

Targeting cholesterol at different levels in the mevalonate pathway protects fatty liver against ischemia–reperfusion injury

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Background & Aims: Liver steatosis enhances ischemia/reperfusion (I/R) injury and is considered a primary factor in graft failure after liver transplantation. Although previous reports have shown a role for qualitative steatosis (macrovesicular vs. microvesicular) in hepatic I/R injury, no studies have compared side by side the specific contribution of individual lipids accumulating in fatty liver to I/R damage.

Methods: We used nutritional and genetic models of micro and macrovesicular fatty livers exhibiting specific lipid profiles to assess their susceptibility to normothermic I/R injury.

Results: Unlike choline-deficient (CD) diet-fed mice, characterized by predominant liver triglycerides/free fatty acids (TG/FFA) accumulation, mice fed a cholesterol-enriched (HC) diet, which exhibited enhanced hepatic cholesterol loading in mitochondria, were highly sensitive to I/R-induced liver injury. *In vivo* two-photon confocal imaging revealed enhanced mitochondrial depolarization and generation of reactive oxygen species following hepatic I/R in HC-fed but not in CD-fed mice, consistent with decreased mitochondrial GSH (mGSH) observed in HC-fed mice. Moreover, ob/ob mice, characterized by increased hepatic TG, FFA, and cholesterol levels, were as sensitive to I/R-mediated liver injury as mice fed the HC diet. Livers from ob/ob mice displayed increased StAR expression and mitochondrial cholesterol accumulation, resulting in mGSH depletion. Interestingly, atorvastatin

therapy or squalene synthase inhibition *in vivo* attenuated StAR overexpression, mitochondrial cholesterol loading, and mGSH depletion, protecting ob/ob mice from I/R-mediated liver injury.

Conclusions: Cholesterol accumulation, particularly in mitochondria, sensitizes to hepatic I/R injury, and thus represents a novel target to prevent the enhanced damage of steatotic livers to I/R-mediated damage.

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Introduction

Liver transplantation is an effective treatment for chronic end-stage liver disease and acute liver failure. The decreasing number or quality of organs available for transplantation represents a serious hurdle for this therapy, leading to the use of suboptimal-quality grafts, such as steatotic livers, which may compromise the overall success of liver transplantation [1]. Due to the rising prevalence of obesity and type II diabetes among the general population, fatty livers constitute an expanding pool of marginal grafts available for transplantation. Hepatic steatosis is known to impose an additional risk of primary graft dysfunction [1]. Fat accumulation within hepatocytes increases cell volume resulting in a decreased sinusoidal space and impaired microcirculatory blood flow [2]. Nevertheless, the molecular mechanisms, underlying the susceptibility of fatty livers to ischemia/reperfusion (I/R) injury, remain incompletely understood.

Based on the morphology, size, and percentage of hepatocytes exhibiting cytoplasmic fat deposits, it has been previously reported that fatty livers with macrovesicular steatosis are more susceptible to I/R injury than those with microsteatosis, correlating with impaired hepatic perfusion and portal vein flow [3,4]. However, the contribution of microvesicular steatosis to graft dysfunction after transplantation remains unclear. For instance, while some studies showed that livers with moderate microsteatosis are non-functional after transplantation [5], other reports discarded a role for microvesicular steatosis on graft or patient survival [6,7]. Hence, a better understanding of the mechanisms

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Abbreviations: CD, choline-deficient diet; DCF, 2'-7'-dichlorofluorescein; FFA, free fatty acids; HC, hypercholesterolemic diet; HMGCoA R, hydroxymethylglutaryl CoA reductase; I/R, ischemia/reperfusion; LDL, low density lipoprotein; MDA, malondialdehyde; MPT, mitochondrial permeability transition; SAM, S-adenosyl-L-methionine; StAR, steroidogenic acute regulatory protein; TMRE, tetramethylrhodamine ethyl ester; TG, triglycerides; VLDL, very low density lipoprotein.



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involved in the susceptibility of fatty livers to I/R injury may increase the availability of donor organs, providing a better chance for liver transplantation.

Hepatic steatosis is characterized by the accumulation of a heterogeneous population of lipids, predominantly triglycerides (TG), free fatty acids (FFA), and cholesterol (esterified and unesterified) [8]. While hepatic FFA and cholesterol can derive from adipose tissue or LDL uptake from the circulation, they can be synthesized *de novo* in the endoplasmic reticulum by pathways controlled at the transcriptional level by transcription factors SREBP-1c and SREBP-2, respectively [8,9]. Triglycerides are synthesized from FFA and can be stored in lipid droplets or packed as VLDL particles for export to extrahepatic organs. Although previous studies have addressed the impact of qualitative steatosis (macrovesicular vs. microvesicular) to hepatic I/R injury [3–7], no studies have compared side-by-side the specific contribution of the individual lipids accumulating in fatty liver to I/R injury. In order to discern whether the type rather than the amount of fat contributes to the susceptibility of fatty livers to I/R injury, we used nutritional models of hepatic steatosis characterized by predominant TG/FFA or cholesterol accumulation by feeding mice a diet deficient in choline or enriched in cholesterol, respectively [10]. In addition, we used ob/ob mice, a genetic model of hepatic macrovesicular steatosis and cholesterol accumulation, to analyze the influence of cholesterol modulation by blocking hydroxymethylglutaryl CoA reductase (HMGCoAR), the regulatory enzyme in the mevalonate pathway, which is transcriptionally controlled by SREBP-2, or by inhibition of squalene synthase, which catalyzes the first committed step towards cholesterol synthesis [11]. Our data indicate that cholesterol and its trafficking to mitochondria critically contribute to the susceptibility of fatty liver to I/R injury and that targeting may represent a previously unrecognized opportunity for a better option in liver transplantation.

Materials and methods

Animals, diets, and treatments

Male C57BL/6 mice were purchased from Charles River Laboratories (Wilmington, MA). ob/ob Mice (in the C57BL/6 background) were obtained from The Jackson Laboratories (Bar Harbor, Maine). 8–10 week old mice (the number of mice per group is detailed in the corresponding figure legend) were housed under specific pathogen-free conditions with controlled temperature and humidity on a 12 h light–dark cycle. Mice were fed either a choline-deficient (CD) methionine sufficient diet or a sodium cholate-supplemented hypercholesterolemic (2%, HC) diet for 2 days (Dyets Inc., Bethlehem, PA), as described previously [10]. Control mice received the standard chow pellets. ob/ob Mice were dosed daily by oral gavage with atorvastatin (Pfizer) (10 mg/kg), the squalene synthase inhibitor YM-53601 (Sigma) (15 mg/kg) or vehicle 7 days before being subjected to partial normothermic I/R. The experimental animal protocol was approved by the Institut d'Investigacions Biomèdiques Agustí Pi I Sunyer (IDIBAPS) Animal Care and Use Committee.

Partial hepatic ischemia

Male wild-type mice were anesthetized using a vaporizer system to deliver isoflurane/O₂ inhalation. After a midline laparotomy, hepatic inflow to the median and left lobes was occluded by application of a micro-vascular clamp (Biemer clip, 0.29–0.39 N) for 60–90 min, as described previously [12,13], to prevent hepatic blood flow for 90 min. Mesenteric venous congestion was prevented by portal decompression through the right and caudate lobes. Blood samples and liver

biopsies were taken at different periods after reperfusion for further evaluation, typically 4–6 h post-reperfusion when massive liver injury is observed [12,13]. Control animals were sham operated.

Mitochondria isolation

In some cases, livers after reperfusion were collected and processed for mitochondrial isolation by Percoll density gradient centrifugation, checking for mitochondrial purity and cross contamination with extramitochondrial compartments, as described previously [10,14].

In vivo two-photon confocal imaging

Hepatic partial warm ischemia was performed for 60 min in mice fed the CD or HC diets. After reperfusion, the left lobe of the liver was taken out via an abdominal incision, gently pressuring the abdomen to allow the edge of the lobe to emerge, as described before [15]. 2'-7'-Dichlorofluorescein (DCF, 200 μ M, incubated for 45 min) and tetramethylrhodamine ethyl ester (TMRM, 5 μ M incubated for 30 min), to monitor reactive oxygen species generation and mitochondrial membrane potential, respectively, were added on the lobe for 30–45 min and imaged using one photon excitation at 485 nm and emission at 380–520 nm for the DCF, and excitation at 516 nm and emission at 582–677 nm for the TMRM. Both emissions were acquired with an internal spectral detector (PMT) at high speed (31 frames, line average 4) in order to avoid movement from animal breathing and heart beating during acquisition. Images were collected in a 512 \times 512 format, zoom 1.7, and pinhole completely open. Imaging of the liver of living mice was performed using spectral confocal inverted microscope Leica TCS SP5, equipped with 63 \times glycerol immersion (NA1.4) objective and near infrared laser 1.2 ps (titanium-sapphire IR MaiTai Broad laser, 710–990 nm, Broad Band, Spectra Physics), resonant scan (video rate speed), and incubation heating system.

Biochemical determinations

TG, FFA, and cholesterol in plasma and liver homogenates were analyzed by the Clinical Core Laboratories at the Clinic and Provincial Hospital Barcelona on an ADVIA 2400 Chemistry System (Siemens Medical Solutions, Erlangen, Germany) using commercial available kits, ADVIA Chemistry System 1650 (Bayer-Siemens) and CHOD-PAP (Roche Diagnostics). TG, FFA, and cholesterol values in liver homogenates were corrected for protein content.

Total and unesterified cholesterol analysis

Total cholesterol determination in hepatic or mitochondrial extracts (5 mg) was performed upon saponification (alcoholic KOH at 60 °C for 30 min) followed by addition of 10 ml of hexane and 3 ml of distilled water. Hexane layer aliquots were evaporated under nitrogen and used for cholesterol measurement. Free cholesterol was measured from unsaponified samples and analyzed by HPLC using Bondapak C18 10- μ m reversed-phase column (30 cm, 4 mm inner diameter; Waters, Barcelona, Spain), and 2-propanol:acetonitrile:water (60:30:10) as the mobile phase, at a flow rate of 1 ml/min as described [10].

Total and mitochondrial GSH determination

GSH and GSSG in hepatic homogenates or mitochondrial fractions were measured after 10% trichloroacetic acid precipitation by HPLC, as described previously [16,17]. In some cases, total GSH levels in either cytosol or mitochondria were determined by the recycling assay, as reported previously [18,19].

Liver damage and lipid peroxidation

After reperfusion, livers were fixed with 10% formalin, paraffin-embedded, and sections (5 μ m) stained with hematoxylin and eosin (H&E) using standard methods. Slides were then examined with a Zeiss Axioplan microscope (Göttingen, Germany) equipped with a Nikon DXM1200F digital camera (Tokyo, Japan). Serum ALT levels were measured by the Centro de Diagnóstico Médico (Hospital Clinic, Barcelona, Spain). Lipid peroxidation in liver samples was determined after the production of malondialdehyde (MDA), using the thiobarbituric acid (TBA) method as described previously [13].

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StAR expression

Hepatic StAR mRNA levels from ob/ob mice were determined by quantitative real-time RT-PCR analyses (primer sense, CCACCCCTAGCAGCTGGA; primer anti-sense, TCCTGGTCACTGTAGAGAGTCTCTTC) (MyiQ RT-PCR Bio-Rad). RNA was extracted by TRIzol (Invitrogen) method, following the manufacturer's instructions, under sterile conditions. RNA integrity and concentration were analyzed by NanoDrop Spectrophotometer. Real-time PCR was performed with the iScript One-Step RT-PCR kit SYBR Green (Bio-Rad) with the following profile: 50 ng of total RNA, 600 nM of primers and 12.5 μ l of 2 \times Reaction Mix in a total volume of 25 μ l were incubated 10 min at 50 $^{\circ}$ C, 5 min at 95 $^{\circ}$ C, followed by 45 cycles at 95 $^{\circ}$ C for 10 s, 59 $^{\circ}$ C for 30 s, and 72 $^{\circ}$ C for 30 s. Each reaction was done in triplicate and the threshold values (C_t) for each mRNA were subtracted from that of HRP mRNA, as a housekeeping gene, averaged, and converted from log-linear to linear term.

Statistical analyses

Results were expressed as mean \pm standard deviation with the number of individual experiments detailed in Figure legends. Statistical significance was established by one-way ANOVA followed by Tukey-Kramer as post hoc test. Calculations were performed using the GraphPad Prism 4 software package.

Results

Nutritional and genetic models of hepatic steatosis with distinct lipid profile

Since our aim was to address the specific role of individual lipids accumulating in hepatic steatosis to I/R injury, we used nutritional models of fatty livers exhibiting a different lipid profile. Choline is an essential nutrient required for efficient phosphatidylcholine synthesis necessary for the packaging and export of VLDL particles to extrahepatic organs. Feeding mice a CD diet resulted in hepatic steatosis with predominant TG content and unchanged cholesterol levels compared to chow-fed mice (Fig 1A), consistent with previous reports [10,20,21]. By contrast, increased hepatic cholesterol levels but unchanged TG content were observed in mice fed the HC diet (Fig 1B). Filipin staining and HPLC analyses indicated that most of the total cholesterol levels were unesterified (Fig. 1B and E). In line with our prior observations, the content of FFA increased to a similar level in both CD or HC-fed mice, with respect to chow fed mice (Fig. 1C). Oil red staining indicated the appearance of microvesicular steatosis with a strong filipin staining in HC-fed mice, while the steatosis of CD-fed mice was macrovesicular, with little filipin staining, compared to HC-fed mice (Fig. 1D and E). Unlike CD or HC-fed mice, the liver of ob/ob mice was characterized by the presence of TG, FFA, and cholesterol, as revealed by biochemical analysis (Supplementary Fig. 1) while oil-red and filipin staining shown the appearance of large lipid droplets, indicative of macrovesicular steatosis and free cholesterol accumulation (Fig. 1D and E). Thus, these nutritional and genetic models induce fatty liver with different lipid composition mainly enriched in TG or cholesterol and similar FFA content.

HC-fed mice and ob/ob mice are more sensitive to hepatic I/R injury than CD-fed mice

We next examined the susceptibility of CD and HC-fed mice to partial hepatic I/R injury. Compared to sham controls, normothermic ischemia (90 min), followed by 6 h after reperfusion, resulted in significant release of serum ALT in control chow fed

mice and CD-fed mice (Fig. 2A). However, the magnitude of ALT release in HC-fed mice was significantly greater compared to control or CD-fed mice (Fig. 2A). In line with this outcome, histologic analyses indicated that the liver damage in HC-fed mice was more severe compared to mice fed the CD diet (Fig. 2B). In addition, ob/ob mice, which exhibit genetic macrovesicular steatosis, were markedly sensitive to hepatic I/R injury compared to CD-fed mice, as determined by transaminase release (Fig. 2C) or histologic analyses (Fig. 2D), and the damage was similar to what observed in mice fed the HC diet. Thus, although the morphological and qualitative appearance of hepatic steatosis in HC-fed and ob/ob mice was strikingly different, displaying a microvesicular and macrovesicular pattern, respectively, both exhibited a high sensitivity towards hepatic I/R injury. Despite the fact that TG are a predominant determinant of hepatic steatosis and a major component of lipid droplets [22], these data suggest that the presence of cholesterol rather than TG plays a significant role in the susceptibility to hepatic I/R injury.

Mitochondrial cholesterol potentiates mitochondrial GSH depletion following I/R

Although mitochondria are cholesterol-poor organelles, mitochondrial cholesterol has emerged as an important player in pathophysiology, including liver diseases such as steatohepatitis [11]. Therefore, we next evaluated the status of mitochondrial cholesterol in mice fed HC or CD diets. HC-fed mice but not CD-fed mice exhibited increased mitochondrial cholesterol content (Fig. 3A), paralleling the increase observed in hepatic extracts (Fig. 1B). However, this pool of GSH was insensitive to I/R, with similar levels found in the different nutritional groups compared to sham operated controls (3.5 ± 0.8 , 7.2 ± 0.9 , and 3.1 ± 0.7 mg cholesterol/mg protein for control, HC and CD groups, respectively). Moreover, since GSH homeostasis plays a critical role in hepatic I/R injury, we examined the status of total GSH vs. the specific pool of GSH in mitochondria, during I/R. The level of GSH in hepatic extracts decreased following I/R regardless of the nutritional regimen and independent of the hepatic lipid profile (Fig. 3B). The total GSH levels in HC and CD groups did not change with respect to sham controls. By contrast, the hepatic mitochondrial GSH content decreased significantly by 40% ($p < 0.05$) in sham HC-fed mice, consistent with the negative impact of mitochondrial cholesterol in mitochondrial GSH transport [18,23]. I/R depleted mitochondrial GSH in control and CD-fed mice, likely reflect the decrease of cytosolic GSH (Fig. 3B). However, this effect of I/R on mitochondrial GSH depletion was further potentiated in HC-fed mice (Fig. 3C) because of the additional contribution of mitochondrial cholesterol loading. Thus, these findings correlate the susceptibility of HC-fed mice with the increased mitochondrial cholesterol trafficking and subsequent mitochondrial GSH depletion.

In vivo confocal imaging of fatty livers from mice fed CD or HC diets following I/R

The mechanisms underlying hepatic I/R injury are multifactorial, with the overgeneration of reactive oxygen species (ROS) playing a critical role. Moreover, mitochondria not only are a major source of ROS but they are instrumental in the predominant necrotic cell death during I/R injury via mitochondrial permeability transition (MPT) [24,25]. Having observed the depletion of

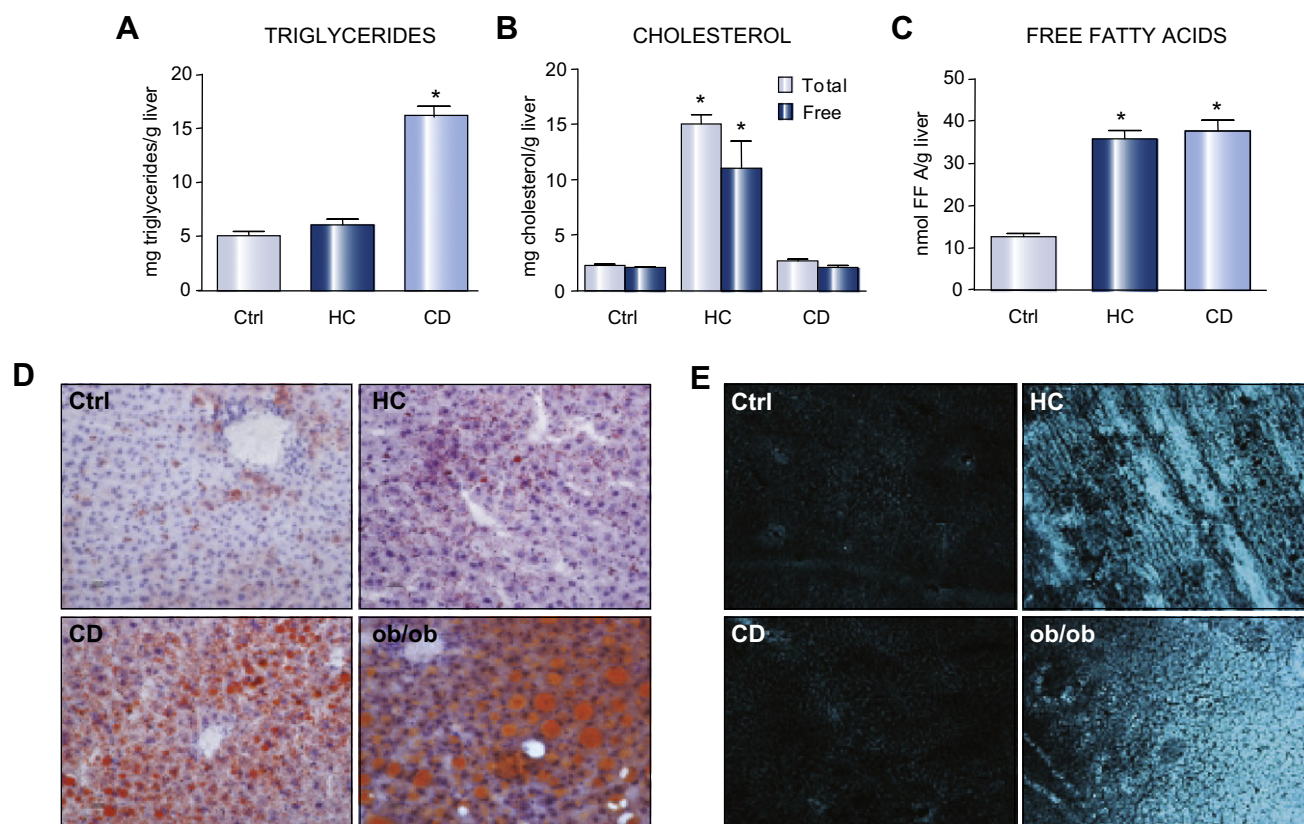


Fig. 1. Nutritional and genetic models of micro and macrosteatosis. Livers, from mice fed an HC or CD diet or from ob/ob mice, were analyzed biochemically for TG (A), cholesterol (B) or FFA (C) levels. In addition, samples were taken for oil red (D) or filipin (E) staining to monitor the appearance of neutral lipids or free cholesterol, respectively, and representative images of all groups were selected. Magnification of images in D is $\times 20$, while in E is $\times 10$. Results in the Ctrl, HC, and CD groups are expressed as mean \pm SD of 6, 6, and 4 mice, respectively. * $p < 0.01$ vs. control group.

mitochondrial GSH in fatty livers of HC-fed mice, which are particularly susceptible to I/R damage, we next analyzed the burst of ROS and mitochondrial membrane potential *in vivo* by two-photon confocal imaging of livers during I/R. ROS stimulation and mitochondrial membrane potential were recorded by DCF and TMRM labeling and imaged with an internal spectral detector at high speed, to avoid the movement due to animal breathing and heart beating during acquisition. As shown, while I/R stimulated the ROS generation and the mitochondrial depolarization in control livers, these effects were markedly enhanced in ischemic livers of HC-fed mice but not in mice fed the CD diet (Fig. 4), consistent with the preceding findings on the mitochondrial GSH status, which is known to regulate MPT. Thus, HC feeding potentiates ROS stimulation and mitochondrial depolarization *in vivo* during hepatic I/R.

Atorvastatin and squalene synthase inhibition prevents mitochondrial cholesterol loading and protects ob/ob mice from I/R injury

Given the above findings pointing to cholesterol as a potential culprit in the sensitization to hepatic I/R injury, we next examined the effect of cholesterol downregulation in ob/ob mice. We targeted two steps in the mevalonate pathway of *de novo* cholesterol synthesis, namely, HMGCoA R, and the squalene synthase (Fig. 5A), examining the impact on the mitochondrial cholesterol

trafficking. Although there was a trend for lower cholesterol levels in hepatic extracts of ob/ob mice after atorvastatin (Fig. 5B), it significantly attenuated the increase in mitochondrial cholesterol (Fig. 5C). Biochemical analyses indicated that the atorvastatin was effective in decreasing cholesterol levels in plasma (Fig. 5D), suggesting that enhanced LDL uptake may contribute to the maintenance of total hepatic cholesterol pool following statin therapy and that mitochondrial cholesterol derives predominantly from *de novo* synthesis. Moreover, consistent with the increased mitochondrial cholesterol, ob/ob mice exhibited enhanced expression of StAR (Fig. 5E), a mitochondrial cholesterol transporting polypeptide [26,27]. Interestingly, atorvastatin therapy blunted StAR expression in ob/ob mice (Fig. 5E).

We next tested the effect of squalene synthase inhibition by YM-53601, which is expected to prevent cholesterol synthesis from squalene without interfering with the formation of the non-sterol branch of the mevalonate pathway (Fig. 5A). Neither atorvastatin nor the squalene synthase inhibitor affected the total cholesterol (14.3 ± 1.8 μ g cholesterol/mg protein) or the mitochondrial cholesterol pool (6.5 ± 0.8 μ g cholesterol/mg protein) in lean mice. However, the effect of YM-53601 on total cholesterol levels was similar to that observed in presence of atorvastatin, but was able to significantly ameliorate the increase of the hepatic mitochondrial cholesterol in ob/ob mice (Fig. 5B and C). In parallel with these observations, we found that both atorvastatin and YM-53601 protected ob/ob mice against I/R

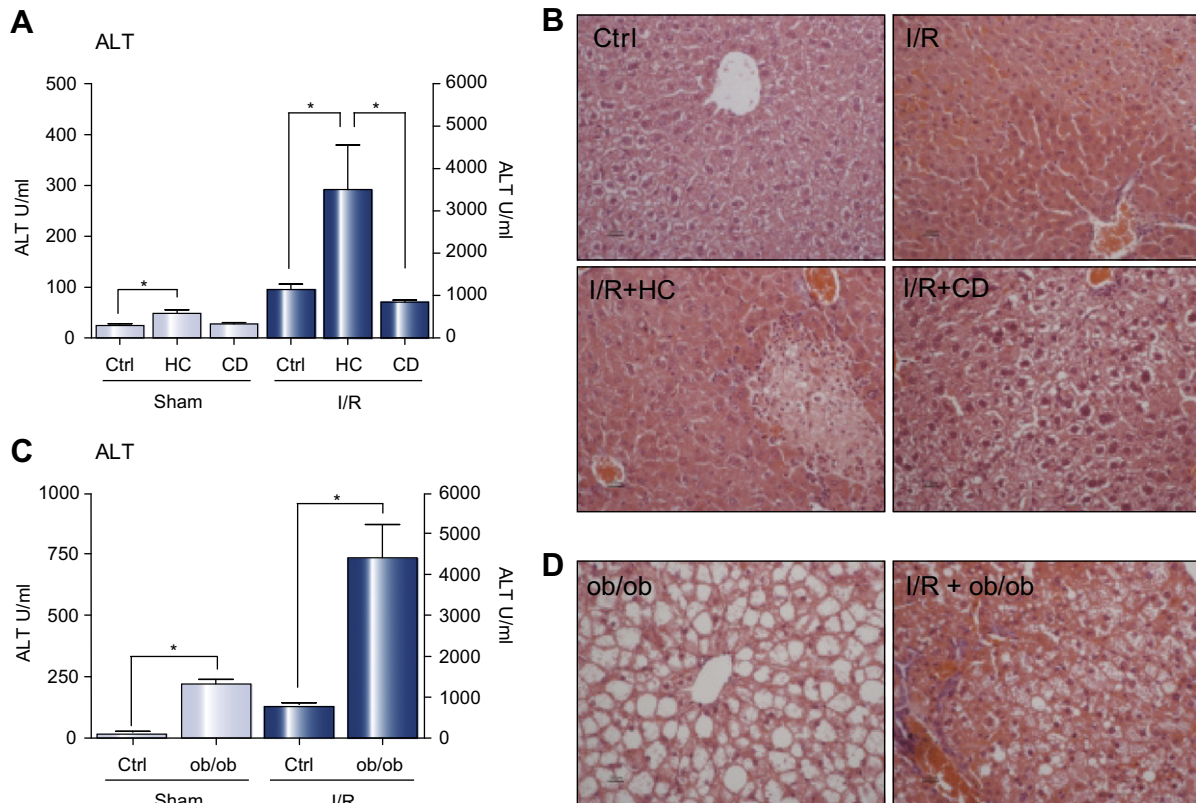


Fig. 2. Differential susceptibility of steatotic livers to I/R injury. Mice fed CD or HC diets were analyzed for serum transaminase levels (A), or histology (B) to assess their sensitivity to I/R. Alternatively, ob/ob mice were used to determine transaminase values (C) or histology (D) after I/R. Results of the Ctrl, HC, CD, and ob/ob groups are the mean \pm SD of 4, 6, 4, and 6 mice, respectively. * p < 0.01 vs. corresponding control groups with or without I/R. Magnification of images in B is 20 \times .

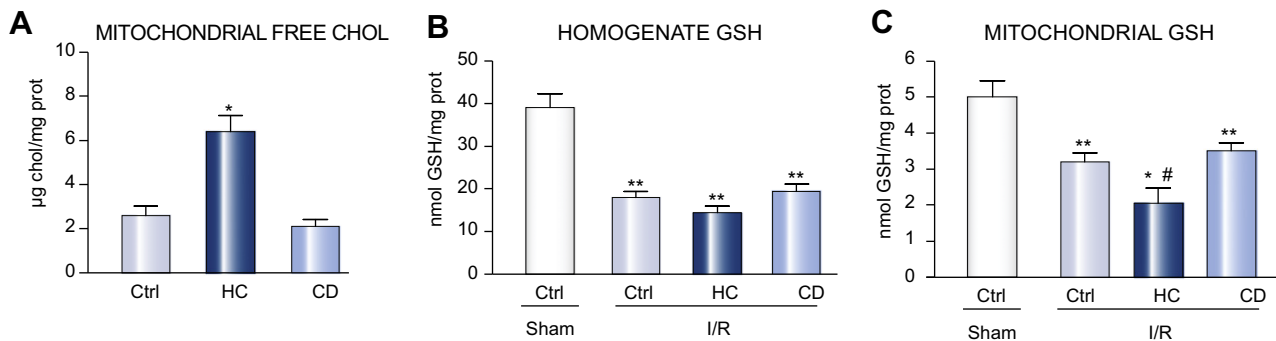


Fig. 3. Cholesterol and GSH compartmentation after I/R. (A) Livers from mice fed CD or HC diets were processed for mitochondrial isolation to analyze cholesterol content. Alternatively, samples were used for GSH determination in homogenate (B) or mitochondria (C). Results of the Ctrl, HC, and CD groups are the mean \pm SD of 7, 7, and 5 mice, respectively. * p < 0.01 vs. control mice. ** p < 0.05 vs. control mice. # p < 0.05 vs. I/R-exposed control mice.

injury, based on serum ALT values and histologic examination, following I/R injury (Fig. 6). Moreover, the H&E staining suggested that both therapeutic options ameliorated the hepatic steatosis of ob/ob mice that reflected decreased TG deposition (Supplementary Fig. 2). Thus, these findings suggest that the newly synthesized cholesterol traffics to mitochondria, and that the downregulation by statins or squalene synthase inhibition protects ob/ob mice from I/R liver injury.

Restoration of mitochondrial GSH in ob/ob mice by atorvastatin and squalene synthase inhibition following I/R

Mitochondrial GSH is a critical antioxidant that regulates hepatocyte survival in response to oxidative stress and hepatic I/R injury [28]. Since mitochondrial GSH regulation is dependent on cholesterol-mediated control of mitochondrial membrane dynamics, we next examined the effect of atorvastatin and YM-53601 on

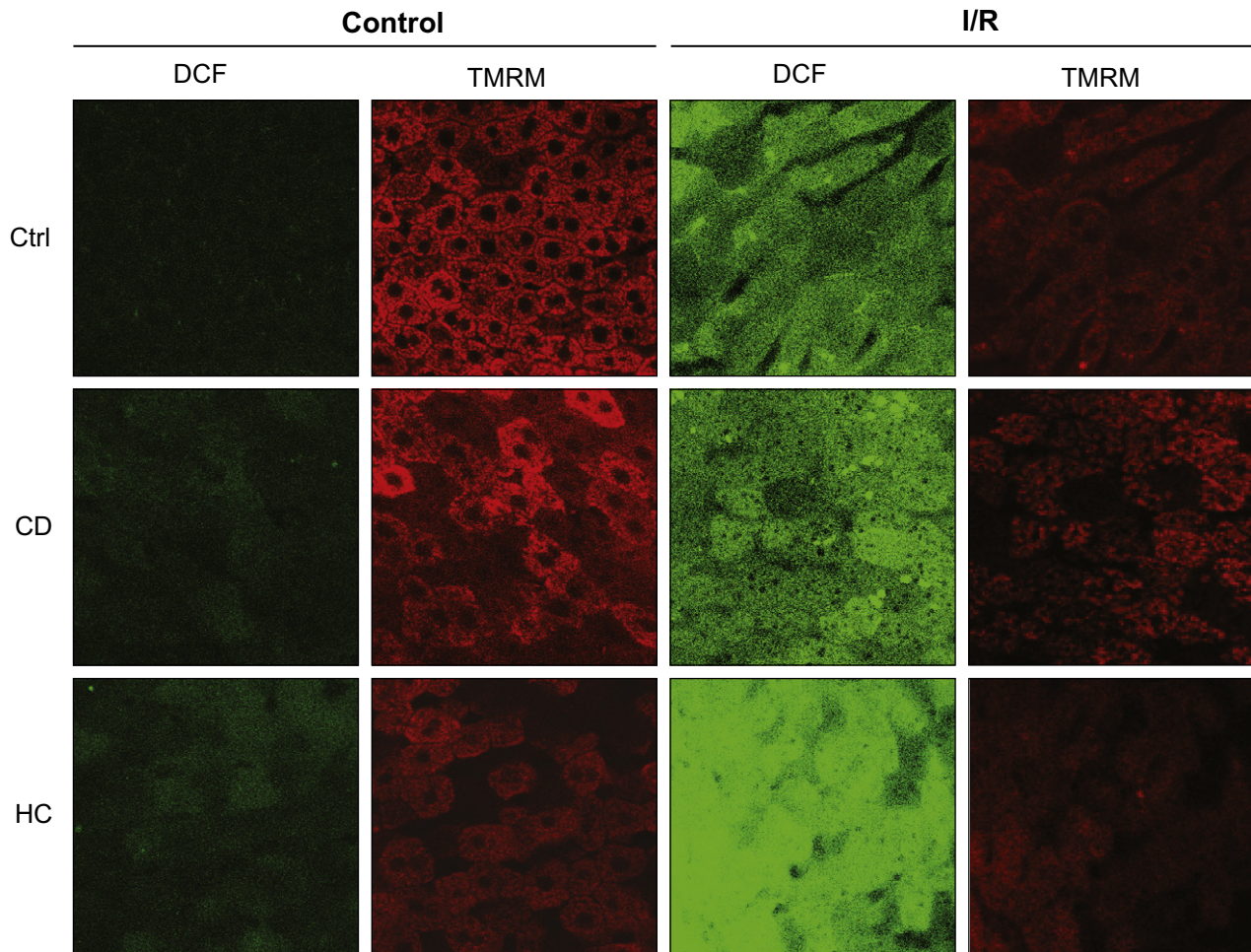


Fig. 4. *In vivo* confocal imaging of mitochondrial polarization and ROS generation after I/R. *In vivo* two-photon confocal microscopy during partial I/R in mice fed CD or HC diets. ROS generation and mitochondrial polarization were assessed from DCF and TMRE fluorescence. The imaging of the liver of living mice was performed using spectral confocal inverted microscope Leica TCS SP5. The emissions were acquired with internal spectral detector (PMT) at high speed in order to avoid the movement from animal breathing and heart beating during acquisition. Images are representative of four independent experiments.

mitochondrial GSH homeostasis, in ob/ob mice following I/R. Consistent with the effects observed on the mitochondrial cholesterol pool, atorvastatin and YM-53601 restored the hepatic mitochondrial GSH content of sham control ob/ob mice to levels close to those observed in lean mice (Fig. 7A). Importantly, while this particular pool of GSH decreased further in ob/ob mice during I/R, both therapies significantly increased the mitochondrial GSH levels in ob/ob mice following I/R (Fig. 7B), in agreement with the effect produced by atorvastatin and YM-53601 on the mitochondrial cholesterol content (Fig. 5C). Similar protective results were observed when the pool of mGSH was restored by GSH ethyl ester (data not shown), a permeable form of GSH [21]. Consistent with the reversal of the mitochondrial GSH stores, atorvastatin, and the squalene synthase inhibitor attenuated oxidative stress determined by the increase in MDA levels (Supplementary Fig. 3). Thus, these findings indicate that the regulation of mitochondrial cholesterol content modulates the levels of mitochondrial GSH whose replenishment attenuates hepatic I/R injury.

Discussion

The mechanisms whereby hepatic steatosis sensitizes to I/R injury remain incompletely understood, and their elucidation may provide ways to increase the graft load available for use in diverse clinical settings requiring I/R. In this study, we analyzed the susceptibility of fatty livers with specific lipid profiles to I/R damage. Using nutritional and genetic models of hepatic steatosis, we observed that regardless of the qualitative appearance of steatosis (micro vs. macrosteatosis), the presence of cholesterol, particularly in mitochondria, plays a previously unrecognized role in normothermic ischemic injury. Previous studies indicated that livers with microsteatosis induced by CD diet feeding were less sensitive to I/R damage than those with macrosteatosis observed in ob/ob mice [3]. Although we confirm this outcome here, we believe the relative qualitative aspect of steatosis plays a minor role in hepatic I/R susceptibility. While the steatosis of CD-fed mice may be microvesicular as compared to ob/ob mice, it is more macrovesicular than that of HC-fed mice.

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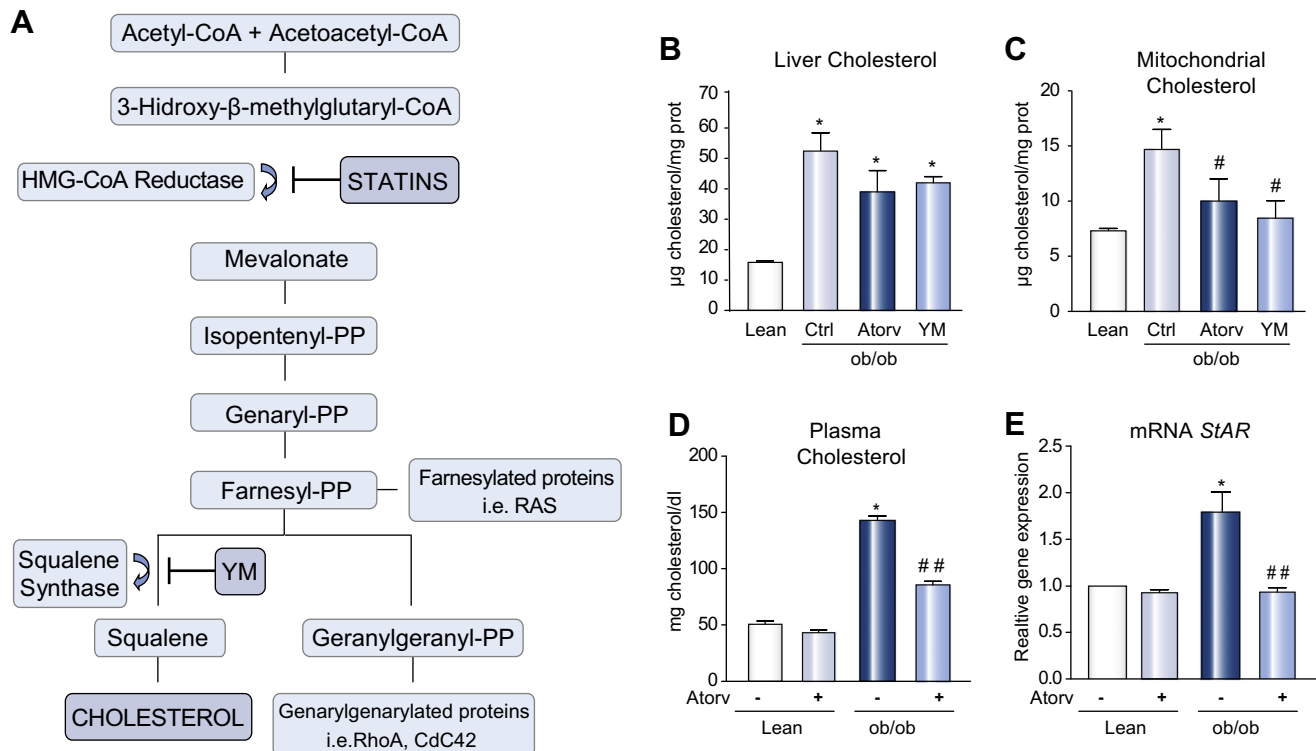


Fig. 5. Effect of atorvastatin and squalene synthase inhibition on mitochondrial cholesterol trafficking. (A) mevalonate pathway showing the branching of farnesyl-PP into cholesterol synthesis via squalene formation or the formation of non-sterol intermediates and the target of statins and YM-53601. Livers from lean and ob/ob mice were processed for cholesterol analyses in homogenates (B), mitochondria (C) as well as in plasma (D). (E) Shows the mRNA expression for StAR in livers from lean and ob/ob mice with or without atorvastatin treatment. Results of the lean, ctrl-, atorv- and YM-ob/ob groups are the mean \pm SD of 4, 6, 6, and 4 mice, respectively. * $p < 0.01$ vs. control lean mice; # $p < 0.05$ vs. ob/ob mice. ## $p < 0.05$ vs. ob/ob mice.

Moreover, although HC-fed mice exhibit microvesicular steatosis, their livers are as sensitive to I/R-induced damage as livers of ob/ob mice with macrovesicular steatosis. Rather than the relative contribution of micro vs. macrosteatosis in discriminating the susceptibility to I/R injury, we provide evidence that hepatic cholesterol plays a so far unappreciated role in the sensitization of fatty liver to ischemic injury. CD-fed mice are characterized by steatosis with TG and FFA accumulation but unchanged cholesterol, in contrast to livers from HC-fed mice which exhibit a predominant cholesterol loading. Our findings, showing a critical role for cholesterol in this process, are consistent with previous reports in LDLr^{-/-} mice or rabbits fed a high-cholesterol diet [29,30]. Moreover, the susceptibility of LDLr^{-/-} mice to hepatic I/R injury was ameliorated by anti TNF antibodies [29], pointing to a critical role of TNF in hepatic I/R damage. Considering previous findings favoring the transition of steatosis to steatohepatitis by cholesterol [10], the present findings broaden the implications of cholesterol in liver pathology.

The role of cholesterol in sensitizing to normothermic hepatic I/R injury is likely mediated by its trafficking and accumulation in mitochondria and subsequent depletion of mitochondrial GSH. Indeed, we observed, by confocal imaging, *in vivo* mitochondrial depolarization and ROS generation in HC-fed mice as opposed to CD-fed mice, consistent with the critical role of mitochondrial GSH in cell survival and defense against oxidative stress. Mitochondrial cholesterol loading is known to perturb membrane dynamics affecting selective carriers, including the GSH mitochondrial transporter but not the S-adenosyl-L-methionine

(SAM) carrier [31]. Hence, unlike CD-fed mice, substantial hepatic mitochondrial GSH depletion is observed in HC-fed and ob/ob mice, both exhibiting marked susceptibility to I/R. Although I/R itself depletes hepatic GSH levels and mitochondrial GSH in parallel, the decrease of this latter specific pool is more dramatic upon mitochondrial cholesterol loading as shown in HC-fed and ob/ob mice. Quite interestingly, we observed for the first time that livers from ob/ob mice exhibit enhanced expression of StAR, a mitochondrial cholesterol transporting polypeptide [26,27], consistent with the mitochondrial cholesterol accumulation seen in these samples. Although we did not address the contribution of StAR in the regulation of mitochondrial cholesterol in ob/ob mice, it is conceivable that it may play a significant role, as shown in human hepatocytes. Overexpression of StAR in HepG2 cells has been reported to cause the upregulation of 27-hydroxycholesterol, a read-out metabolite of the increased mitochondrial cholesterol pool [32]. Moreover, StAR silencing by siRNA has been shown to decrease this pool of cholesterol, sensitizing human hepatocarcinoma cells to chemotherapy [33].

Additional evidence supporting a role for cholesterol, particularly in mitochondria, in the susceptibility of ob/ob mice to hepatic I/R damage, is provided by preventing cholesterol synthesis in the mevalonate pathway. Atorvastatin, which targets HMGCoA R (the regulatory enzyme in the *de novo* cholesterol synthesis from acetyl-CoA), downregulated mitochondrial cholesterol loading, and consequently prevented mitochondrial GSH depletion during I/R. Quite intriguingly, atorvastatin also prevented the upregulation of StAR by an unknown mechanism, consistent with the above

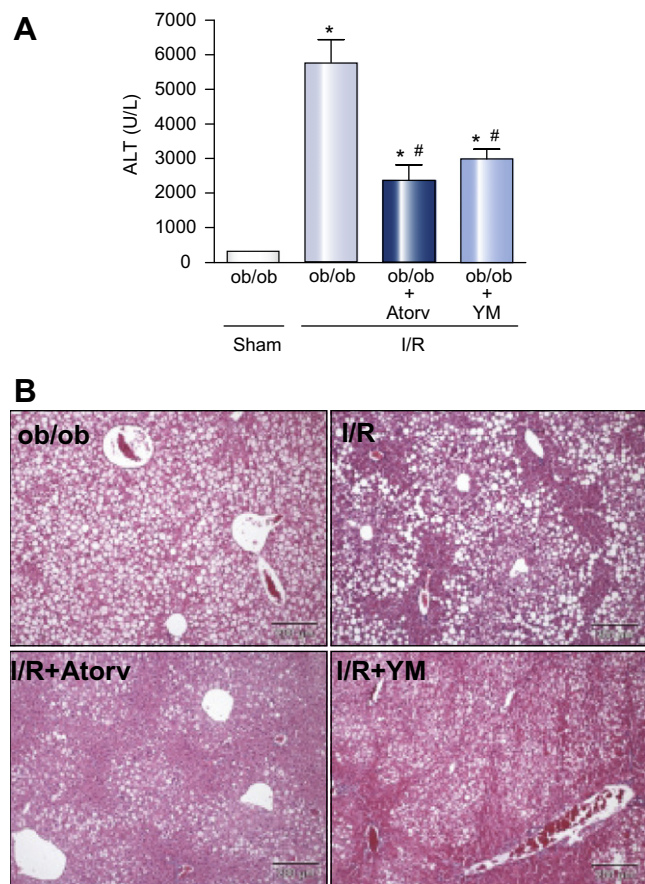


Fig. 6. Atorvastatin and YM-53601 protect ob/ob mice from I/R injury. ob/ob mice were pretreated with atorvastatin or YM-53601 for seven days before I/R at the dose of 10 mg/kg or 15 mg/kg, respectively, or vehicle. Six hours after reperfusion serum or liver biopsies were processed for assessment of transaminases (A) or histology (B). Results of ob/ob-sham, ob/ob-, ob/ob + Atorv- and ob/ob + YM-I/R groups are the mean \pm SD of 4, 6, 6, and 4 mice, respectively. * p < 0.01 vs. ob/ob-sham mice; # p < 0.01 vs. vehicle-treated ob/ob I/R mice. Magnification of images in B is 20 \times .

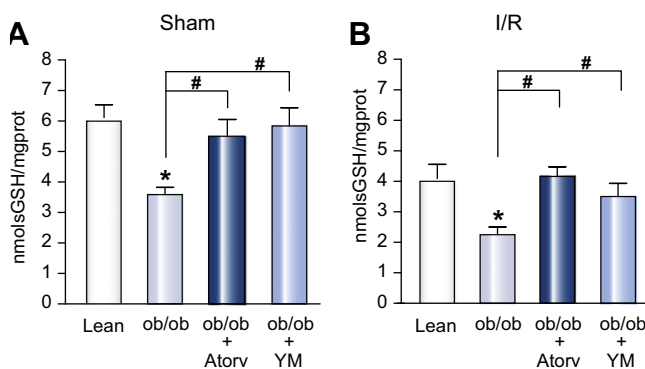


Fig. 7. Mitochondrial GSH levels in ob/ob mice following I/R with or without atorvastatin or YM-53601 therapy. Samples from ob/ob mice following sham operation (A) or I/R (B) with or without atorvastatin and YM-53601 therapy were processed for mitochondrial isolation and GSH determination. Results of ob/ob-sham, ob/ob-, ob/ob + Atorv- and ob/ob + YM-I/R groups are the mean \pm SD of 4, 6, 6, and 4 mice, respectively. * p < 0.01 vs. lean mice, # p < 0.05 vs. ob/ob mice.

described effects on mitochondrial cholesterol. By targeting HMG-CoA R, statins may have broad effects far from just preventing cholesterol synthesis, as the conversion of mevalonate into farnesyl-PP can branch into non-sterol intermediates including isoprenoids, which can regulate a number of target proteins posttranslationally. To confirm whether the therapeutic effect of atorvastatin in ob/ob mice against hepatic I/R injury is due to the downregulation of cholesterol and its trafficking to mitochondria, we inhibited squalene synthase, which catalyzes the first committed step in cholesterol synthesis. Squalene synthase inhibition paralleled the effects observed with atorvastatin with respect to mitochondrial cholesterol depletion and subsequent mitochondrial GSH restoration, strongly suggesting that the beneficial effects of atorvastatin in hepatic I/R susceptibility is due to cholesterol regulation. Consistent with these effects, previous studies have shown that simvastatin reduces the mortality and hepatic injury after hemorrhage/resuscitation in rats or during I/R [34,35]. By comparing the effect of atorvastatin in StAR and mitochondrial cholesterol regulation in ob/ob mice, it appears that the statin prevented StAR upregulation while it attenuated mitochondrial cholesterol loading, which suggests the possibility for the involvement of other StAR family members. Whether or not MLN64, which has been shown to mediate the egress of cholesterol from endosomes to mitochondria in the absence of Niemann–Pick type C1 protein [36], is involved in the upregulation of mitochondrial cholesterol in ob/ob mice remains to be established.

In summary, by comparing side-by-side the susceptibility of fatty livers with disparate lipid composition, we uncovered a critical role for mitochondrial cholesterol in the sensitization of fatty livers against ischemic injury and we found that this effect is due to mitochondrial GSH depletion. Consistent with this outcome, previous studies reported that the depletion of this pool of GSH during hepatic I/R damage, and its restoration by GSH ethyl ester [37] or SAM [38] protected steatotic livers against I/R damage. Although this concept remains to be tested in human fatty liver, mitochondrial GSH depletion has been shown in nonalcoholic steatohepatitis [39], which is associated with increased free cholesterol accumulation and StAR overexpression [40]. If confirmed the role of cholesterol and its accumulation in mitochondria in human fatty livers and its correlation with graft failure, then analyzing the presence of cholesterol or cholesterol-related proteins such as StAR in steatotic donor grafts may represent a valuable discriminating tool to expand the pool of available organs for transplantation.

Conflict of interest

The authors who have taken part in this study declared that they do not have anything to disclose regarding funding or conflict of interest with respect to this manuscript.

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Research Article

Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.jhep.2010.08.031](https://doi.org/10.1016/j.jhep.2010.08.031).

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