FAST**TRACK** BASIC SCIENCE

The Sirt1 activator SRT3025 provides atheroprotection in *Apoe*$^{-/-}$ mice by reducing hepatic Pcsk9 secretion and enhancing Ldlr expression

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Aims	The deacetylase sirtuin 1 (Sirt1) exerts beneficial effects on lipid metabolism, but its roles in plasma LDL-cholesterol regulation and atherosclerosis are controversial. Thus, we applied the pharmacological Sirt1 activator SRT3025 in a mouse model of atherosclerosis and in hepatocyte culture.
Methods and results	Apolipoprotein E-deficient (*Apoe*$^{-/-}$) mice were fed a high-cholesterol diet (1.25% w/w) supplemented with SRT3025 (3.18 g kg^{-1} diet) for 12 weeks. *In vitro*, the drug activated wild-type Sirt1 protein, but not the activation-resistant Sirt1 mutant; *in vivo*, it increased deacetylation of hepatic p65 and skeletal muscle Foxo1. SRT3025 treatment decreased plasma levels of LDL-cholesterol and total cholesterol and reduced atherosclerosis. Drug treatment did not change mRNA expression of hepatic LDL receptor (Ldlr) and proprotein convertase subtilisin/kexin type 9 (Pcsk9), but increased their protein expression indicating post-translational effects. Consistent with hepatocyte Ldlr and Pcsk9 accumulation, we found reduced plasma levels of Pcsk9 after pharmacological Sirt1 activation. *In vitro* administration of SRT3025 to cultured AML12 hepatocytes attenuated Pcsk9 secretion and its binding to Ldlr, thereby reducing Pcsk9-mediated Ldlr degradation and increasing Ldlr expression and LDL uptake. Co-administration of exogenous Pcsk9 with SRT3025 blunted these effects. Sirt1 activation with SRT3025 in *Ldlr*$^{-/-}$ mice reduced neither plasma Pcsk9, nor LDL-cholesterol levels, nor atherosclerosis.
Conclusion	We identify reduction in Pcsk9 secretion as a novel effect of Sirt1 activity and uncover Ldlr as a prerequisite for Sirt1-mediated atheroprotection in mice. Pharmacological activation of Sirt1 appears promising to be tested in patients for its effects on plasma Pcsk9, LDL-cholesterol, and atherosclerosis.
Keywords	Sirt1 • LDL-cholesterol • Pcsk9 • LDL receptor • Atherogenesis

Translational perspective

The deacetylase Sirt1 exerts beneficial effects on metabolic and inflammatory diseases. However, its effects on lipid metabolism and atherosclerosis remain controversial. Lowering plasma Pcsk9 emerges as a promising therapeutic strategy to lower plasma LDL-cholesterol. Unlike current antibody-based strategies that act on extracellular Pcsk9 activity, we found an alternative route to decrease Pcsk9-mediated Ldlr degradation: pharmacological Sirt1 activation reduced hepatic Pcsk9 secretion, increased Ldlr expression, and decreased plasma LDL-cholesterol and atherosclerosis in mice. Thus, Sirt1 activation appears as a promising approach to be tested for atheroprotection in patients.

Introduction

Atherosclerosis results from a complex interplay between innate and adaptive immunity involving modified LDL-cholesterol, activated endothelial cells, and monocyte-derived macrophages within the arterial wall. Sirt1 is a member of the sirtuin family of NAD$^+$-dependent deacetylases.[1] Studies on the role of Sirt1 in atherosclerosis have reported controversial effects.

Sirt1 has been shown to be atheroprotective in apolipoprotein E-deficient (*Apoe*$^{-/-}$) mice[2–4] whereas genetic overexpression of Sirt1 in LDL-receptor-deficient (*Ldlr*$^{-/-}$) mice enhanced atherosclerosis.[5] The role of Sirt1 in regulation of plasma LDL-cholesterol concentration, the key trigger of atherogenesis,[6] remains incompletely understood. Hepatic deletion of Sirt1 in C57BL/6 mice fed a high-cholesterol diet induced mild hypercholesterolemia.[7] Conversely, administration of a Sirt1 activating drug to elderly volunteers and cigarette smokers decreased plasma levels of total and LDL-cholesterol.[8,9] These studies suggest that Sirt1 regulates plasma LDL-cholesterol.

Hepatic Ldlr clears LDL-cholesterol from the blood stream.[10,11] Transcription of Ldlr is controlled by the sterol-responsive element binding protein 2 (Srebp2),[12] while its turnover depends on proprotein convertase subtilisin/kexin type 9 (Pcsk9), a serine protease.[13] Secreted Pcsk9 targets hepatic Ldlr for lysosomal degradation and thus prevents recycling of internalized Ldlr to the cell surface.[14]

We hypothesized that hepatic Ldlr mediates the effects of Sirt1 on plasma LDL-cholesterol levels and thus provides atheroprotection. To test this hypothesis, we fed *Apoe*$^{-/-}$ or *Ldlr*$^{-/-}$ mice a high-cholesterol diet supplemented with the novel Sirt1 activator SRT3025 or placebo, and investigated atherogenesis and lipid metabolism.

Methods

Detailed information is available in Supplementary material online.

Animals

Male *Apoe*$^{-/-}$ or *Ldlr*$^{-/-}$ mice on a pure C57BL/6J background were housed with a 12 h light–dark cycle and fed a high-cholesterol diet containing 1.25% cholesterol (D12108; Research Diets) supplemented with or without (SRT3025, 3.18 g kg^{-1} diet, provided by Sirtris, Cambridge, MA, USA) for 12 weeks starting at the age of 8 weeks. After this treatment period, mice were sacrificed (after overnight fasting), EDTA blood was taken and tissues were harvested. All experiments and animal care procedures were approved by the local veterinary authorities and carried out in accordance with our institutional guidelines.

Cell culture

AML12 mouse hepatoma cells were cultured in a 1:1 (v/v) mixture of DMEM and Ham's F12 medium supplemented with insulin (5 μg ml^{-1}), transferrin (5 μg ml^{-1}), selenium (5 ng ml^{-1}), dexamethasone (40 ng ml^{-1}), and 10% FBS (v/v). Where indicated, AML12 cells were exposed to 10 μM SRT3025 in 1% DMSO (v/v).

Statistics

All data are presented as means ± SD. Data distribution was assessed using the Kolmogorov–Smirnov test. Normally distributed data were compared by an unpaired two-tailed Student's *t*-test; for non-parametric data the Mann–Whitney test was used. Three or more groups were compared using a Kruskal–Wallis test followed by a Dunn's post-hoc comparison (non-parametric data). At least three independent experiments in triplicates were performed. Significance was accepted at $P < 0.05$. Analyses were done using Graphpad Prism (version 5.0d, 2010).
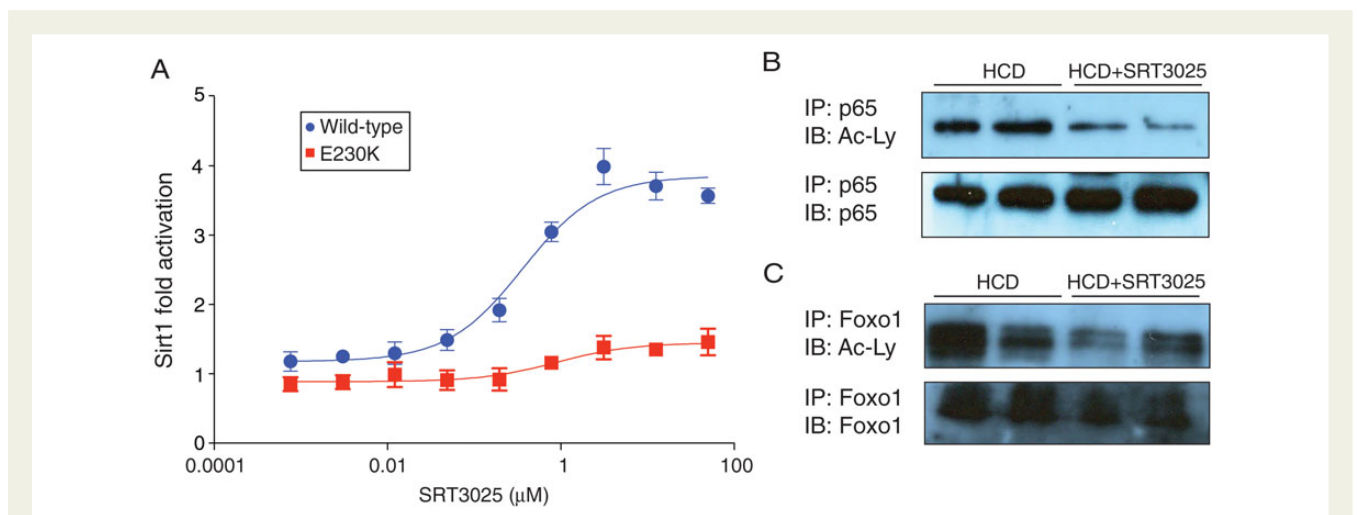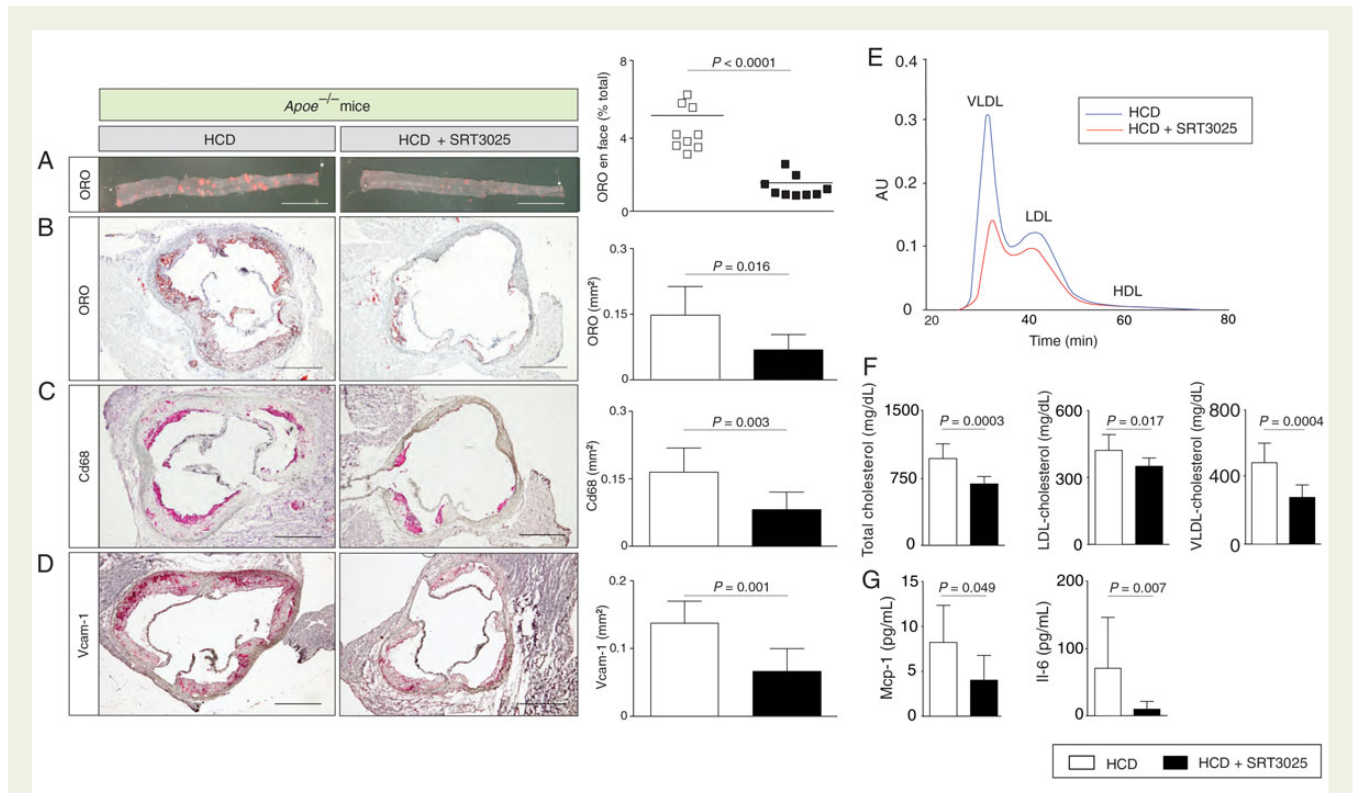
Results

SRT3025 reduces plasma cholesterol, inflammation, and atherosclerosis in Apoe$^{-/-}$ mice
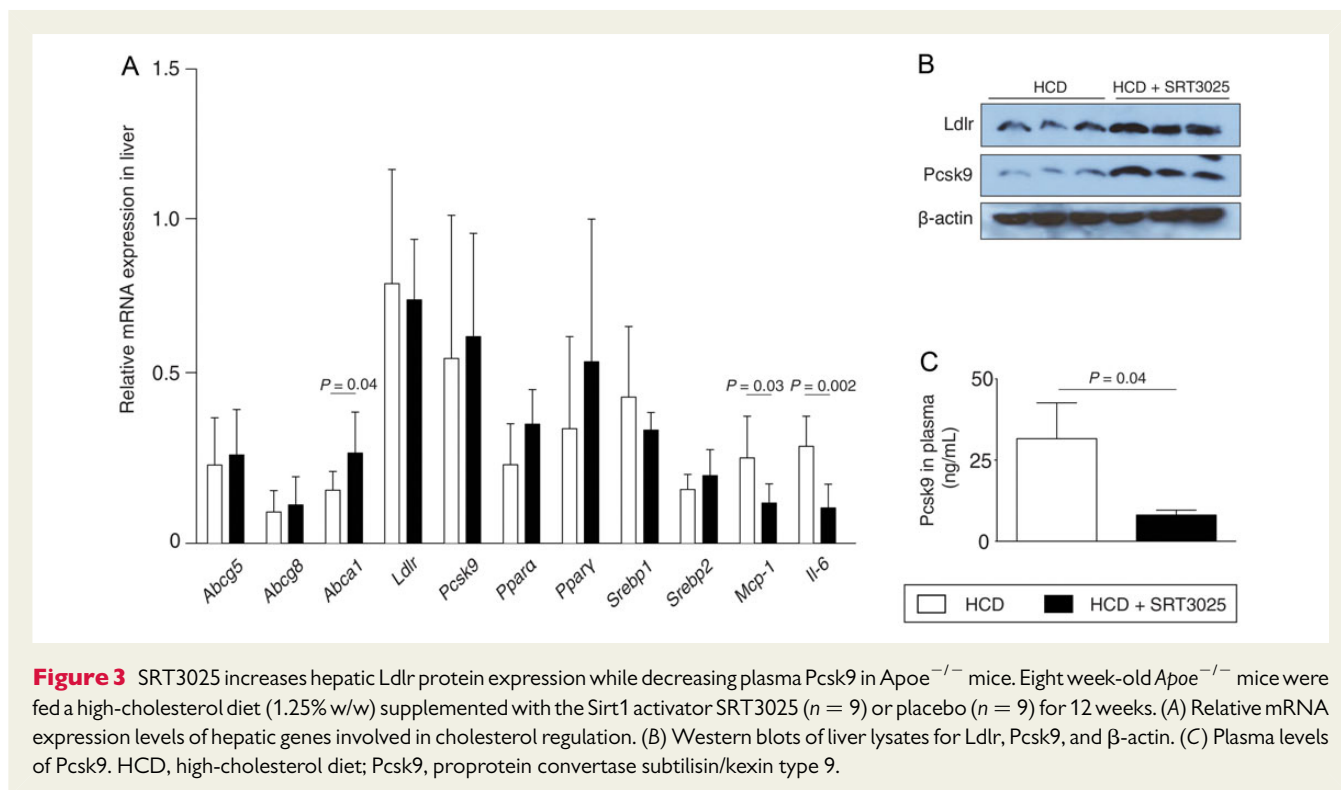
Histomorphometry of thoraco-abdominal aortae *en face* and cross-sections of aortic roots revealed a significant reduction in plaque size in SRT3025-treated *Apoe*$^{-/-}$ mice compared with placebo-treated controls (*Figure 1A* and *B*). Moreover, a marked reduction of Cd68-positive macrophages within the plaque and Vcam-1 expression in aortic roots was observed (*Figure 1C* and *D*). Interestingly, plasma levels of total-, LDL- and VLDL-cholesterol were significantly lower after SRT3025 treatment compared with placebo (*Figure 1E* and *F*). Triglycerides and HDL-cholesterol remained unchanged (Supplementary material online, *Figure S1A*). In addition, we observed reduced plasma levels of Mcp-1 and Il-6 (*Figure 1G*) and lower hepatic mRNA expression of these cytokines (*Figure 3A*).

These findings indicate that SRT3025 administration to *Apoe*$^{-/-}$ mice provides atheroprotection and reduces plasma LDL-cholesterol and inflammation.

SRT3025 mimics Sirt1 activity in vitro and in Apoe$^{-/-}$ mice

SRT3025 concentration-dependently activated wild-type Sirt1, but failed to activate the activation-resistant Sirt1 mutant E230K *in vitro* (*Figure 2A*). Increased deacetylation of known Sirt1 targets upon SRT3025 treatment, hepatic p65 and forkhead transcription factor family O1 (Foxo1) in skeletal muscle (*Figure 2B* and *C*) indicate successful Sirt1 activation *in vivo*. SRT3025 prevented an increase in weight gain and epididymal white adipose tissue without affecting food intake, thereby mimicking a caloric restriction phenotype

Figure 1 SRT3025 confers atheroprotection, reduces plasma cholesterol and systemic inflammation in Apoe$^{-/-}$ mice. Eight-week-old *Apoe*$^{-/-}$ mice were fed a high-cholesterol diet (1.25% w/w) supplemented with the Sirt1 activator SRT3025 (*n* = 9) or placebo (*n* = 9) for 12 weeks. Representative micrographs (left) and quantifications (right) of thoraco-abdominal aortae *en face* (A) and of aortic root cross sections (B−D) stained with ORO or immunohistochemically for macrophages (Cd68) or Vcam-1; (E) cholesterol distribution in the different lipoprotein subfractions separated by gel filtration chromatography; (F) Plasma total cholesterol, LDL-, and VLDL-cholesterol concentrations; (G) Plasma levels of Mcp-1 and Il-6. Scale bars in photomicrographs: 1 mm (A) and 500 μm (B−D). HCD, high-cholesterol diet; AU, arbitrary units; LDL, low-density lipoprotein; ORO, oil-red O; VLDL, very low-density lipoprotein; Vcam-1, vascular cell adhesion molecule 1; Mcp-1, monocyte chemoattractant protein 1; Il-6, interleukin 6.

Figure 2 SRT3025 mimics Sirt1 activity *in vitro* and in Apoe$^{-/-}$ mice. (A) Concentration-response curve of SRT3025 on the activity of wild-type Sirt1 and activation-resistant mutant E230K *in vitro*. (B, C) Western blots for acetylation status of Sirt1 target proteins (B) p65 and (C) Foxo1 immunoprecipitated from nuclear extracts of liver and skeletal muscle, respectively, from *Apoe*$^{-/-}$ mice fed a high-cholesterol diet (1.25% w/w) supplemented with the Sirt1 activator SRT3025 or placebo for 12 weeks. HCD, high-cholesterol diet; Ac-Ly, anti-acetyl-lysine antibody.

Figure 3 SRT3025 increases hepatic Ldlr protein expression while decreasing plasma Pcsk9 in Apoe$^{-/-}$ mice. Eight week-old *Apoe*$^{-/-}$ mice were fed a high-cholesterol diet (1.25% w/w) supplemented with the Sirt1 activator SRT3025 (*n* = 9) or placebo (*n* = 9) for 12 weeks. (*A*) Relative mRNA expression levels of hepatic genes involved in cholesterol regulation. (*B*) Western blots of liver lysates for Ldlr, Pcsk9, and β-actin. (*C*) Plasma levels of Pcsk9. HCD, high-cholesterol diet; Pcsk9, proprotein convertase subtilisin/kexin type 9.

(Supplementary material online, *Figure S1B−D*). Pharmacokinetic analysis of the drug in *Apoe*$^{-/-}$ mice showed that the drug indeed reached target tissues (Supplementary material online, *Table S1*). Plasma protein levels of glutamic oxaloacetic transaminase, glutamic pyruvic transaminase, and alkaline phosphatase were not different between drug- and placebo-treated mice (Supplementary material online, *Figure S1E*).

SRT3025 increases hepatic Ldlr expression and Pcsk9 accumulation in Apoe$^{-/-}$ mice

Pharmacological Sirt1 activation increased liver expression of *Abca1*, but did not affect *Abcg5*, *Abcg8*, *Ldlr*, *Pcsk9*, *Pparα*, *Pparγ*, *Srebp1*, and *Srebp2* (*Figure 3A*). Despite no changes in *Ldlr* and *Pcsk9* mRNA expression, both were markedly increased at the protein level (*Figure 3A* and *B*). This intracellular accumulation of Pcsk9 protein with no change in mRNA suggests a disturbed transport and/or secretion of the protein. In agreement with this, we found reduced plasma Pcsk9 protein levels following pharmacological Sirt1 activation in *Apoe*$^{-/-}$ mice compared with placebo-treated controls (*Figure 3C*).

SRT3025 increases Ldlr expression and Pcsk9 accumulation in AML12 hepatocytes

To delineate the mechanisms by which SRT3025 affects Ldlr protein expression, we performed *in vitro* experiments administering SRT3025 to mouse hepatoma AML12 cells. We observed a concentration- and time-dependent increase in Ldlr and Pcsk9 protein expression upon SRT3025 administration in cell lysates (*Figure 4A* and *B*). As observed *in vivo*, mRNA levels of *Ldlr* and

Pcsk9 were not altered by SRT3025 (*Figure 4C*), indicating that post-translational effects cause the changes in protein expression.

Incubation of AML12 cells with 10 μM SRT3025 was associated with a time-dependent decrease in Pcsk9 secretion into the supernatant (*Figure 4D*). Moreover, co-immunoprecipitation of endogenous Pcsk9 and Ldlr after 24 h incubation with 10 μM SRT3025 revealed that Pcsk9 binding to Ldlr was impaired after SRT3025 treatment compared with vehicle control (*Figure 4E*). Thus, the question arises whether the increase in hepatic Ldlr protein expression upon Sirt1 activation is related to limited extracellular availability of Pcsk9 and/or a defective degradation of internalized Ldlr.

SRT3025 impairs Pcsk9-dependent degradation of Ldlr in AML12 hepatocytes

To address the above question, we stimulated AML12 cells with 10 μM SRT3025 for 24 h and compensated for the decrease in extracellular Pcsk9 by adding exogenous active Pcsk9 protein. Co-administration of Pcsk9 [3 ng ml^{-1}, based upon concentrations measured in the supernatants of untreated AML12 (*Figure 4D*)] and SRT3025 to AML12 hepatocytes attenuated the drug-dependent increase in Ldlr protein expression (*Figure 5A*). These data indicate that the internalization and degradation process of Ldlr is not defective and that limited extracellular availability of Pcsk9 contributes to the increase in Ldlr protein expression.

Fluorescence analysis revealed an increase in labelled LDL uptake upon 10 μM SRT3025 treatment compared with vehicle controls (*Figure 5B*), suggesting a *functional* relevance of the SRT3025-dependent increase in Ldlr expression. Moreover, co-administration of exogenous active Pcsk9 also attenuated the drug-induced increase
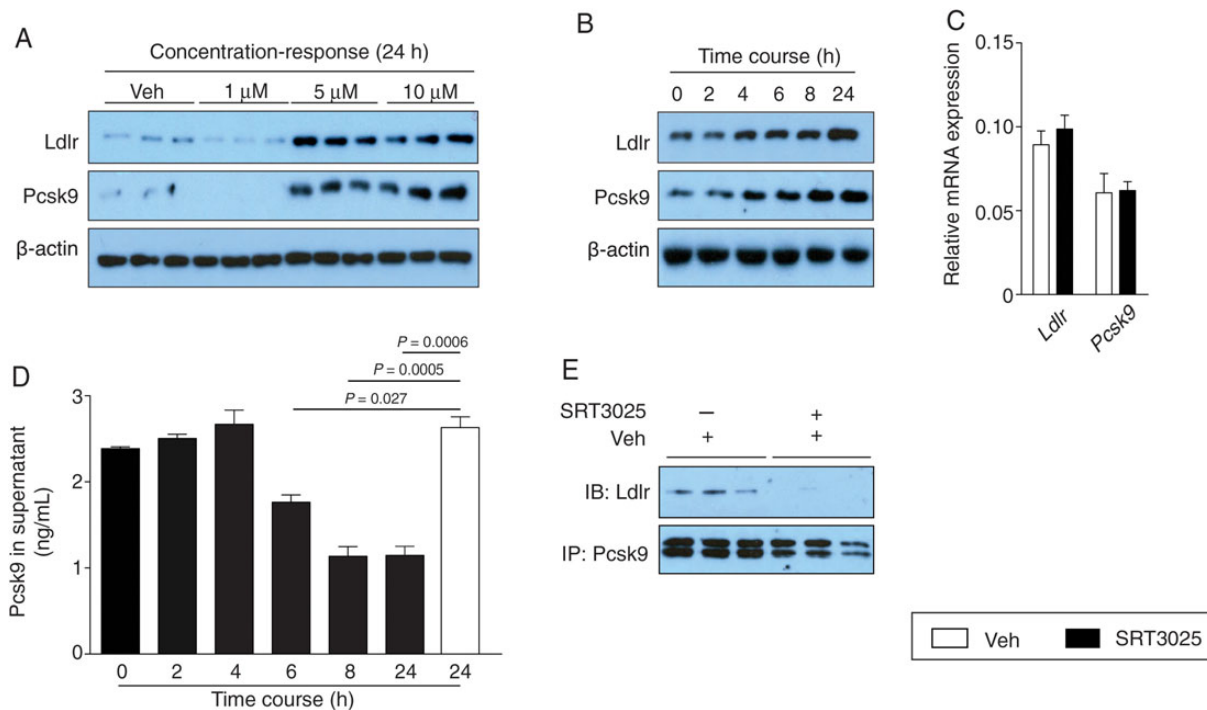
Figure 4 SRT3025 increases Ldlr expression in AML12 hepatocytes and decreases Pcsk9 in the supernatant. Western blots of Ldlr, Pcsk9, and β-actin in cultured AML12 cells (*A*) treated with SRT3025 at indicated concentrations for 24 h and (*B*) incubated with 10 μM SRT3025 for the times indicated. (C) Relative mRNA expression levels of *Ldlr* and *Pcsk9* in AML12 cells after incubation with 10 μM SRT3025 for 24 h. (D) Pcsk9 protein levels in the supernatant of AML12 cells incubated with 10 μM SRT3025 for the times indicated. (*E*) Pcsk9 immunoprecipiated from AML12 cells incubated with vehicle (Veh, DMSO) or 10 μM SRT3025, and blotted for Ldlr and Pcsk9. Pcsk9, proprotein convertase subtilisin/kexin type 9.
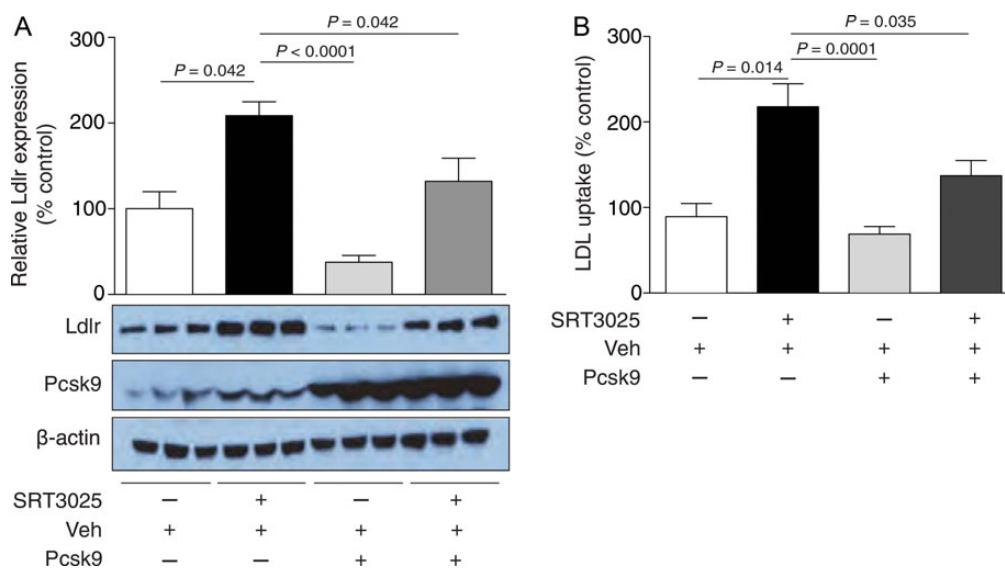
Figure 5 Exogenous Pcsk9 prevents SRT3025-induced increase in Ldlr expression and activity in AML12 hepatocytes. (*A*) Western blot and corresponding quantifications of AML12 cells treated with vehicle (Veh, DMSO) or 10 μM SRT3025 and incubated with or without Pcsk9 active protein (3 ng ml^{-1}) for 1 h. (*B*) BODIPY-labelled LDL uptake in AML12 cells incubated for 24 h with 10 μM SRT3025 or Veh and incubated with or without Pcsk9 active protein (3 ng ml^{-1}) for 1 h. Fluorescence intensity and western blot quantifications are given as percentage of Veh control. BODIPY, 4,4-difluoro-3a,4a-diaza-s-indacene; AU, arbitrary units; Pcsk9, proprotein convertase subtilisin/kexin type 9.

in LDL uptake (*Figure 5B*), consistent with the observed attenuation of Ldlr protein expression (*Figure 5A*).

These data indicate that SRT3025 decreases hepatic Pcsk9 release, impairs Pcsk9 binding to hepatic Ldlr, and thereby prevents hepatic Ldlr degradation. These events result in increased hepatic Ldlr expression and enhanced LDL-cholesterol plasma clearance.

Increased Ldlr protein expression in AML12 hepatocytes is mediated by Sirt1

To assess whether this increase in Ldlr protein expression is Sirt1-dependent, *Sirt1* knockdown in AML12 cells was performed in the presence of 10 μM SRT3025. In contrast to control scramble siRNA-treated cells, cells transfected with *Sirt1* siRNA did not show an increase in Ldlr expression upon SRT3025 addition (*Figure 6A*). Conversely, genetic overexpression of *Sirt1* increased Ldlr protein expression in AML12 cells compared with control transfection (*Figure 6B*). Thus, Sirt1 is required for SRT3025-induced increase in Ldlr protein expression.

## Genetic deletion of Ldlr abolishes atheroprotective effects of SRT3025 in vivo

Given the critical role of hepatic Ldlr in the clearance of plasma cholesterol and our observation of increased hepatic Ldlr expression in SRT3025-treated $Apoe^{-/-}$ mice, we investigated whether Ldlr accounts for the atheroprotective effects of SRT3025. For that purpose, similar experiments were performed in $Ldlr^{-/-}$ mice. Plaque analyses of thoraco-abdominal aortae *en face* and cross-sections of aortic roots revealed no difference in the extent of atherosclerosis between drug- and placebo-treated mice (*Figure 7A* and *B*). Furthermore, the number of plaque-resident macrophages (Cd68) and Vcam-1 expression in aortic roots did not differ between the groups (*Figure 7C* and *D*).

Plasma lipids showed an increase in total and VLDL-cholesterol in SRT3025-treated $Ldlr^{-/-}$ mice compared with placebo-treated controls (*Figure 7E* and *F*), whereas plasma LDL-cholesterol, HDL-cholesterol, and triglycerides were unaffected by drug treatment (*Figure 7F* and Supplementary material online, *Figure S2A*). As in $Apoe^{-/-}$ mice, SRT3025 prevented an increase in weight gain and epididymal white adipose tissue without affecting food intake (Supplementary material online, *Figure S2B−D*), and lowered plasma levels of pro-inflammatory cytokines Mcp-1 and Il-6 (*Figure 7G*). Compared with $Apoe^{-/-}$ mice, baseline plasma Pcsk9 levels in $Ldlr^{-/-}$ mice were about 20-fold higher (*Figure 7G*). SRT3025 induced a minimal but significant increase in plasma Pcsk9 levels in $Ldlr^{-/-}$ mice (*Figure 7G*). Pharmacological Sirt1 activation decreased the expression of *Ppara*, but did not affect *Abcg5*, *Abcg8*, *Abca1*, *Pcsk9*, *Pparγ*, *Srebp1*, *Srebp2*, *Mcp-1* and *Il-6* (Supplementary material online, *Figure S2E*).
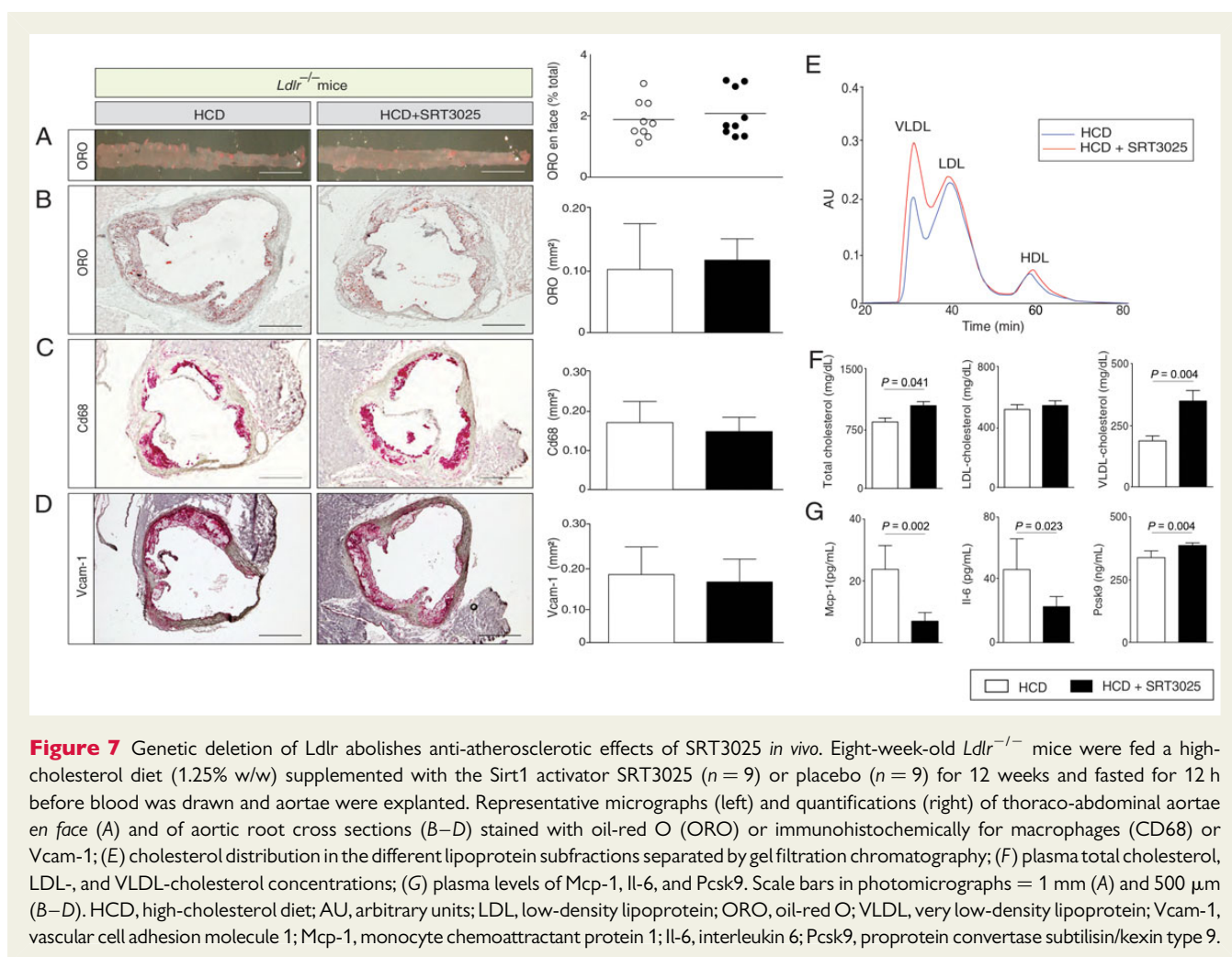
Discussion

We demonstrate that pharmacological Sirt1 activation using SRT3025 attenuated Pcsk9 secretion from murine hepatocytes *in vitro* and lowered plasma levels of Pcsk9 in atherosclerosis-prone $Apoe^{-/-}$ mice *in vivo*. As a consequence, hepatocyte Ldlr expression and activity were increased leading to a decrease in plasma LDL-cholesterol and atherosclerotic plaques in $Apoe^{-/-}$ mice. None of these variables were changed in $Ldlr^{-/-}$ mice despite a similar decrease in systemic inflammation. Thus, our findings identify reduced Pcsk9 secretion and increased Ldlr expression as novel downstream effects of Sirt1 activity and highlight the potential of pharmacological Sirt1 activation as a novel anti-atherosclerotic strategy.

SRT3025 was found to activate wild-type Sirt1 protein but failed to activate the E230K mutant, an activation-resistant Sirt1 protein
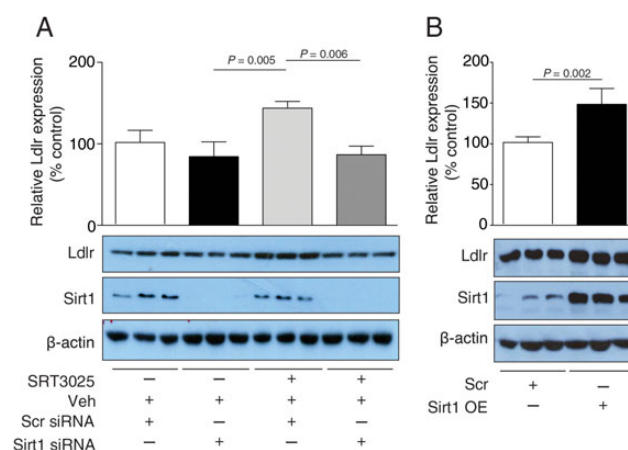
Figure 6 Sirt1 knockdown reduces and Sirt1 overexpression enhances SRT3025-induced increase in Ldlr expression in AML12 hepatocytes. (*A*) Western blots of Ldlr, Sirt1, and β-actin with corresponding quantifications of AML12 cell lysates following transfection with Sirt1 siRNA or scrambled siRNA for 24 h and incubated with 10 μM SRT3025 or vehicle (Veh, DMSO) for additional 24 h. (*B*) Western blots of Ldlr, Sirt1, and β-actin with corresponding quantifications of AML12 cell lysates following Sirt1 overexpression plasmid or scramble control for 24 h and incubated with 10 μM SRT3025 or Veh for additional 24 h. Western blot quantifications are given as a percentage of Veh control. Scr, scramble plasmid; Sirt1 OE, Sirt1 overexpression plasmid.

Figure 7 Genetic deletion of Ldlr abolishes anti-atherosclerotic effects of SRT3025 *in vivo*. Eight-week-old $Ldlr^{-/-}$ mice were fed a high-cholesterol diet (1.25% w/w) supplemented with the Sirt1 activator SRT3025 ($n = 9$) or placebo ($n = 9$) for 12 weeks and fasted for 12 h before blood was drawn and aortae were explanted. Representative micrographs (left) and quantifications (right) of thoraco-abdominal aortae *en face* (A) and of aortic root cross sections (B–D) stained with oil-red O (ORO) or immunohistochemically for macrophages (CD68) or Vcam-1; (E) cholesterol distribution in the different lipoprotein subfractions separated by gel filtration chromatography; (F) plasma total cholesterol, LDL-, and VLDL-cholesterol concentrations; (G) plasma levels of Mcp-1, Il-6, and Pcsk9. Scale bars in photomicrographs = 1 mm (A) and 500 μm (B–D). HCD, high-cholesterol diet; AU, arbitrary units; LDL, low-density lipoprotein; ORO, oil-red O; VLDL, very low-density lipoprotein; Vcam-1, vascular cell adhesion molecule 1; Mcp-1, monocyte chemoattractant protein 1; Il-6, interleukin 6; Pcsk9, proprotein convertase subtilisin/kexin type 9.

(due to a mutation at position 230). Thus, similar to previously described Sirt1 activators,[15] SRT3025 acts by allosteric binding to Sirt1 at the lysine site 230, which is located at its catalytic core. Analyses of the acetylation status of the Sirt1 target Foxo1 in skeletal muscle and p65 in the liver show that SRT3025 increases deacetylation of Sirt1 target proteins *in vivo*. Furthermore, the increase in Ldlr protein expression in AML12 cells *in vitro* in response to stimulation with the Sirt1 activator was time- and concentration- dependent and could be attenuated by knockdown of *Sirt1*, while genetic *Sirt1* overexpression mimicked the effects of SRT3025. These data indicate that the SRT3025-associated changes in Ldlr expression are Sirt1-dependent.

Endothelial-specific overexpression of *Sirt1* in $Apoe^{-/-}$ mice was reported to protect against atherosclerosis by increasing endothelial eNOS activity.[2] Furthermore, using partial *Sirt1* deletion in $Apoe^{-/-}$ mice, we have shown that Sirt1-induced inhibition of NFκB impairs endothelial expression of the macrophage scavenger receptor Lox-1, and thus attenuates foam cell formation.[3] Although these findings address beneficial effects of Sirt1 in a particular setting of atherosclerosis, they provide limited insight into the effects of Sirt1 on cholesterol metabolism. Interestingly, hepatic deletion of *Sirt1* in C57BL/6 mice fed a high-cholesterol diet was associated with a

mild increase in plasma LDL-cholesterol,[7] suggesting that hepatic Sirt1 regulates plasma LDL-cholesterol. In line with these findings, $Apoe^{-/-}$ mice treated with SRT3025 showed an increase in hepatic Ldlr expression accompanied by a significant reduction in plasma LDL-cholesterol levels. Moreover, the extent of aortic atherosclerosis and the plasma levels of LDL-cholesterol were unchanged in $Ldlr^{-/-}$ mice, highlighting the importance of Ldlr for the athero-protective and lipid-lowering effects of Sirt1. Of note, we observed a similar reduction in plasma levels of pro-inflammatory cytokines in both $Apoe^{-/-}$ and $Ldlr^{-/-}$ mice, whereas a reduction in plaque formation was only observed in $Apoe^{-/-}$ mice with endogenous Ldlr. Therefore, our data suggest that not the reduction in inflammation, which still occurs in the absence of Ldlr, but the decrease in plasma LDL-cholesterol accounted for reducing atherosclerosis in $Apoe^{-/-}$ mice treated with SRT3025. Moreover, since we observed a reduction in weight gain in both $Apoe^{-/-}$ and $Ldlr^{-/-}$ mice despite unaltered food intake, the atherosclerotic phenotype is also independent of changes in body weight. Taken together, we demonstrate that the increased expression of hepatic Ldlr is essential for the cholesterol-lowering effects of SRT3025.

In line with our findings, clinical studies with another Sirt1 activator have shown a reduction in plasma total cholesterol and

LDL-cholesterol.[8,9] The presently observed reduction in VLDL-cholesterol in mice has yet to be assessed in patients. Furthermore, constitutive Sirt1 overexpression in *Ldlr*$^{-/-}$ mice was associated with increased atherosclerosis.[5] Pharmacological Sirt1 activation using an oral Sirt1 activator and constitutive genetic *Sirt1* overexpression are likely to differ in efficiency and may exert differential effects on genes involved in lipid metabolism. Moreover, a difference in NAD$^+$ availability between both models may affect Sirt1 activity.[16] It remains to be seen whether constitutive *Sirt1* overexpression is associated with enhanced hepatic expression of Ldlr in *Apoe*$^{-/-}$ mice.

Ldlr plays a critical role in the regulation of plasma LDL-cholesterol levels,[10,11] a key determinant of atherogenesis.[17] Mice overexpressing hepatic Ldlr have reduced plasma LDL-cholesterol levels and are protected from plaque formation, whereas *Ldlr*-deficient mice exhibit increased levels of plasma LDL- and VLDL-cholesterol and are prone to atherosclerosis when exposed to a high-cholesterol diet.[4,18] We show that Ldlr protein expression is increased despite no change in *Ldlr* mRNA, indicating a post-translational mechanism. Indeed, degradation of Ldlr protein in liver cells is regulated via secreted Pcsk9, a serine protease that predominantly originates from the liver.[14,19] By binding to the EGF-A domain of Ldlr, Pcsk9 targets this receptor for lysosomal degradation rather than for recycling to the cell surface.[20,21] Ldlr was reported to be the main route of Pcsk9 clearance.[22] In agreement with this, we found markedly increased plasma Pcsk9 levels in mice lacking *Ldlr*.

In our study, both SRT3025 treatment and *Sirt1* overexpression increased Ldlr protein expression in AML12 cells, while reducing the concentration of Pcsk9 in the supernatant and lowering the amount of Pcsk9 bound to Ldlr, despite no change in Pcsk9 transcription. Notably, exogenous addition of active Pcsk9 to AML12 cells treated with SRT3025 decreased Ldlr protein expression and reduced LDL uptake by the cells. These data indicate that Ldlr internalization and degradation are not disrupted by SRT3025 treatment and can be re-induced upon exogenous addition of Pcsk9. Moreover, these data demonstrate that it is the limited extracellular availability of Pcsk9 that contributes to the increase in Ldlr protein expression, suggesting that plasma Pcsk9 levels are an important determinant of hepatic Ldlr protein surface expression in our model. The mechanisms by which Sirt1 affects Pcsk9 secretion remain to be investigated. Yet, the specific investigation of Pcsk9-dependent alterations on atherosclerosis may be hampered by reciprocal changes in Ldlr.[22]

Conclusions and perspectives

Our study describes a novel mechanism that causally links Sirt1 to the metabolism of LDL-cholesterol *in vitro* and *in vivo*. We demonstrate that Sirt1 activation increases hepatic Ldlr protein expression through a reduction in Pcsk9-mediated Ldlr degradation leading to decreased plaque formation.

Of note, statin therapy not only increases hepatic Ldlr, but also plasma Pcsk9 activity, thus limiting its effect on LDL-cholesterol.[23] Antibody-induced inhibition of Pcsk9 binding to Ldlr is currently investigated as a very promising therapy to reduce plasma LDL-cholesterol and atherosclerosis in patients.[24,25] Our study demonstrates a Sirt1-dependent alternative route to target Pcsk9 activity in a mouse model. Thus, a Sirt1 activator combined with a statin may confer the advantage of lowering plasma Pcsk9 activity. Future

studies are needed to translate the effects of pharmacological Sirt1 activation to patients.

Supplementary material

Supplementary material is available at *European Heart Journal* online.

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