Hepatic injury after hepatic stress is caused by several mechanisms, including inflammatory reaction and microcirculatory disturbance. Levels of thromboxane, a vasoconstrictive eicosanoid, have been shown to increase in systemic circulation after different types of hepatic stress such as endotoxemia, hepatic ischemia-reperfusion, hepatectomy, liver transplantation, hemorrhagic shock and resuscitation, hepatic cirrhosis, and alcoholic liver injury. The production of thromboxane from the liver is also enhanced under these stresses, which may act on the liver in an autocrine or a paracrine fashion. Kupffer cells, resident hepatic macrophages, may be a major source of stress-induced thromboxane, although other cell types in the liver such as sinusoidal endothelial cells and hepatocytes may also produce this eicosanoid. Thromboxane induces hepatic damage through vasoconstriction, platelet aggregation, induction of leukocyte adhesion, up-regulation of proinflammatory cytokines, and induction of other vasoconstrictor release. In this regard, administration of cyclooxygenase inhibitor, specific thromboxane synthase inhibitor, and specific thromboxane receptor antagonists has been shown to protect from severe hepatic injury elicited by these hepatic stresses. Furthermore, blockade of Kupffer cell function by administration of gadolinium chloride showed salutary effects in preventing hepatic damage in bile duct ligation models. This review article summarizes the recent knowledge of the role of thromboxane in various types of hepatic stress and the effects of thromboxane inhibitors in these models.
vasoactive agents, which might further influence the effects of TXA2, are also discussed.

Figure 1. Hepatic microcirculatory regulation by vasoactive agents. A fine balance between vasoconstrictors and vasodilators is important in maintaining normal hepatic microcirculation. An impaired balance leads to heterogeneous perfusion in the liver and subsequent hepatic injury. TXA₂, thromboxane A₂; NO, nitric oxide; PGI₂, prostacyclin (prostaglandin I₂); and TXA₂, thromboxane A₂.

Figure 2. Cascade of prostanoid synthesis. Arachidonic acid is produced from phospholipids by an activation of phospholipase A₂. Thromboxane A₂ (TXA₂), prostacyclin (prostaglandin I₂ [PGI₂]), and other prostanoids are synthesized through the activation of cyclooxygenase (COX), whereas leukotrienes (LT) are produced through the activation of lipoxygenase. 5-HPETE indicates 5-hydroperoxyeicosatetraenoic acid.

ROLE OF THROMBOXANE IN VARIOUS HEPATIC STRESS MODELS

Endotoxia-Induced Hepatic Injury

Endotoxia produces severe hepatic damage through the activation of an inflammatory process and derangement of microcirculation. In this regard, TXA₂ produced from the liver has been proposed as one of the responsible mediators. Administration of lipopolysaccharide (LPS) in the isolated perfused liver results in a rapid release of TXB₂, a stable metabolite of TXA₂, into the perfusate, suggesting that the liver is an important source of TXA₂ after endotoxia. In the liver, Kupffer cells are responsible for the increased production of TXA₂, although sinusoidal endothelial cells could also serve as a source of TXA₂ release in response to LPS administration. Other resident macrophages such as peritoneal macrophages and alveolar macrophages are also found to release TXA₂ during endotoxia. Thromboxane A₂ is involved in endotoxia-induced hepatic microcirculatory disturbance through its vasoconstrictive effect. Analogues of TXA₂ not only directly contract the vascular smooth muscle cells but also contract the hepatic stellate cells, which have been shown to regulate sinusoidal perfusion. This action leads to a heterogeneous sinusoidal flow and impairs hepatic microcirculation. Enhanced release of TXA₂ from the liver has also been shown to be responsible for the production of tumor necrosis factor α (TNF-α), a representative proinflammatory cytokine, from the liver. Furthermore, TXA₂ is associated with the LPS-induced increase in intercellular adhesion molecule 1 expression in the intrahepatic vasculatures, which facilitates leukocyte adhesion and contributes to the enhancement of hepatic inflammatory process. These results indicate that the increased production of TXA₂ from the liver and its autocrine or paracrine action on the liver contribute to hepatic injury in endotox-
emia. This hypothesis is supported by studies that showed the protective effects of TXA2 synthase inhibitors in endotoxin-induced hepatic damage by improving microcirculatory blood flow, inhibiting TNF-α production, and suppressing the expression of intercellular adhesion molecule 1.

**Ischemia-Reperfusion–Induced Hepatic Injury**

Hepatic damage after ischemia-reperfusion is a serious problem in a number of clinical settings, including hepatic resection, liver transplantation, and hemorrhagic shock and resuscitation. The mechanisms of ischemia-reperfusion–induced hepatic injury include the activation of inflammatory response, formation of reactive oxygen species, and microcirculatory disturbance. A variety of humoral mediators are included in these mechanisms such as TNF-α, interleukin 1β, interleukin 6, endothelins, prostaglandins, and TXA2.

**Ischemia-Reperfusion Model.** Thromboxane A2 plays a pivotal role in hepatic injury after ischemia-reperfusion. Numerous animal studies have shown that COX-1 inhibitors, COX-2 inhibitors, selective TXA2 synthase inhibitors, and specific TXA2 receptor antagonists protect the liver from injury after ischemia-reperfusion. These treatments reduce the damage to sinusoidal lining cells, ameliorate histological liver necrosis, lower the levels of serum transaminase, normalize amino acid metabolism and lipid peroxidation, and restore hepatic tissue blood flow. Administration of PGI2 analogues, which counteract the action of TXA2 in vasoconstrictive and platelet-aggregating effects, also showed hepatoprotective effects in the hepatic ischemia-reperfusion model.

**Hepatic Resection.** Circulating TXB2 levels are remarkably increased during and after hepatic resection, and inhibition of TXA2 synthesis substantially reduces hepatic damage after hepatectomy. These effects have been shown in animal and human hepatectomy cases. In a canine model, the plasma levels of TXB2 increased significantly within 24 hours after 84% hepatectomy. This was associated with insufficient blood flow in the portal vein and hepatic tissue. However, administration of TXA2 synthase inhibitor dramatically improved the 2-week survival rate (from 12.5% to 58.3%) after 84% hepatectomy, which suggests the potential value of TXA2 inhibitor in extending the resectability of the liver. In human hepatectomy cases under hemihepatic vascular control, the levels of total prostanoids (6-keto-prostaglandin-F1α, prostaglandin-E2, TXB2) were significantly increased after hepatectomy, and these levels were positively correlated with the hepatic ischemic time. In the same study, administration of TXA2 synthase inhibitor reduced the plasma TXB2 levels and concomitantly reduced serum glutamic oxaloacetic transaminase levels. Thromboxane A2 is produced in the organ upstream from the liver and may act on the liver during and after hepatectomy. A report indicated that the spleen could be the source of TXA2 hypersecretion during hepatectomy because the level of TXB2 in the splenic vein was found to be significantly higher than that in the mesenteric vein.

Furthermore, splenic macrophages after extensive hepatectomy produced more TXA2, and a splenectomy in conjunction with an extensive hepatectomy prevented remnant hepatic dysfunction.

**Liver Transplantation.** Vasoactive agents liberated from the liver after initiation of reperfusion have been proposed as the responsible factors underlying the pathophysiology of transplantation-related liver failure. The levels of prostanoids in the hepatic vein immediately after liver grafting are markedly increased, and this is significantly associated with poor early graft function. Thus, pretreatment with TXA2 synthase inhibitor not only significantly reduced the serum levels of TXA2 but also provided a better graft function and survival rate after liver transplantation. Kupffer cells have been shown to play an important role in eicosanoids production and in the activation of nuclear factors (nuclear factor-kB and activating protein 1) of liver grafts from non–heart-beating donors, which are strongly associated with reperfusion injury after liver transplantation. In this regard, suppression of Kupffer cell function substantially reduces graft damage after liver transplantation.

**Hemorrhagic Shock and Resuscitation.** Hemorrhagic shock and resuscitation is a hepatic hypoxemia-reoxygenation model. Although the extent of hypoxia in this model is relatively mild compared with the model of total vascular occlusion, prolonged mild hypoxemia results in liver damage similar to that observed after severe ischemia for a shorter interval. Previous studies have shown a decreased clearance of indocyanine green, increased plasma alanine aminotransferase levels, and im-
Hepatic Cirrhosis

In hepatic cirrhosis, increased resistance in the portal venous system is the primary factor in the pathophysiology of portal hypertension. Increased resistance in the portal venous system is induced by the destruction of normal hepatic structure as a result of fibrin deposition or by the impaired balance between the action of vasodilators and vasoconstrictors. Studies have shown that cirrhotic livers exhibit hyperresponse to vasoconstrictors such as catecholamine, endothelin, and leukotriene D4. In addition to these vasoconstrictors, the production of TXA2 is enhanced in the cirrhotic liver and has been shown to be responsible for an increased resistance in the portal venous system. This phenomenon was observed in 2 different cirrhotic models such as bile duct ligation and carbon tetrachloride intoxication. The expression of COX-2 increases in both models; however, the expression of COX-1 does not change after stress. Furthermore, Kupffer cells have been implicated as a major source of TXA2 in both models. In this regard, the blockade of Kupffer cell functions by gadolinium chloride results in the attenuation of TXB2 release from the bile duct ligation–induced cirrhotic liver. Furthermore, this decreased production of TXB2 leads to the attenuation of portal hypertension and hepatic injury. Indomethacin, a nonspecific COX inhibitor, and specific TXA2 receptor antagonists also showed the same protective effects on the liver as the blockade of Kupffer cell functions under cirrhotic conditions.

Alcoholic Liver Disease

Severity of liver injury in experimental alcoholic liver disease has been shown to be positively correlated with plasma levels of alcohol. Subsequent studies in the same laboratory showed increased expression of hepatic COX-2 in ethanol-fed animals. This enhanced COX-2 expression in the liver is associated with increased TNF-α messenger RNA expression, lipid peroxidation, and synthesis of TXB2 in the liver. In this regard, treatment with TXA2 receptor antagonists or TXA2 synthase inhibitors decreased TNF-α production and prevented inflammatory changes in ethanol-fed rats. In experimental alcoholic liver disease, Kupffer cells are most likely the source of TXB2, although endothelial cells and hepatocytes might also produce this prostanoid. Furthermore, the expression of TXA2 receptor messenger RNA is highest in Kupffer cells compared with other cell types in the liver, suggesting the existence of autocrine effects of TXA2 on Kupffer cells.

EFFECT OF THROMBOXANES ON OTHER VASOACTIVE AGENTS

A relationship between TXA2 release and other vasoactive mediators has been described in a number of studies. Those mediators include endothelin and angiotensin II as vasoconstrictors and NO and PGI2 as vasodilators.

Endothelin

Endothelin, one of the most potent vasoconstrictors, has been shown to increase in circulation under various hepatic stresses. Increased production of endothelin activates vascular smooth muscle cells and hepatic stellate cells in the liver, which causes stenosis on the presinusoidal portal vein and sinusoids, respectively. Several studies have shown that the release of endothelin is regulated by TXA2. Treatment of rat heart smooth muscle cells by a stable TXA2 mimetic induces up-regulation of endothelin 1 messenger RNA. Increased serum endothelin levels after allograft liver transplantation are significantly decreased by the treatment with TXA2 synthase inhibitors given at the time of liver harvesting. These results indicate that TXA2 induces the release of endothelin, which may cause more potent and long-lasting vasoconstrictive effects. However, in other reports that used cultured endothelial cells, TXA2 showed no effect on endothelin secretion, whereas vasodilator prostaglandins such as prostaglandin E2 and PGI2 significantly inhibited endothelin 1 secretion. In view of these results, it can be postulated that these mechanisms may be tissue or cell type-specific. The release of TXA2 is also regulated by endothelin. Endothelin 1 evoked the release of endogenous TXA2 from the cultured rabbit airway smooth muscle cells. Sustained contraction of rat aorta induced by endothelin at least partly requires persistent activation of TXA2 receptor (TP receptors). In the liver, preadministration of indomethacin or a specific TXA2 synthetase inhibitor significantly inhibits the decreases in hepatic blood flow induced by endothelin. Despite sufficient evidence of the interaction between endothelin and TXA2, detailed mechanisms including the signaling pathway are still unknown, although protein kinase C may play some role in this interaction.

Angiotensin II

As with endothelin, angiotensin II is an effective vasoconstrictor for the hepatic vasculature and may be at least partly responsible for stress-induced hepatic injury. Angiotensin II receptors of the AT1 subtype are present on the hepatic stellate cell, and the activation of the receptors induces stellate cell contraction. It also induces a proliferation and activation of hepatic stellate cells and promotes the process of liver fibrosis. Furthermore, chronic elevation of circulating angiotensin II levels damages the liver by activating proinflammatory events. In this regard, blockade of angiotensin II receptor leads to attenuation of hepatic fibrosis and a reduction in inflammatory response–mediated hepatic injury under stressful conditions. Vasoconstriction induced by TXA2 is significantly inhibited by an angiotensin receptor antagonist in the isolated human internal mammary artery, suggesting cross-interaction between the TP receptor and angiotensin II receptor. A TXA2 synthase inhibitor causes a decrease in the vasoconstrictor effect of angiotensin II in the isolated rabbit kidney and abolishes edema produced by angiotensin II in the isolated rat lung. Although an interaction between TXA2 and angiotensin II in the liver has...
not yet been fully elucidated, it could be speculated that these vasoconstrictors synergistically act on hepatic circulation under stressful conditions.

Nitric Oxide

In addition to vasoconstrictors, TXA₂ also causes “cross talk” with the vasodilators.¹⁰³ Up-regulation of inducible NO synthase (iNOS) and release of its product NO by Kupffer cells in the liver is markedly enhanced by LPS administration.¹⁰⁰ Although the production of TXB₂ is also induced by LPS, this effect is partly attenuated by NO.¹⁰⁰ Therefore, an inhibition of NO synthesis results in a further increase in TXB₂ production by Kupffer cells. The levels of TXB₂ derived from platelets are also significantly increased in iNOS-deficient animals.¹⁰¹ These results indicated that NO has an inhibitory effect on TXA₂ production. Other evidence showed the regulatory role of TXA₂ on NO production. Vascular smooth muscle cells, when stimulated with LPS or proinflammatory cytokines, showed exaggerated NO production due to up-regulation of iNOS. However, endogenous TXA₂ reduced iNOS expression and NO production.¹⁰² Cytokine-induced NO production was significantly higher in TP receptor knockout mice. Furthermore, vasodilating prostanooids such as prostaglandin E₂ and PGI₂ have been shown to increase iNOS expression and thus antagonize TXA₂ action.¹⁰³ These results indicate the existence of a mutual inhibitory mechanism between NO and TXA₂. However, this mechanism is not available in cirrhotic livers. Although COX-derived TXA₂ plays a major role in methoxamine-induced portal venous hyperresponse in cirrhotic livers, this is not modulated by an inhibition of NO production.⁷¹ An increased production of TXA₂ from the liver is involved in the pathogenesis of endothelial dysfunction in cirrhotic rat livers.⁷² However, this is not affected by NO synthase inhibitor, indicating a lack of regulatory mechanism between NO and TXA₂ in cirrhotic livers.

Prostacyclin

Prostaglandin I₂ induces vasodilation, inhibits platelet aggregation, and antagonizes the effects of TXA₂. The plasma TXA₂/PGI₂ ratio changes in some pathological conditions.¹⁰⁴ It increases during liver ischemia and could influence the extent of hepatic injury⁷⁵ and survival rate of animals.¹⁰⁶ Therefore, administration of PGI₂, which reduces the TXA₂/PGI₂ ratio, improves the outcome of ischemia-reperfusion-induced hepatic injury.⁵⁴ Administration of PGI₂ after liver transplantation also improved hepatic-splanchnic oxygenation and reduced reperfusion injury in human randomized controlled trials.¹⁰⁷ Moreover, modulation of the TXA₂/PGI₂ ratio by inhibiting TXA₂ production or by administering PGI₂ analogue significantly ameliorated the functional impairment of the residual liver after major hepatectomy.⁷⁴ The specific TP antagonists have been shown to protect hepatic tissue from ischemia-reperfusion injury by increasing PGI₂ levels.⁵⁰ A recent study¹⁰⁸ showed that the activation of PGI₂ receptors in platelets completely inhibits TXA₂-mediated TP receptor signaling in a protein kinase A-dependent but not a protein kinase C-dependent manner, suggesting inhibitory effects of PGI₂ on TXA₂ action. This is mediated through the activation of TPα but not TPβ receptors in platelets.¹⁰⁹

Although the liver expresses TP receptors,⁷³¹¹⁰ it remains unknown whether the same regulatory mechanism in the balance between PGI₂ and TXA₂ exists in the liver.

CONCLUSIONS

The mechanisms of hepatic injury during hepatic stress have been extensively investigated. The available information from clinical and animal studies strongly indicates that TXA₂ plays a pivotal role in producing hepatic injury during various forms of stress. Moreover, TXA₂ up-regulates other vasoconstrictors and down-regulates vasodilators, and these effects further exacerbate the vasoconstrictive effects of TXA₂ (Figure 4). Nonetheless, blockade of TXA₂ action prevents the hepatic damage elicited by these stresses. It is, however, disappointing to note that only a few randomized clinical trials have been performed to determine the usefulness of thromboxane inhibitors in preventing hepatic injury. Such trials should be undertaken in the future because thromboxane inhibitors are relatively safe and are not expected to produce any deleterious effects in the patients. Moreover, additional studies to elucidate the precise mechanism of TXA₂-mediated hepatic injury should be performed to establish more effective therapy against hepatic injury after various adverse circulatory conditions.

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Correspondence: Ishrad H. Chaudry, PhD, Center for Surgical Research, University of Alabama at Birmingham, Volker Hall G094, 1670 University Blvd, Birmingham, AL 35294-0019 (Ishrad.Chaudry@ccc.uab.edu).

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