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ORIGINAL ARTICLE

Oxidative stress and extracellular matrices after hepatectomy and liver transplantation in rats

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Abstract

AIM: To investigate oxidative stress (OS)-mediated damage and the behavior of extracellular matrices in various rat models because shear stress with portal hypertension and cold ischemia/warm reperfusion injury trigger the liver regeneration cascade after surgery. These injuries also cause fatal liver damage.

METHODS: Rats were divided into four groups according to the surgery performed: control; hepatectomy with 40% liver remnant (60% hepatectomy); orthotopic liver transplantation (OLT) with whole liver graft (100% OLT); and split OLT (SOLT) with 40% graft (40% SOLT). Survival was evaluated. Blood and liver samples were collected at 6 h after surgery. Biochemical and histopathological examinations were performed. OS-induced damage, 4-hydroxynonenal, ataxia-telangiectasia mutated kinase, histone H2AX, phosphatidylinositol 3-kinase (PI3K) and Akt were evaluated by western blotting. Behavior of extracellular matrices, matrix metalloproteinase (MMP)-9, MMP-2, tissue inhibitor of metalloproteinase (TIMP)-1 and TIMP-2 were also evaluated by western blotting and zymography.

RESULTS: Although 100% OLT survived, 60% hepatectomy and 40% SOLT showed poor survival. Histopathological, immunohistological, biochemical and protein assays revealed that 60% hepatectomy, 100% OLT and 40% SOLT showed liver damage. PI3K and Akt were decreased in 60% hepatectomy and 40% SOLT. For protein expression, 40% SOLT showed differences in MMP-9, MMP-2 and TIMP-2. TIMP-1 showed differences in 60% hepatectomy and 40% SOLT. For protein activity, MMP-9 demonstrated significant differences in 60% hepatectomy, 100% OLT and 40% SOLT.

CONCLUSION: Under conditions with an insufficient liver remnant, prevention of OS-induced damage *via* the Akt/PI3K pathway may be key to improve the postoperative course. MMP-9 may be also a therapeutic target after surgery.

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Key words: Free radicals; Akt; Phosphatidylinositol 3-kinase; Matrix metalloproteinase; Tissue inhibitors of metalloproteinase

Core tip: Although shear stress with portal hypertension and cold ischemia/warm reperfusion injury trigger the liver regeneration cascade after surgery, these injuries also cause fatal liver damage. Postoperative liver damage is still a critical matter in the field of liver surgery. Oxidative stress and extracellular matrices are important for liver regeneration after surgery and these may be important keys to overcome current problems in the field of liver surgery. Here, we investigated oxidative stress-mediated damage and the behavior of extracellular matrices in various rat models with liver surgery.

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INTRODUCTION

Liver resection is considered the standard treatment for primary malignant tumors and liver metastases. Advanced surgical techniques for hepatectomy, development of preoperative evaluation, and improvements in intensive postoperative care have resulted in a decline in perioperative morbidity and mortality. However, postoperative liver failure still occurs despite these developments. Extended hepatectomy has the advantage of high curability but increases morbidity and mortality[1]. Insufficient volume of the remnant liver is correlated with perioperative morbidity and mortality[1]. Prognosis of postoperative liver failure due to insufficient liver remnant is poor[1,2].

Orthotopic liver transplantation (OLT) is an accepted therapy for end-stage liver disease and currently provides long-term survival and good quality of life. However, cold ischemia/warm reperfusion (CIWR) injury is still a major cause of morbidity and mortality after OLT[3]. Currently, strategic procedures are needed to improve the liver tolerance against CIWR injury. A small-for-size graft (SFSG) is used for deceased donor liver transplantation (DDLT) and living donor liver transplantation (LDLT)[4,5]. The SFSG is defined as a ratio of graft weight against standard liver volume < 40%[6,7]. An inevitable insufficiency of graft size cannot be avoided in the LDLT or split orthotopic liver transplantation (SOLT) for DDLT. The SFSG in LDLT or SOLT is accompanied with CIWR injury and shear stress with portal hypertension. Hence, the SFSG results in high mortality and morbidity. The choice of a left-side graft is preferred from the viewpoint of greater donor safety and expanded donor candidates in LDLT[7,8]. Guaranteed SOLT with successful outcomes resolves a donor shortage in DDLT[4,5]. Currently, the 40% SFSG is a critical matter to overcome the donor shortage in DDLT and ensure donor safety in LDLT[4].

Oxygen is required for cell survival. However, it also poses a potential hazard *via* reactive oxygen species (ROS) and reactive nitrogen species (RNS), with biological and functional alterations of lipids, proteins and DNA[9-11]. Control of ROS/RNS production plays physiological roles, especially in regulating cell signaling, cell proliferation, differentiation and apoptosis[9-11]. Oxidative stress (OS) mediated by free radicals is defined as an imbalance between the production of ROS/RNS and the antioxidant capacity of the cell[9-11].

The extracellular matrix has important effects on inflammation, carcinogenesis and regeneration[12-14]. There are diverse types of proteases that control remodeling of the extracellular matrix, trigger liver regeneration and drive tumor progression[12-14]. Matrix metalloproteinases (MMPs) are a family of enzymes that degrade constituents of extracellular matrices and basement membranes. Currently, a total of 28 MMPs have been identified[14]. MMPs have been intensively studied and shown to play key roles in inflammation, carcinogenesis and regeneration[12-15]. MMP-2 and MMP-9 are implicated in liver injury and remodeling. In particular, previous researchers reported that MMP-9 and MMP-2 contribute to liver failure after liver surgery[12-21]. Tissue inhibitors of metalloproteinases (TIMPs) are a family of endogenous inhibitors of MMPs. Alteration in the MMP-TIMP balance is linked to pathophysiological conditions[22,23]. Currently, four members have been identified in the TIMP family which can inhibit various MMPs[24]. In particular, many researchers have focused on TIMP-1 and TIMP-2 during liver regeneration[25-28].

Although shear stress with portal hypertension and CIWR injury trigger the liver regeneration cascade after liver surgery, these injuries also cause fatal liver damage[29-31]. Initial damage is confirmed at the early postoperative period after liver surgery[3,12,13,18,29-31]. Therapeutic strategies to reduce this damage have the advantage of improving clinical results after liver surgery and overcoming the current issue of insufficient liver volume in the field of liver surgery. In the present preliminary study, we investigated OS-mediated damage and the behavior of extracellular matrices in various rat models with shear stress and portal hypertension and/or CIWR injury.

MATERIALS AND METHODS

Animals

Lewis rats (RT-1^l) were purchased from Harlan Laboratories (Indianapolis, IN, United States). Male rats were 8-12 wk old and weighed 250 g. The experimental protocols were approved by the Ethical Committee of our institution (Mayo Clinic, Institutional Animal Care and Use Committee, No. A19609). Rats were cared for in accordance with the Institutional Guidelines for Animal Welfare based on The National Institutes of Health Guide for the Care and Use of Laboratory Animals.

Surgical procedures and postoperative care

Comprehensive details of the surgical procedures for rat

Table 1 Study design

Group	Hepatic remnant volume	Cold ischemia warm reperfusion	Shear stress portal hypertension
Control	100%, native liver	-	-
60%-hepatectomy	40%, native liver	-	+
100%-OLT	100%, syngeneic graft	+	-
40%-SOLT	40%, syngeneic graft	+	+

OLT: Orthotopic liver transplantation; SOLT: Split orthotopic liver transplantation.

and postoperative care in our institution have been previously described[32-34]. In the hepatectomy model, 40% of liver remnant consisted of the left median and lateral segments[32,33]. In the transplantation model, the syngeneic graft had a cold ischemic time of 3-4 h at 4 ℃ in normal Ringer's solution[33]. The 40% SFSG was also formed by the left median and lateral segments at the back table[34]. To avoid any irrelevant signaling, the hepatic artery was reconstructed by ultramicrosurgery[33]. Each rat was kept separately after surgery and body temperature was maintained by a heating pad. Postoperative observation was performed every 30 min until 6 h after surgery and 1.0 mL of warm lactate Ringer's solution was routinely administered every 1 h until 6 h after surgery. In the transplantation model, we previously demonstrated the importance of a shortened anhepatic phase and exclusion of unreliable samples based on autopsy findings[33,34]. In this study, the anhepatic phase was kept within 20 min in the transplantation model. No surgical complications were observed in each case at sampling autopsy.

Study design

Rats were divided into four groups according to the surgery performed: (1) laparotomy only (control); (2) hepatectomy with 40% liver remnant (60% hepatectomy); (3) OLT with whole liver graft (100% OLT); and (4) SOLT with 40% SFSG (40% SOLT) (Table 1). The survival study was performed on 10 rats in each group. Cell signaling involved in proliferation, differentiation and apoptosis was confirmed at the early postoperative period after liver surgery and subsequently progressive necrosis was observed, as described previously[3,12,13,18,29-31]. Serum and plasma were collected at 6 h after surgery (n = 5, in each group). Liver samples were also collected at 6 h after surgery for histopathological/immunohistological assessments, western blotting and gelatin zymography (n = 5, in each group).

Biochemical assays and coagulation profile

Aspartate aminotransferase (AST), alanine aminotransferase (ALT), total bilirubin (T-Bil), the international normalized ratio of prothrombin time (PT-INR) and hyaluronic acid (HA) were measured. Serum AST, ALT and T-Bil were assessed by commercial kits (SGOT, SGPT and total bilirubin reagent, respectively; Biotron, Hemet, CA, United States). The PT-INR in the plasma was measured by the i-STAT System (Abbott, Princeton, NJ, United States). Serum HA was measured using a commercial kit (Quantikine Hyaluronan ELISA Kit; R and D Systems, Minneapolis, MN, United States).

Histopathological and immunohistological assessments

Liver tissue was fixed in 10% neutral-buffered formalin, embedded in paraffin, and sliced into 4-μm sections. The morphological characteristics and graft injury scores were assessed after hematoxylin-eosin (HE) staining. The graft damage score has been described previously[34]. Scores were counted in 10 fields (× 100 magnification) in each slide and these scores were averaged in each HE slide.

Induction of apoptosis was assessed by immunostaining of terminal deoxynucleotidyl transferase-mediated deoxyuridine triphosphate nick-end labeling (TUNEL) (ApopTag Peroxidase *In Situ* Apoptosis Detection Kit, S7100; Chemicon International, Billerica, MA, United States) and cysteine aspartic acid protease (caspase) 3 [Cleaved Caspase-3 (Asp175) Antibody, 9661S; Cell Signaling Technology, Danvers, MA, United States]. A TUNEL-positive nucleus was stained brown and a negative nucleus was counterstained light blue. A caspase-3-positive nucleus was stained brown and a negative nucleus was counterstained blue. Slides were scanned with an automated high-throughput scanning system (Scanscope XT, Aperio Technologies, Vista, CA, United States). To quantify the immunohistological findings, positive-stained nuclei were counted by Aperio Imagescope software (Aperio Technologies). All nuclei were classified into four color intensity levels and the higher two levels were considered as positive. The ratio of positive-stained nuclei to all nuclei was calculated and the mean ratio/mm^2 was determined.

Western blotting and gelatin zymography

The primary antibodies for malondialdehyde (MDA) (Anti-Malondialdehyde antibody, ab6463; Abcam, Cambridge, MA, United States); 4-hydroxynonenal (4-HNE) (4 Hydroxynonenal antibody, ab46545; Abcam); ataxia telangiectasia mutated kinase (ATM) (Phospho-ATM/ATR Substrate Rabbit mAb, 2909; Cell Signaling Technology); phosphorylated histone H2AX (γH2AX) (Phospho-Histone H2A.X Antibody, 2577; Cell Signaling Technology); phosphatidylinositol 3-kinase (PI3K) (Phospho-PI3K p85/p55 Antibody, 4228; Cell Signaling Technology); Akt (Phospho-Akt Rabbit mAb, 4058; Cell Signaling Technology); superoxide dismutase (SOD) (Cu/Zn Superoxide Dismutase, LS-B2907; LifeSpan BioSciences, Seattle, WA, United States); catalase (Catalase, LS-B2554; LifeSpan BioSciences); MMP-9 (Anti-MMP-9, Catalytic domain, AB19016; Millipore, Temecula, CA,

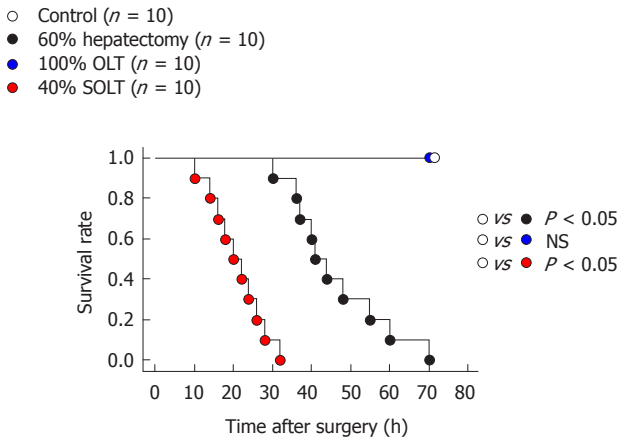


Figure 1 Survival curves. OLT: Orthotopic liver transplantation; SOLT: Split orthotopic liver transplantation.

United States); MMP-2 [MMP-2 antibody (MMP2/8B4), ab7032; Abcam]; TIMP-1 [Anti-TIMP-1 Mouse mAb (102D1), IM63; Calbiochem, San Diego, CA, United States]; and TIMP-2 [Anti-TIMP2 antibody (3A4), ab1828; Abcam] were used. Glyceraldehyde-3-phosphate dehydrogenase served as a control. Signals were quantified using ImageQuant 5.0 software (Molecular Dynamics, Sunnyvale, CA, United States). Gelatinase activity was visualized by fluorescence microscopy (Olympus BX50; Olympus Optical, Tokyo, Japan).

Statistical analysis

The results were presented as mean ± SD. Student's *t* test was used for the comparison of unpaired continuous variables between groups. Survival curves were constructed by the Kaplan-Meier method (Log-rank test). Statistical calculations were performed using SPSS version 16.0 (SPSS Inc., Chicago, IL, United States). $P < 0.05$ was considered statistically significant.

RESULTS

Survival curves

Survival curves for each group are shown in Figure 1. All rats that underwent a laparotomy or 100% OLT survived. The 60% hepatectomy and 40% SOLT groups clearly showed poorer survival than the controls ($P < 0.0001$). Insufficient liver remnant resulted in poor survivals after 60% hepatectomy. Especially, 40% SOLT showed very poor survivals.

Liver parenchymal damage

In comparison with the controls (0.1 ± 0.1 points), there were significant differences in the graft damage score for 60% hepatectomy (3.7 ± 0.7 points, $P < 0.0001$), 100% OLT (4.0 ± 0.6 points, $P < 0.0001$) and 40% SOLT (5.8 ± 1.1 points, $P < 0.0001$) (Figure 2A).

Immunohistological assessment of apoptosis induction

In comparison with the controls (0.003 ± 0.004), the rates of TUNEL-positive nuclei showed significant differences in 60% hepatectomy (0.017 ± 0.009, $P = 0.0278$), 100% OLT (0.107 ± 0.012, $P = 0.0001$) and 40% SOLT (0.166 ± 0.052, $P < 0.0001$) (Figure 2B). In comparison with the controls (0.002 ± 0.002), the rates of caspase-3-positive nuclei revealed significant differences in 60% hepatectomy (0.044 ± 0.023, $P = 0.0033$), 100% OLT (0.063 ± 0.014, $P < 0.0001$) and 40% SOLT (0.115 ± 0.019, $P < 0.0001$) (Figure 2C).

Conventional liver function tests, coagulation profile and endothelial damage

In comparison with the controls (42.5 ± 8.6 U/L), AST levels showed significant differences in 60% hepatectomy (202.4 ± 41.9 U/L, $P < 0.0001$), 100% OLT (290.5 ± 31.9 U/L, $P < 0.0001$) and 40% SOLT (387.4 ± 36.8 U/L, $P < 0.0001$) (Figure 3A). In comparison with the controls (59.8 ± 9.6 U/L), ALT levels showed significant differences in 60% hepatectomy (213.8 ± 57.0 U/L, $P < 0.0001$), 100% OLT (309.4 ± 38.3 U/L, $P < 0.0001$) and 40% SOLT (392.2 ± 76.7 U/L, $P < 0.0001$) (Figure 3B). In comparison with the controls (0.41 ± 0.13 mg/dL), there were no significant differences in T-Bil levels in 60% hepatectomy (0.50 ± 0.26 mg/dL, $P = 0.4798$) and 100% OLT (0.58 ± 0.15 mg/dL, $P = 0.0801$), but there was in 40% SOLT (1.37 ± 0.29 mg/dL, $P = 0.0001$) (Figure 3C).

In comparison with the controls (0.99 ± 0.04), PT-INR values revealed significant differences in 60% hepatectomy (1.16 ± 0.09, $P = 0.0052$), 100% OLT (1.12 ± 0.04, $P = 0.0008$) and 40% SOLT (1.22 ± 0.06, $P < 0.0001$) (Figure 3D).

In comparison with the controls (76.6 ± 14.9 ng/mL), HA levels demonstrated significant differences in 60% hepatectomy (264.0 ± 58.8 mg/dL, $P = 0.0001$), 100% OLT (188.0 ± 29.0 mg/dL, $P < 0.0001$) and 40% SOLT (350.2 ± 136.6 mg/dL, $P = 0.0021$) (Figure 3E).

Oxidative stress

The western blotting intensities of MDA in each group are shown in Figure 4A. In comparison with the controls (1.00 ± 0.10), normalized MDA showed significant differences in 60% hepatectomy (1.64 ± 0.39, $P = 0.0074$), 100% OLT (2.12 ± 0.78, $P = 0.0133$) and 40% SOLT (2.30 ± 0.26, $P < 0.0001$) (Figure 4B).

Lipid peroxidation

In comparison with the controls (1.00 ± 0.09), normalized 4-HNE showed significant differences in 60% hepatectomy (1.30 ± 0.20, $P = 0.0152$), 100% OLT (1.41 ± 0.20, $P = 0.0028$) and 40% SOLT (1.40 ± 0.19, $P = 0.0032$) (Figure 4C).

Responses and repairs to DNA damage

In comparison with the controls (1.00 ± 0.098), normalized ATM showed significant differences in 60% hepatectomy (1.15 ± 0.09, $P = 0.0336$), 100% OLT (1.28 ± 0.10, $P = 0.0015$) and 40% SOLT (1.21 ± 0.09, $P = 0.0053$) (Figure 4D). In comparison with the controls (1.00 ± 0.17), normalized γH2AX showed significant differences

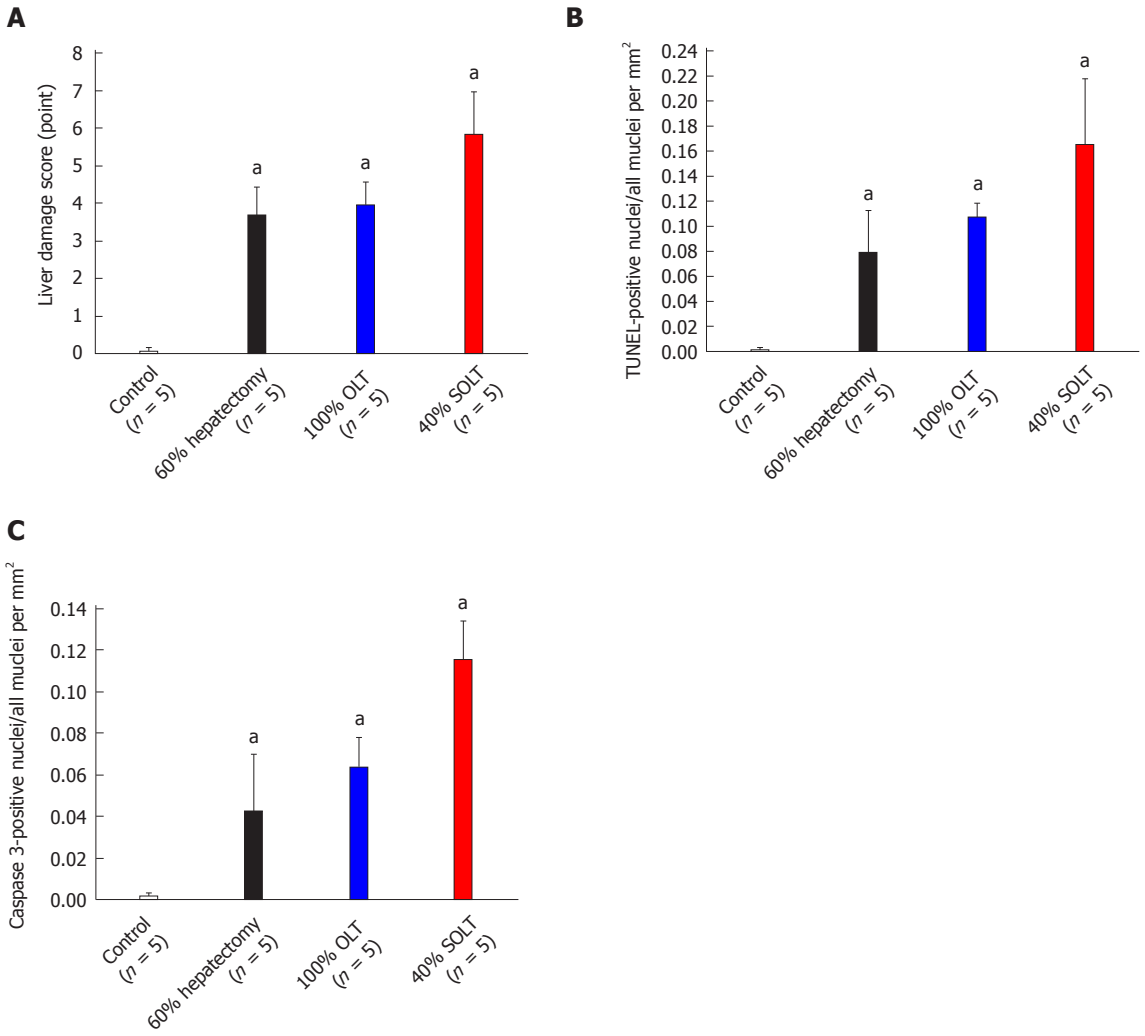


Figure 2 Histopathological and immunohistological assessments. A: Liver damage score in HE staining; B: TUNEL-positive rate; C: Caspase-3-positive rate. [a]*P* < 0.05 *vs* control. OLT: Orthotopic liver transplantation; SOLT: Split orthotopic liver transplantation.

in 60% hepatectomy (1.39 ± 0.29, *P* = 0.0071), 100% OLT (1.67 ± 0.38, *P* = 0.0303) and 40% SOLT (2.59 ± 0.66, *P* = 0.0008) (Figure 4E).

Promotion of cell survival

The western blotting intensities of PI3K and Akt in each group are shown in Figure 4F.

In comparison with the controls (1.00 ± 0.08), there was no significant difference in normalized PI3K in 100% OLT (0.92 ± 0.09, *P* = 0.1726), but there were significant differences in 60% hepatectomy (00.36 ± 0.11, *P* < 0.0001) and 40% SOLT (0.42 ± 0.19, *P* = 0.0002) (Figure 4G). In comparison with the controls (1.00 ± 0.12), there was no significant difference in normalized Akt in 100% OLT (0.92 ± 0.37, *P* = 0.6486), but there were significant differences in 60% hepatectomy (0.37 ± 0.23, *P* = 0.0007) and 40% SOLT (0.34 ± 0.24, *P* = 0.0006) (Figure 4H).

Activities of antioxidant enzymes

In comparison with the controls (1.00 ± 0.09), normalized SOD did not show significant differences in 60% hepatectomy (0.97 ± 0.09, *P* = 0.6503), 100% OLT (0.96 ± 0.11, *P* = 0.5461) and 40% SOLT (0.87 ± 0.09, *P* = 0.0595) (Figure 4I). In comparison with the controls (1.00 ± 0.17), normalized catalase also revealed no significant differences in 60% hepatectomy (0.91 ± 0.11, *P* = 0.3665), 100% OLT (0.90 ± 0.15, *P* = 0.3365) and 40% SOLT (0.95 ± 0.14, *P* = 0.6454) (Figure 4J).

Behavior of MMP-9, MMP-2, TIMP-1 and TIMP-2

Protein expression and activity of MMP-9 are shown in Figure 5A. Protein expression was evaluated by western blot densitometry (Figure 5B-D). In comparison with the controls (1.00 ± 0.34), there were no significant differences in normalized MMP-9 in 60% hepatectomy (1.14 ± 0.43, *P* = 0.5811) and 100% OLT (1.18 ± 0.35, *P* = 0.4254), but there was a significant difference in 40% SOLT (2.16 ± 0.26, *P* = 0.0003) (Figure 5B). In comparison with the controls (1.00 ± 0.16), there were no significant differences in normalized MMP-2 in 60% hepatectomy (0.78 ± 0.17, *P* = 0.0716) and 100% OLT (0.80 ± 0.23, *P* = 0.1437), but there was a significant difference in 40% SOLT (0.78 ± 0.12, *P* = 0.0385) (Figure

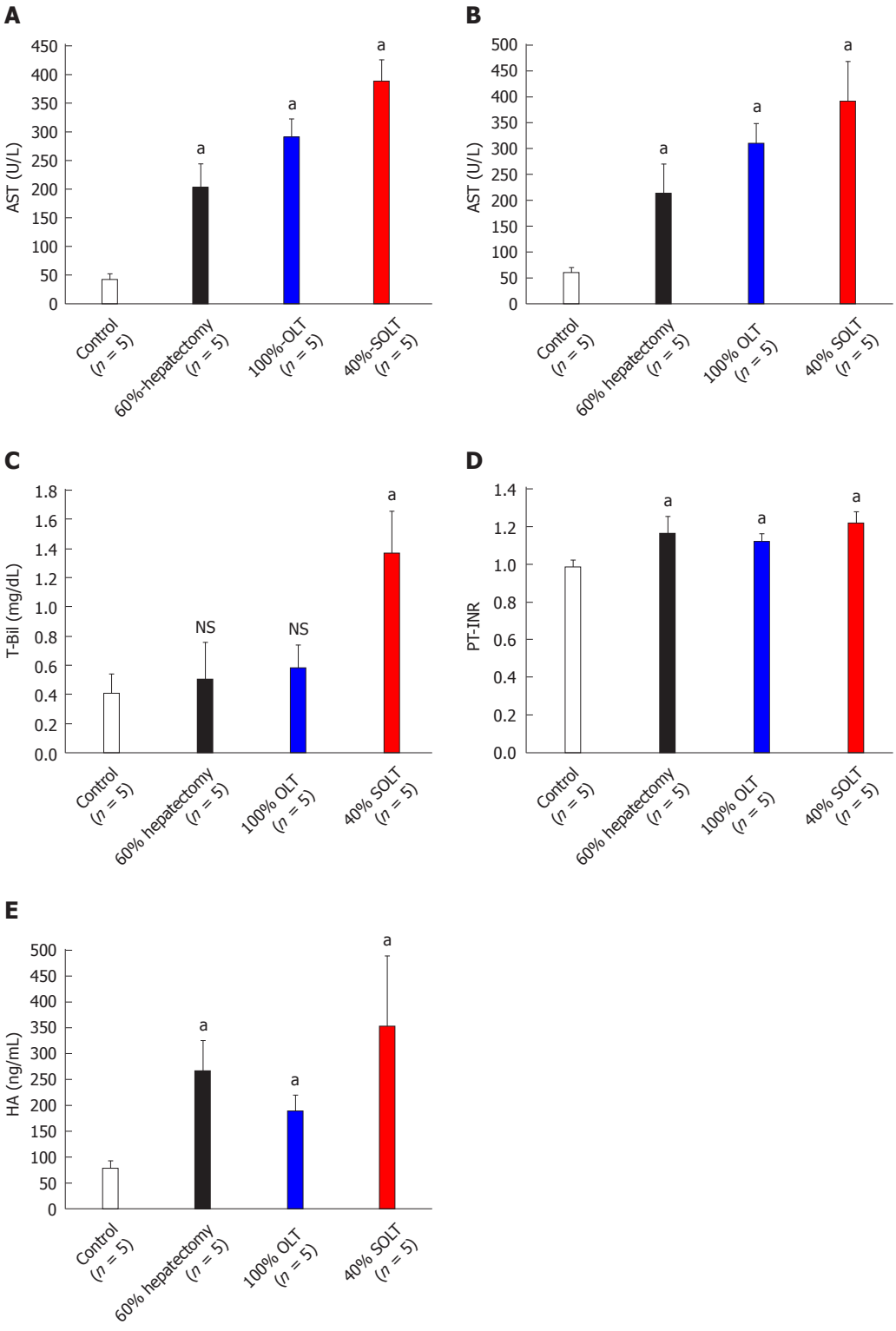
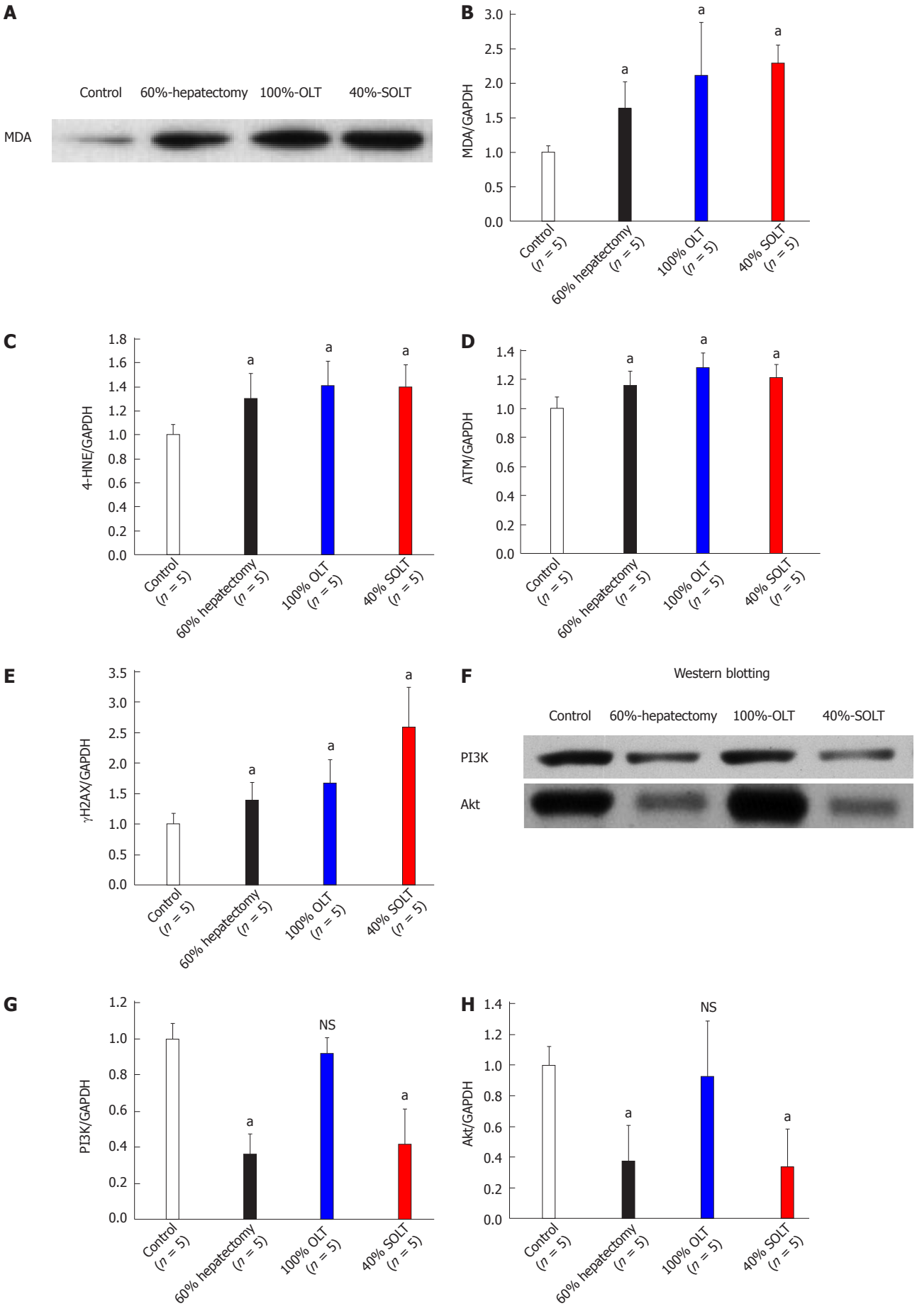


Figure 3 Biochemical and coagulation profiles. A: Serum aspartate aminotransferase (AST); B: Serum alanine aminotransferase (ALT); C: Serum total bilirubin (T-Bil); D: Plasma international normalized ratio of prothrombin time (PT-INR); E: Serum hyaluronic acid (HA). $^{a}P < 0.05$ *vs* control. NS: Not significant ($P \geqslant 0.05$); OLT: Orthotopic liver transplantation; SOLT: Split orthotopic liver transplantation.

5C). In comparison with the controls (1.00 ± 0.30), there was no significant difference in normalized TIMP-1 in 100% OLT (0.82 ± 0.43, $P = 0.4654$), but there were significant differences in 60% hepatectomy (1.41 ± 0.26, $P = 0.0491$) and 40% SOLT (1.46 ± 0.32, $P = 0.0486$) (Figure 5D). In comparison with the controls (1.00 ± 0.24), there were no significant differences in normalized TIMP-2 in 60% hepatectomy (1.23 ± 0.24, $P = 0.1605$) and 100% OLT (0.95 ± 0.17, $P = 0.6846$), but there was a significant difference in 40% SOLT (1.28 ± 0.12, $P = 0.0471$) (Figure 5E).

Protein activities were evaluated by intensity in zy-


A
Control
60%-hepatectomy
100%-OLT
40%-SOLT
MDA
B
MDA/GAPDH
C
4-HNE/GAPDH
D
ATM/GAPDH
E
γH2AX/GAPDH
F
Western blotting
Control
60%-hepatectomy
100%-OLT
40%-SOLT
PI3K
Akt
G
PI3K/GAPDH
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NS
Control (n = 5)
60% hepatectomy (n = 5)
100% OLT (n = 5)
40% SOLT (n = 5)

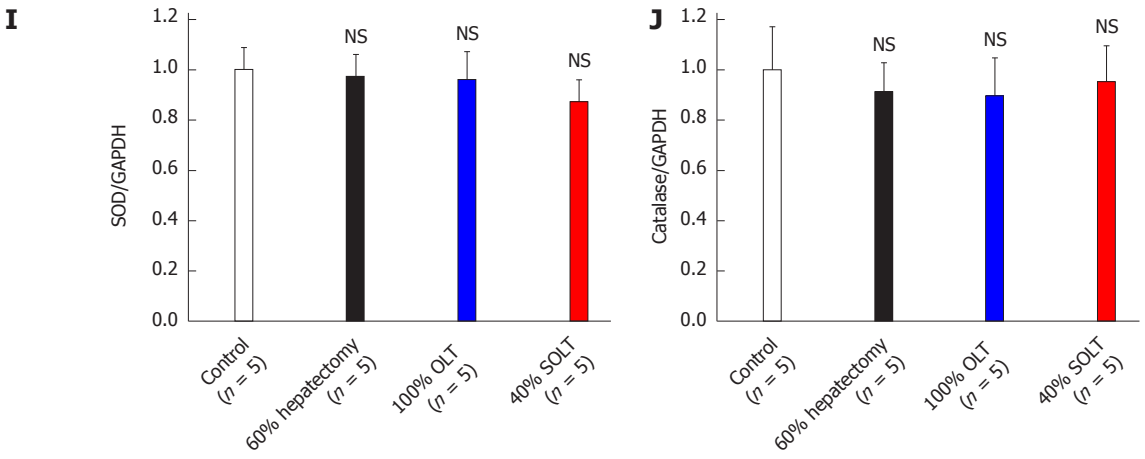


Figure 4 Protein expression of malondialdehyde, 4-hydroxynonenal, ataxia-telangiectasia mutated kinas/H2AX, phosphatidylinositol 3-kinase/Akt and antioxidant enzymes. A: Actual intensities of malondialdehyde (MDA) in western blotting; B: Normalized MDA; C: Normalized 4-hydroxynonenal (4-HNE); D: Normalized ataxia-telangiectasia mutated kinase (ATM); E: Normalized γH2AX; F: Actual intensities of phosphatidylinositol 3-kinase (PI3K) and Akt in western blotting; G: Normalized PI3K; H: Normalized Akt; I: Normalized superoxide dismutase (SOD); J: Normalized catalase. $^{a}P < 0.05$ *vs* control. NS: Not significant ($P \geqslant 0.05$); OLT: Orthotopic liver transplantation; SOLT: Split orthotopic liver transplantation.

mography (Figure 5F-I). In comparison with the controls (1.00 ± 0.15), relative MMP-9 clearly demonstrated significant differences in 60% hepatectomy (1.37 ± 0.23, $P = 0.0156$), 100% OLT (1.47 ± 0.33, $P = 0.0211$) and 40% SOLT (2.10 ± 0.75, $P = 0.0125$) (Figure 5F). In comparison with the controls (1.00 ± 0.17), relative MMP-2 did not reveal significant differences in 60% hepatectomy (1.03 ± 0.12, $P = 0.7444$), 100% OLT (0.98 ± 0.15, $P = 0.8821$) and 40% SOLT (1.04 ± 0.13, $P = 0.6847$) (Figure 5G). In comparison with the controls (1.00 ± 0.15), relative TIMP-1 did not reveal significant differences in 60% hepatectomy (0.96 ± 0.29, $P = 0.7926$), 100% OLT (0.98 ± 0.09, $P = 0.8217$) and 40% SOLT (0.91 ± 0.26, $P = 0.5347$) (Figure 5H). In comparison with the controls (1.00 ± 0.12), relative TIMP-2 did not show significant differences in 60% hepatectomy (1.04 ± 0.09, $P = 0.5974$), 100% OLT (1.03 ± 0.11, $P = 0.6845$) and 40% SOLT (1.03 ± 0.16, $P = 0.7495$) (Figure 5I).

Statistical differences between groups

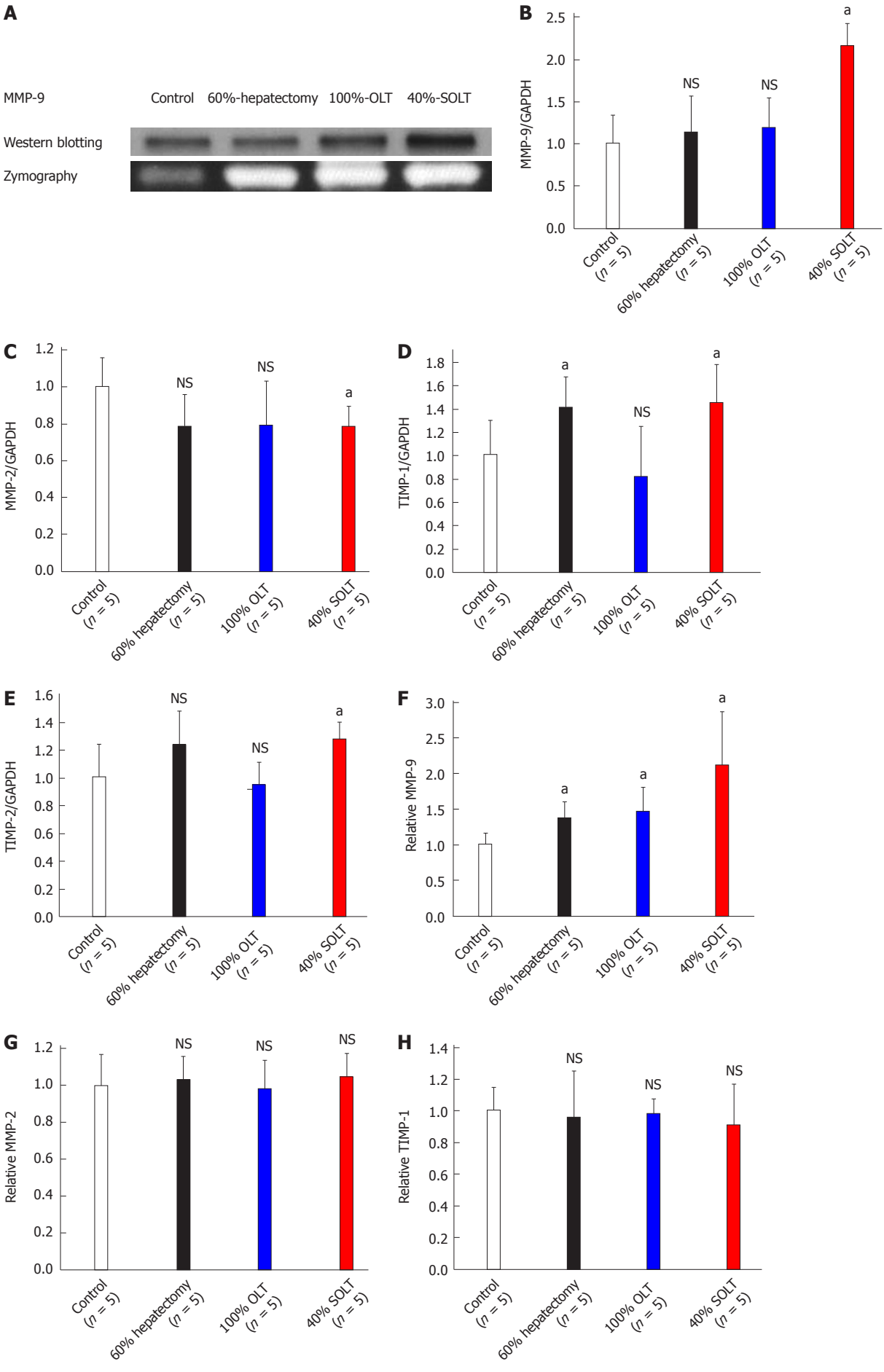
As described above, the data in comparisons with the controls are shown. Statistical differences between groups are summarized in Table 2.

DISCUSSION

In survival and histopathological studies, 40% SOLT involved dual damage (*i.e.*, shear stress with portal hypertension and CIWR injury) and showed the poorest survival and most severe liver damage. Although 100% OLT showed good survival, CIWR injury was observed by histopathological and biochemical findings. Here, we used plasma PT-INR and serum HA levels as markers of sinusoidal endothelial damage and all groups showed significant differences. Survival in the 60% hepatectomy and 40% SOLT groups seemed to be higher than in the 100% OLT group and this may reflect the damage induced by shear stress and portal hypertension. Our histopathological, immunohistological and biochemical findings revealed that liver damage and apoptotic induction were observed in the early postoperative period after liver surgery, as in previous studies[3,12,13,18,29-31]. Paradoxically, the early postoperative period may have a therapeutic potential for a subsequent course after liver surgery.

OS causes DNA damage and subsequent apoptosis and is an imbalance between production of free radicals and antioxidant defenses[9-11]. From the viewpoint of production of free radicals, ROS/RNS can attack and damage a variety of critical biological molecules, including lipids, essential cellular proteins and DNA[9-11]. Products of lipid peroxidation can be easily detected in biological fluids and tissues and can reliably and rapidly reflect the sensitive and specific signals of lipid peroxidation that occur *in vivo*[35,36]. The compound 4-HNE is an end product of lipoperoxidation with antiproliferative and proapoptotic properties[35,36]. Our results with MDA and 4-HNE confirmed that OS occurred even in the early postoperative period.

With regard to DNA damage responses, the protein kinase ATM can be initiated through rapid intermolecular autophosphorylation induced by DNA damage, phosphorylate various proteins and subsequently amplify the responses to DNA damage[36,37]. This DNA damage-inducible kinase activates H2AX[38]. H2AX is required for cell cycle arrest and DNA repair following double-stranded DNA breaks[38,39]. DNA damage results in the rapid phosphorylation of H2AX by ATM[38,40]. Within minutes of DNA damage, H2AX is phosphorylated at the sites of the DNA damage[38]. This early event in the DNA-damage response is required for the recruitment of many DNA-damage response proteins. Therefore, histone H2AX is activated by ATM after DNA dam-


A
MMP-9
Control
60%-hepatectomy
100%-OLT
40%-SOLT
Western blotting
Zymography
B
MMP-9/GAPDH
C
MMP-2/GAPDH
D
TIMP-1/GAPDH
E
TIMP-2/GAPDH
F
Relative MMP-9
G
Relative MMP-2
H
Relative TIMP-1
NS
a
Control (n = 5)
60% hepatectomy (n = 5)
100% OLT (n = 5)
40% SOLT (n = 5)

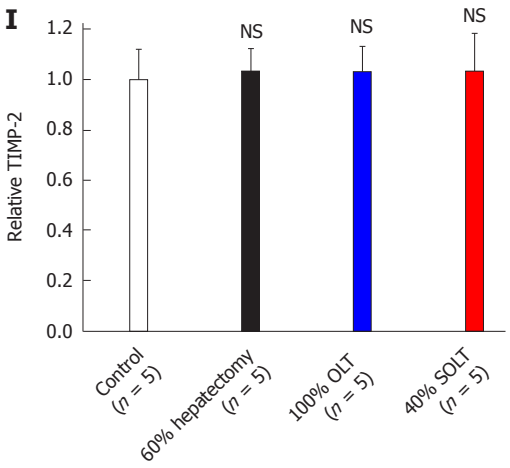


Figure 5 Protein expression and activities of matrix metalloproteinases and tissue inhibitor of metalloproteinases. A: Actual protein expression and activities of matrix metalloproteinase (MMP)-9; B: Normalized MMP-9; C: Normalized MMP-2; D: Normalized tissue inhibitor of metalloproteinase (TIMP)-1; E: Normalized TIMP-2; F: Relative MMP-9; G: Relative MMP-2; H: Relative TIMP-1; I: Relative TIMP-2. [a]$P < 0.05$ *vs* control. NS: Not significant ($P \geqslant 0.05$); OLT: Orthotopic liver transplantation; SOLT: Split orthotopic liver transplantation.

Table 2 Statistical differences between groups

	Control *vs* 60%-hepatectomy	Control *vs* 100%-OLT	Control *vs* 40%-SOLT	60%-hepatectomy *vs* 100%-OLT	60%-hepatectomy *vs* 40%-SOLT	100%-OLT *vs* 40%-SOLT
Survival rate	$P < 0.05$	NS	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$
Liver damage score	$P < 0.05$	$P < 0.05$	$P < 0.05$	NS	$P < 0.05$	$P < 0.05$
TUNEL positive ratio	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$
Caspase-3 positive ratio	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$
AST	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$
ALT	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$	NS
T-Bil	NS	NS	$P < 0.05$	NS	$P < 0.05$	$P < 0.05$
PT-INR	$P < 0.05$	p <0.05	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$
HA	$P < 0.05$	p <0.05	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$
Western blotting						
MDA	$P < 0.05$	$P < 0.05$	$P < 0.05$	NS	$P < 0.05$	NS
4-HNE	$P < 0.05$	$P < 0.05$	$P < 0.05$	NS	NS	NS
ATM	$P < 0.05$	$P < 0.05$	$P < 0.05$	NS	NS	NS
γH2AX	$P < 0.05$	$P < 0.05$	$P < 0.05$	NS	$P < 0.05$	$P < 0.05$
PI3K	$P < 0.05$	NS	$P < 0.05$	$P < 0.05$	NS	$P < 0.05$
Akt	$P < 0.05$	NS	$P < 0.05$	$P < 0.05$	NS	$P < 0.05$
SOD	NS	NS	NS	NS	NS	NS
Catalase	NS	NS	NS	NS	NS	NS
MMP-9	NS	NS	$P < 0.05$	NS	$P < 0.05$	$P < 0.05$
MMP-2	NS	NS	$P < 0.05$	NS	NS	NS
TIMP-1	$P < 0.05$	NS	$P < 0.05$	$P < 0.05$	NS	$P < 0.05$
TIMP-2	NS	NS	$P < 0.05$	$P < 0.05$	NS	$P < 0.05$
Zymography						
MMP-9	$P < 0.05$	$P < 0.05$	$P < 0.05$	NS	$P < 0.05$	p <0.05
MMP-2	NS	NS	NS	NS	NS	NS
TIMP-1	NS	NS	NS	NS	NS	NS
TIMP-2	NS	NS	NS	NS	NS	NS

OLT: Orthotopic liver transplantation; SOLT: Split orthotopic liver transplantation; AST: Aspartate aminotransferase; ALT: Alanine aminotransferase; T-Bil: Total bilirubin; PT-INR: International normalized ratio of prothrombin time; HA: Hyaluronic acid; MDA: Malondialdehyde; 4-HNE: 4-hydroxynonenal; ATM: Ataxia-telangiectasia mutated kinase; PI3K: Phosphatidylinositol 3-kinase; SOD: Superoxide dismutase; MMP: Matrix metalloproteinase; TIMP: Tissue inhibitor of metalloproteinase.

age[38]. Thus, the ATM/H2AX signaling pathway is important in the response to and repair of DNA damage induced by OS[38,41]. Our results with ATM and H2AX clearly showed that OS after liver surgery caused DNA damage signaling and triggered subsequent DNA repair. In this study, groups with only CIWR injury (*i.e.*, 100% OLT) caused OS-induced damage and subsequent apoptotic process. However, this group showed differences not in PI3K/Akt, but in ATM/H2AX. These results suggested that CIWR injury induce apoptosis due to OS *via* the ATM/H2AX pathway.

Akt also plays a critical role in controlling apoptosis

and promotes cell survival to prohibit apoptosis[42-44]. Apoptotic machinery is inhibited by the activation of Akt[42-44]. Akt is an integral component of the antiapoptotic process related to the activation of PI3K[42-45]. Our results clearly showed that groups with accompanying shear stress and portal hypertension (*i.e.*, 60% hepatectomy and 40% SOLT) had decreased PI3K and Akt. This suggested that a subsequent apoptotic process was triggered in these groups. Shear stress and portal hypertension due to insufficient liver volume induce apoptosis due to OS *via* the Akt/PI3K pathway.

With regard to antioxidant defense, scavenging enzymes of free radicals, such as SOD and catalase, also play an important role in reducing DNA damage and subsequent apoptosis[10,11]. Cells are normally able to defend themselves against OS-induced damage through this scavenging system[10,11]. Our results revealed that this scavenging system did not appear to be triggered, although these scavenging enzymes can cope with large amounts of ROS[46]. Shear stress with portal hypertension and/or CIWR injury after liver surgeries in this study caused considerable liver damage. A possible explanation is that this scavenging system failed to stimulate some reactive molecules because of considerable damage after liver surgery.

MMPs have been intensively studied and shown to play key roles in inflammation, carcinogenesis and regeneration and many researchers have already focused on MMP-2 and MMP-9 after liver surgery[12-21]. In the present study, 40% SOLT increased protein expression of MMP-2 in western blotting, although zymography did not show any differences. Contrary to MMP-2, postoperative MMP-9 clearly showed differences in protein expression and function. Additionally, MMP-9 showed high reproducibility in our previous studies[20,47,48]. The present results for MMP-9 suggested that MMP-9 clearly increased even in the early postoperative period after liver surgery and MMP-9 is a major therapeutic target after liver surgery.

TIMPs are also important after liver surgery. Many researchers have focused on TIMP-1 and TIMP-2 during liver regeneration[25-28]. Some researchers have focused on postoperative behavior of TIMP-1[28]. In particular, TIMP-1 has extrahepatic effects during liver failure[23,49-52] and therefore we initially expected that TIMP-1 would show differences in the liver samples. However, zymography for TIMP-1 did not show any differences, although groups with shear stress and portal hypertension (*i.e.*, 60% hepatectomy and 40% SOLT) showed increased protein expression of TIMP-1 in western blotting. TIMP-1 is an endogenous inhibitor of MMP-9 and a balance of MMP-9/TIMP-1 is linked[22,23]. However, the behavior of TIMP-1 in the postoperative liver is still unclear and further studies are required.

Liver damage and apoptotic induction are confirmed even in the early postoperative period after liver surgery but liver injury triggers the liver regeneration cascade after surgery. Once hepatic failure occurs after liver surgery, this damage is usually intractable and fatal. Therefore, the early postoperative period may be a suitable time for treatment to achieve a good postoperative course after liver surgery and our lab focused on OS-mediated damage and the behavior of extracellular matrices after liver surgery[20,48,51,53-56]. The inhibition of apoptotic induction due to OS *via* the ATM/H2AX pathway may be important for a strategy against CIWR injury, even in the condition of sufficient liver volume. Under conditions with insufficient liver remnant, the prevention of apoptotic induction due to OS *via* the Akt/PI3K pathway may be key to improving postoperative course. Also, MMP-9 may be a reliable therapeutic target, especially in the condition of CIWR injury with insufficient liver volume. We hope that our results will be informative for researchers in the hepatology field.

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COMMENTS

Background

After liver surgery, shear stress with portal hypertension and cold ischemia/warm reperfusion injury trigger the liver regeneration cascade and also cause fatal liver damage.

Research frontiers

Changes and behaviors of oxidative stress and extracellular matrices are still unknown.

Innovations and breakthroughs

Here, the authors investigate the oxidative stress-mediated damage and the behavior of extracellular matrices after liver surgery in various rat models.

Applications

Under conditions with insufficient liver remnant, prevention of oxidative stress-induced damage *via* the Akt/PI3K pathway may be key to improve postoperative course. MMP-9 may be also a therapeutic target after liver surgery.

Terminology

Regulations for oxidative stress and MMP-9 may have a therapeutic potential, in order to resolve the current problems after liver surgery.

Peer review

This is a very interesting paper about the pathophysiology of hepatic failure after hepatectomy and liver transplantation.

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