse aortic constriction was more severe after ablation of rictor, a specific component of mTOR2⁷⁵. Thus, in terms of cardiac protection, HDL could be an important activator of mTOR signaling.

Conclusion

Increasing evidence in clinical and in experimental studies has underlined that HDL exerts many beneficial effects in addition to anti-atherogenic effects on the heart. Given that HF usually develops gradually on the basis of multifactorial disorders, including vascular, myocardial, and metabolic disorders, pleiotropic properties of HDL potentially help in maintaining normal cardiac function (Fig. 2). HDL may protect the myocardium by functioning as an energy fuel, NO-mediated vasodilator, and signaling molecule and by promoting anti-inflammatory and anti-oxidative effects. Although recent clinical trials using cholesteryl ester transfer protein (CETP) inhibitors⁷⁶ or niacin⁷⁷ did not verify the beneficial effects of HDL-C increasing therapy, the primary outcome in these studies largely seems to depend on the onset of atherosclerotic vascular diseases. Conversely, it has been shown that pharmacological modification of HDL phospholipids can improve HDL functions^{78, 79}. A better understanding of the direct cardioprotective effects of HDL needs to be determined in humans for seeking novel therapeutic strategies of HF.

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None

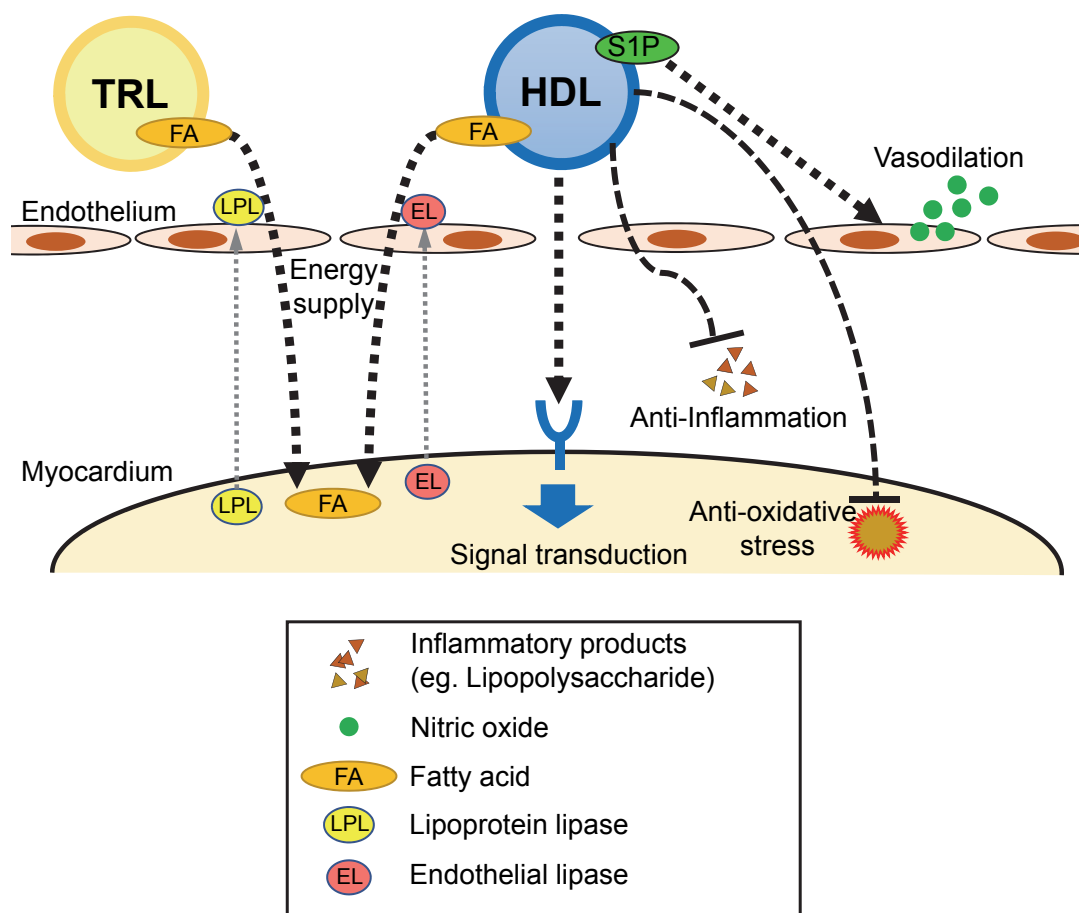


Fig.2. Potential molecular mechanisms for HDL-mediated direct cardioprotective effects

HDL may protect the myocardium by fueling energy from its fatty acid (FA), stimulating nitric oxide (NO)-mediated vasodilation, activating intracellular signaling pathways, and promoting anti-inflammatory and anti-oxidative effects. TRL, TG-rich lipoprotein.

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Conflicts of Interest

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