Editorial Expression of Concern and Corrections

EDITORIAL EXPRESSION OF CONCERN. PNAS is publishing an Editorial Expression of Concern regarding the following three articles:

(i) PHYSIOLOGY. “NCX-1000, a NO-releasing derivative of ursodeoxycholic acid, selectively delivers NO to the liver and protects against development of portal hypertension,” by Stefano Fiorucci, Elisabetta Antonelli, Olivia Morelli, Andrea Mencarelli, Alessandro Casini, Tommaso Mello, Barbara Palazetti, Dominique Tallet, Piero del Soldato, and Antonio Morelli, which appeared in issue 15, July 17, 2001, of Proc Natl Acad Sci USA (98:8897–8902; first published July 10, 2001; 10.1073/pnas.151136298);

(ii) PHARMACOLOGY. “NCX-1015, a nitric-oxide derivative of prednisolone, enhances regulatory T cells in the lamina propria and protects against 2,4,6-trinitrobenzene sulfonic acid-induced colitis in mice,” by Stefano Fiorucci, Elisabetta Antonelli, Eleonora Distrutti, Piero Del Soldato, Roderick J. Flower, Mark J. Paul Clark, Antonio Morelli, Mauro Perretti, and Louis J. Ignarro, which appeared in issue 24, November 26, 2002, of Proc Natl Acad Sci USA (99:15770–15775; first published November 11, 2002; 10.1073/pnas.232583599); and


The editors wish to note that a reader has raised questions about the apparent duplication in the use of certain figures in the foregoing articles. We have been informed by the University of Perugia, Italy, of an ongoing review conducted by an inquiry committee at the university. We are awaiting the findings of the committee to determine the appropriate next steps.

Randy Schekman, Editor-in-Chief

www.pnas.org/cgi/doi/10.1073/pnas.0803890105

PLANT BIOLOGY. For the article “Salt tolerance of Arabidopsis thaliana requires maturation of N-glycosylated proteins in the Golgi apparatus,” by Jae Sook Kang, Julia Frank, Chang Ho Kang, Hiroyuki Kajiura, Meenu Vikram, Akihiro Ueda, Sewon Kim, Jeong Dong Bahk, Barbara Triplett, Kazuhiro Fujiiyama, Sang Yeol Lee, Antje von Schaewen, and Hisashi Koiwa, which appeared in issue 15, April 15, 2008, of Proc Natl Acad Sci USA (105:5933–5938; first published April 11, 2008; 10.1073/pnas.0800237105), the authors note that the affiliation for Kazuhiro Fujiiyama should have appeared as Osaka University. The corrected author line, the affiliation line, and a related footnote appear below.

Jae Sook Kang*, Julia Frank†, Chang Ho Kang‡, Hiroyuki Kajiura§, Meenu Vikram†, Akihiro Ueda‡, Sewon Kim*, Jeong Dong Bahk*, Barbara Triplett¶, Kazuhiro Fujiiyama§, Sang Yeol Lee*, Antje von Schaewen†, and Hisashi Koiwa‡

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NEUROSCIENCE. For the article “Organization of the core structure of the postsynaptic density,” by Xiaobing Chen, Christine Winters, Rita Azzam, Xiang Li, James A. Galbraith, Richard D. Leapman, and Thomas S. Reese, which appeared in issue 11, March 18, 2008, of Proc Natl Acad Sci USA (105:4453–4458; first published March 7, 2008; 10.1073/pnas.0800897105), the authors note that on page 4455, right column, in “AMPAR-Type Structures,” paragraph 2, line 10, the phrase “from replica labeling (20 ± 4 nm) (28)” should instead read: “from replica labeling (20 ± 4 nm) (48).” The authors also wish to add the following reference citation:


www.pnas.org/cgi/doi/10.1073/pnas.0803900105
NCX-1000, a NO-releasing derivative of ursodeoxycholic acid, selectively delivers NO to the liver and protects against development of portal hypertension

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Edited by Louis J. Ignarro, University of California School of Medicine, Los Angeles, CA, and approved May 17, 2001 (received for review March 21, 2001)

Portal hypertension resulting from increased intrahepatic resistance is a common complication of chronic liver diseases and a leading cause of death in patients with liver cirrhosis, a scarring process of the liver that includes components of both increased fibrogenesis and wound contraction. A reduced production of nitric oxide (NO) resulting from an impaired enzymatic function of endothelial NO synthase and an increased contraction of hepatic stellate cells (HSCs) have been demonstrated to contribute to high intrahepatic resistance in the cirrhotic liver. 2-(Acetyloxy) benzoic acid 3-(nitrooxymethyl) phenyl ester (NCX-1000) is a chemical entity obtained by adding an NO-releasing moiety to ursodeoxycholic acid (UDCA), a compound that is selectively metabolized by hepatocytes. In this study we have examined the effect of NCX-1000 and UDCA on liver fibrosis and portal hypertension induced by i.p. injection of carbon tetrachloride in rats. Our results demonstrated that although both treatments reduced liver collagen deposition, NCX-1000, but not UDCA, prevented ascite formation and reduced intrahepatic resistance in carbon tetrachloride-treated rats as measured by assessing portal perfusion pressure. In contrast to UDCA, NCX-1000 inhibited HSC contraction and exerted a relaxing effect similar to the NO donor S-nitroso-N-acetylpenicillamine. HSCs were able to metabolize NCX-1000 and release nitrite/nitrate in cell supernatants. In aggregate these data indicate that NCX-1000, releasing NO into the liver microcirculation, may provide a novel therapy for the treatment of patients with portal hypertension.

Portal hypertension resulting from increased intrahepatic resistance is a common complication of chronic liver diseases and a leading cause of death in patients with liver cirrhosis, a scarring process of the liver that includes components of both increased fibrogenesis and wound contraction (1). A close relationship occurs between the progression of liver fibrosis and development of portal hypertension. In particular, the development of portal-central anastomosis and arterialization/capillarization of liver sinusoids represents the hallmark of the fibrogenic process as well as the key determinant for increased intrahepatic vascular resistance (2). Portal-central anastomoses are embedded in developing scar tissue where a complex interplay between several cell types and soluble mediators occurs. Recent evidence links perisinusoidal hepatic stellate cells (HSCs), also known as Ito cells or lipocytes, which are analogous to tissue pericytes or vascular smooth muscle cells, to a role in portal hypertension (3–5). Indeed, not only are HSCs involved in collagen deposition and development of liver fibrosis, but they also regulate intrahepatic blood flow by sinusoid contraction/constriction (3–5). In the injured liver, HSCs undergo a striking functional transition process termed activation. A critical feature of the activation process is the acquisition of smooth muscle isoforms of actin and myosin and enhanced contractile properties (5). The transition/activation process is associated with an enhanced expression of receptors for endothelins, suggesting that increases in intrahepatic resistance are, at least in part, caused by an enhanced contractile response to these vasoconstrictor agents (6, 7). HSC contraction is counterbalanced by vasorelaxing agents such as nitric oxide (NO) (8). NO is an ubiquitous messenger produced from conversion L-arginine to L-citrulline by either constitutive or inducible NO synthase (NOS) (9, 10). The constitutive NOS isoforms are localized predominantly in neuronal cells and endothelial cells (eNOS) (9, 10). There is evidence that in the injured liver endothelin-1 production is increased (as a result of enhanced production by HSCs) whereas NO release from sinusoidal endothelial cells is reduced, ostensibly owing to impaired function of endothelial cell eNOS (11–13). Because NO relaxes HSCs and antagonizes the effect of endothelin-1, a reduced production of NO will modify the dynamic balance of endothelin-1 and NO, favoring sinusoidal and vascular wall constriction by perisinusoidal stellate cells and hepatic vascular smooth muscle cells (14–16). Given the apparent defect of eNOS function in sinusoidal endothelial cells of the cirrhotic liver, several pharmacological approaches have been attempted to deliver NO directly to the liver and reduce intrahepatic resistance (17–20). Nitrovasodilators have been the focus of current therapeutic approaches aimed at intrahepatic vasodilation. Although these agents reduce portal pressure in experimental animals and humans, recent studies indicate that their systemic vasodilatory actions may have detrimental effects on portal hypertension patients, suggesting that developing a compound(s) that selectively releases NO in the liver without affecting systemic arterial pressure could represent a major advance in the treatment of this life-threatening disease (21).

NO-releasing nonsteroidal anti-inflammatory drugs (NO-NSAIDs) are a recently described class of NSAID derivatives that delivers NO to the liver and modifies the dynamic balance of NO and vasoconstrictor agents to the benefit of the portal circulation. NO-NSAIDs are a recently described class of NSAID derivatives that may provide a novel therapy for the treatment of patients with portal hypertension.

Abbreviations: CCl4, carbon tetrachloride; eNOS, endothelial NO synthase; HSC, hepatic stellate cell; iNOS, inducible NO synthase; MCP-1, monocytic chemotactic protein-1; NCX-1000, 2-(acetyloxy) benzene acid 3-(nitrooxymethyl) phenyl ester; NO, nitric oxide synthase; NSAID, nonsteroidal anti-inflammatory drug; SNAP, S-nitroso-N-acetylpenicillamine; TNFα, tumor necrosis factor α; UDCA, ursodeoxycholic acid.

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generated by adding an NO-releasing moiety to parental NSAIDs (22–24). NO-NSAIDs not only lack the gastrointestinal damaging effect of classical NSAIDs, but the slow release of NO in a biological microenvironment also confers novel activities not shared by parent molecules (24). We and others have previously demonstrated that, owing to their chemical structure, these NO-NSAIDs release little amounts of NO in the systemic circulation but transport NO to the liver where they are metabolized (24). Based on this background, we have hypothesized that adding a NO-releasing moiety to ursodeoxycholic acid (UDCA), a compound with an almost exclusive liver metabolism, would have conferred to this new chemical entity the property of selectively releasing significant amount of NO directly to the liver and compensated for defective NO production in cirrhosis (25). Indeed, in a previous study we have demonstrated that this compound is metabolized in vitro by isolated hepatocytes to release NO and NO-derived compounds and exerts potent anti-apoptotic effects in animal models of liver injury (25).

The present study was designed to investigate whether NO-UDCA, hereon referred to as NCX-1000 [2-(acetyloxy) benzoic acid 3-(nitrooxyxymethyl) phenyl ester] (25) reduces portal hypertension in an animal model of chronic liver injury and to define the mechanism responsible for the protective effects. Our results demonstrate that NCX-1000 prevents the development of portal hypertension in cirrhotic rats by modulating HSC contractility. The study protocol was approved by the Animal Study Committee of the University of Perugia. Male Wistar rats (150–180 g) were obtained from Charles River Breeding Laboratories and maintained on standard laboratory rat chow on a 12-h light/dark cycle. They were given phenobarbital sodium (35 mg/kg) with their drinking water for 3 days and then cirrhosis was induced by i.p. injection of CCl4, 100 μl/100 g body weight in an equal volume of paraffin oil (21).

Materials and Methods

Materials. Carbon tetrachloride (CCl4), UDCA, and urethane were from Sigma, NCX-1000 was from Nicor (Milan, Italy), and phenobarbital was from Bracco (Milan, Italy).

Induction of Cirrhosis. The study was approved by the Animal Study Committee of the University of Perugia. Male Wistar rats (150–180 g) were obtained from Charles River Breeding Laboratories and maintained on standard laboratory rat chow on a 12-h light/dark cycle. They were given phenobarbital sodium (35 mg/dl) with their drinking water for 3 days and then cirrhosis was induced by i.p. injection of CCl4, 100 μl/100 g body weight in an equal volume of paraffin oil (21).

Study Protocol. Two parallel protocols were carried out. On the first protocol, 54 rats, 12 animals/group unless specified, were randomly allocated to receive one of the following treatments: group 1 had phenobarbital induction and no further treatment; group 2 (16 animals) was treated with CCl4 twice a week for 8 weeks; group 3 had CCl4 twice a week plus UDCA (15 mg/kg); and group 4 had CCl4 twice a week plus NCX-1000 (15 mg/kg). NCX-1000 and UDCA were dissolved in carboxymethyl cellulose and administered daily by gavage. Animal weight was monitored daily through the study period, and the dosage of CCl4 was adjusted accordingly to the animal weight. At the end of the treatment surviving animals were killed by an overdose of urethane, and blood, ascitic fluid, and livers were collected. A portion of each liver was fixed in 10% formalin for histological evaluation. The remaining tissue was partitioned and immediately stored under frozen liquid nitrogen at −80°C until used. On the second protocol, 74 rats were randomly allocated to receive the same treatments as protocol 1. At the end of the study, surviving animals were tested for portal and arterial pressure measurement (see below).

Liver Histology, Collagen Immunohistochemistry, and Biochemical Assays. At least 2–3 liver samples (10–15 mg/each) from each animal were fixed in 10% formalin, embedded in paraffin, sectioned, and stained with hematoxylin and eosin. For evaluation of the liver type I collagen content, cryostat sections were prepared from frozen liver, and immunohistochemistry was carried out as described (28) by using a rabbit polyclonal antibody against monkey plp (procollagen type I N-terminal propeptide), kindly donated by D. Schuppan, University of Erlangen, Erlangen, Germany (16). The immunohistochemical staining for collagen I was analyzed by a computerized videomicrography analysis system, Leica (Cambridge) Quantimet 5000. A total of five fields per liver tissue sample were observed under a light field microscope equipped with a ×10 lens. The specific signal was acquired by a charge-coupled device videocamera connected to the microscope. The signal was converted to digital and transformed into pixel units. The threshold of specific detection was automatically calibrated on control sections stained with preimmune rabbit immunoglobulins. Results were expressed as percent area occupied by the signal. In each case, the area analyzed extended beyond the central or portal vein into the surrounding lobule. The average of the score taken from 10 random fields was used to generate a single score for each animal’s liver. Liver function was assessed by measuring plasma aspartate aminotransferase, bilirubin, albumin, γ-glutamyl transpeptidase, and alkaline phosphatase levels by a 726 Hitachi (Tokyo) automatic analyzer as described (26).

Reverse Transcription–PCR Analysis of Liver eNOS and Aortic Inducible NOS (iNOS). Total RNA was isolated from liver and thoracic aorta by using TRizol reagent (Life Technologies, Milan, Italy) as described (25). Primers (Sigma) for rat eNOS were: 5′-TTCCGCGTTCACCCTAAATAAA-3′ (sense) and 5′-AAACATGGTCTGCACGAGCA-3′ (antisense) and for iNOS were: AACAGTGGCACATCGAGTCGG (sense) and CTCACATCTCGGTGCACATTG (antisense). The β-actin primers were used as a control (25).

Liver eNOS Activity. Liver eNOS activity was assessed by determining the conversion of [3H]-labeled L-arginine to[3H]-l-citrulline based on a modified version of the method by Bredt et al. (27). Briefly, liver tissue was homogenized in a lysis buffer containing 0.1 mm EGTA, 50 mM Tris-HCl, 0.1 mM EDTA, 5 mM leupeptin, 1 mM PMSF, 1% (vol/vol) Nonidet P-40, 0.1% SDS, and 0.1 mM deoxycholate at pH 7.5. Samples then were incubated with a buffer containing 1 mM reduced nicotinamide adenine dinucleotide phosphate, 3 μM tetrahydropterin, 11 nM L-arginine, and 0.2 μM of L-3H arginine at 37°C. To determine NOS activity, samples were incubated for 20 min and the reaction was stopped by adding 1 ml of cold stop buffer containing 20 mM Heps, 2 mM EDTA, and 2 mM EGTA at pH 5.5. The mixture then was passed over a Dowex AG 50WX-8X mesh cationic exchanging resin column (Bio-Rad). The column was washed with an additional 1 ml of the same solution, and L-3H citrulline was collected and quantitated by liquid scintillation. Retrieved L-3H citrulline was normalized to liver weight.

Liver Nitrite/Nitrate. Liver samples were homogenated (see above), and nitrate/nitrite concentrations were measured by a fluorimetric detection kit (Cayman Chemicals, Ann Arbor, MI) following the manufacturer’s instructions, as described. The lower detection limit was ∼4 pM/well.

Portal Pressure and Isolated Liver Perfusion. In vivo portal pressure was measured in urethane anesthetized rats, control animals, and cirrhotic animals, by cannulating the portal vein with a polyethylene catheter (PE-50) and recorded with a strain-gauge transducer connected with PowerLab PC (AD Instruments, Milford, MA), according to a previously published method (13, 21). The bile duct was cannulated with polyethylene tubing (PE-50). The hepatic artery was ligated. A ligature was passed around the inferior vena cava above the renal veins, and the vein was injected with 500 units of heparin. The portal vein then was cannulated with a 16-gauge Teflon catheter. The liver was
perfusion immediately with Krebs solution containing 2 units/ml of heparin and oxygenated with carbogen gas (95% O₂:5% CO₂) at 37°C. The inferior vena cava then was cut below the ligature, thus allowing the perfusate to escape. Thereafter, the thorax was opened and the supradiaphragmatic portion of the inferior vena cava was cannulated with a 14-gauge Teflon catheter, and the ligature around the vein was tied. The liver was perfused in a nonrecirculating mode with Krebs solution equilibrated with carbogen gas at variable rate (≤ 0.5 ml/min) by using a peristaltic pump (Gilson). The perfusion pressure was continuously monitored and recorded with the strain-gauge transducer connected to the portal inflow cannula. Treatment (number of animals)  

<table>
<thead>
<tr>
<th>Treatment (number of animals)</th>
<th>Body weight, g</th>
<th>MAP, mmHg</th>
<th>Albumin, g/dl</th>
<th>γGT, units/liter</th>
<th>AST, units/liter</th>
<th>Ascites, %</th>
<th>Ascitic protein, g/liter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (18)</td>
<td>463 ± 18.2</td>
<td>120 ± 4.1</td>
<td>4.4 ± 0.8</td>
<td>38.7 ± 27.7</td>
<td>50.5 ± 19</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CCl₄ (20)</td>
<td>356 ± 7.0</td>
<td>111 ± 5.2</td>
<td>4.5 ± 0.1</td>
<td>39.7 ± 62.4</td>
<td>93 ± 29</td>
<td>75</td>
<td>1.3 ± 0.04</td>
</tr>
<tr>
<td>CCl₄ + UDCA (18)</td>
<td>356 ± 3.4</td>
<td>114 ± 2.8</td>
<td>3.9 ± 0.4</td>
<td>27.4 ± 17.9</td>
<td>153 ± 52</td>
<td>62.5</td>
<td>1.2 ± 0.1</td>
</tr>
<tr>
<td>CCl₄ + NO-UDCA (18)</td>
<td>386 ± 22.0</td>
<td>116 ± 3.1</td>
<td>4.3 ± 0.2</td>
<td>8.8 ± 6.6*</td>
<td>186 ± 50</td>
<td>28.5*</td>
<td>1.2 ± 0.1</td>
</tr>
</tbody>
</table>

Data are mean ± SE. MAP, mean arterial pressure. AST, aspartate aminotransferase; γGT, γ-glutamyl transpeptidase. *, P < 0.01 versus CCl₄ alone.

Monocyte Chemotactic Protein-1 (MCP-1). HSC activation also was assessed by measuring MCP-1 concentrations (R & D Systems) in supernatants of HSCs (1 × 10⁵/ml) incubated with 100 ng/ml tumor necrosis factor α (TNF-α) and IFN-γ for 24 h (30).

Statistical Analysis. ANOVA or Student’s t test were used for statistical comparisons. For calculation of mean values and statistical variation, n indicates the number of separate experiments each with an individual cell preparation. Data are means ± SEM.

Results

NCX-1000 Prevents Ascite Formation in CCl₄-Treated Rats. Long-term CCl₄ administration resulted in extensive liver damage and nodular transformation. At laparotomy all CCl₄-treated rats showed macroscopically macro/micronodular cirrhosis of the liver. The CCl₄-treated animals had signs of portal hypertension and splenomegaly increased diameter of the portal vein and its intestinal afferents and ascites (Table 1). The weight of cirrhotic rats was found to be significantly lower than that of sex- and age-matched control animals (356.0 ± 27.0 g vs. 463.0 ± 18.0 g, respectively; P < 0.0001) (Table 1). As shown in Table 1, treating animals with UDCA or NCX-1000 had no effect on serum albumin or bilirubin, although NCX-1000 caused a statistically significant reduction of γ-glutamyl transpeptidase. In contrast to UDCA, NCX-1000 significantly reduced the percentage of animals with ascites from 75% to 28.5% (P < 0.001) (Table 1). The analysis of protein content in the ascitic fluid confirmed the noninflammatory origin of the transudates. Moreover, in contrast to UDCA, NCX-1000 significantly decreased the amount of nitrite/nitrate content in the ascitic fluid (P < 0.01). Thus NCX-1000, but not UDCA, reduces ascite formation in a rat model of chronic liver injury.

NCX-1000 and UDCA Reduce Collagen Deposition. At immunohistochemical analysis and semiquantitative scoring evaluation, liver specimens obtained from rats treated with CCl₄ showed extensive central-portal, central-central, and portal-portal bridging fibrosis (Fig. 1). In the CCl₄-treated rats the total amount of type I collagen was ~22.5% of total area (P < 0.01 versus controls). UDCA and NCX-1000 decreased total liver collagen contents of ~50%, compared with the livers of animals treated with CCl₄.
alone (P < 0.01); however, there were no rats with a histologically normal liver (Fig. 1).

**NCX-1000 Reduces Portal Pressure in Cirrhotic Rats.** Because these data demonstrated that NCX-1000 and UDCA reduced liver fibrosis, but UDCA had no effect on the percentage of animals that developed ascites, we have reasoned that the NO-releasing derivative should had protected against ascite development by reducing portal pressure in cirrhotic rats. As shown in Fig. 2, cirrhotic rats exhibited greater increases in perfusion pressure than control rats in response to incremental increases in flow as evidenced by a significantly greater perfusion pressure at each flow rate (P < 0.01 in comparison with control rats; control, n = 10; cirrhosis, n = 7) (Fig. 2). NCX-1000 administration almost completely reverted portal hypertension induced by CCl4 as demonstrated by the fact that incremental increases in flow failed to increase portal perfusion pressure (P < 0.001 in comparison with CCl4 alone; NCX-1000, n = 8). In contrast, incremental increases in flow perfusion of portal vein of UDCA-treated rats increased portal perfusion pressure to the same level documented in rats treated with CCl4 alone (P > 0.05 in comparison with CCl4 alone; UDCA, n = 7). Thus, NCX-1000 significantly reduces intrahepatic resistance in cirrhotic rats as measured by assessing portal perfusion pressure.

To gain insight on the mechanism through which NCX-1000 reduces portal pressure in cirrhotic rats, we measured eNOS activity. Indeed, as shown in Fig. 3A–C, although eNOS mRNA expression was unchanged, eNOS activity was significantly reduced in cirrhotic rats in comparison with control rats. Treating rats with NCX-1000 or UDCA had no effect on eNOS protein expression or activity (Fig. 3C). However, liver nitrite/nitrate concentrations were significantly higher in rats treated with NCX-1000 in comparison with animals treated with CCl4 alone or CCl4 plus UDCA (Fig. 3C). In contrast NCX-1000 administration markedly decreased nitrite/nitrate contents in the ascitic fluid (Fig. 3C). Because ascitic nitrite/nitrate concentrations reflect peripheral NO production, we then assessed eNOS and iNOS expression in the aorta. In contrast to the liver, aortic iNOS was significantly induced by CCl4 administration, an effect that was completely reversed by cotreating the animals with NCX-1000, but not with UDCA (Fig. 3D). No change were measured on eNOS expression (data not shown).

**NCX-1000 Modulates HSC Contraction.** Having found that NCX-1000 had no effect on eNOS activity but reduced portal hypertension and increased liver NO content, we then assessed whether NCX-1000 directly modulated HSC contraction. As shown in Fig. 4A, NCX-1000 reverted HSC contraction induced by FCS, indicating that HSCs are able to directly metabolize NCX-1000. Indeed, as shown in Fig. 4 B and C, incubating HSC with NCX-1000, 0.1 mM, resulted in time-dependent increase in NO-related intracellular fluorescence in HSCs loaded with 4,5-diamino-4-difluorescein diacetate, an NO-reactive fluorochrome, as well as release of nitrite/nitrate in cells supernatants. Similarly to NCX-1000, the NO donor SNAP inhibited FCS-induced contraction of HSCs and caused a time-dependent formation of NO (Fig. 4A–C). NCX-1000 also inhibited MCP-1 release from HSCs stimulated with TNF-α and IFN-γ (Fig. 3D). In contrast to NCX-1000, UDCA had no effect on HSCs contraction, NO generation, and cytokine-induced MCP-1 release (Fig. 4).

**Discussion**

Clinical trials have demonstrated that the combination of β-blockers and nitro-vasodilators is effective in reducing mortality caused by gastrointestinal bleeding in patients with chronic liver diseases. The rationale behind the use of these two drugs is that by acting at separate points in the chain of pathophysiological events that lead to portal hypertension their combination increases the portal pressure-lowering effect of either drug used separately (17). A practical limitation of this approach, however, derives from the fact that conventional NO donors, nitroglycerin and isosorbide-5-mononitrate, release NO in the blood stream, causing systemic hypotension and progression of the vasodilatory syndrome, aggravating renal dysfunction and sodium retention in cirrhotic patients with ascites (19, 20).

The increased intrahepatic vascular resistance in cirrhotic patients is due not only to fixed anatomical changes inherent to cirrhosis but also to active contraction of vascular smooth muscle cells and, possibly, activated HSCs (3–6). This active contraction is caused mainly by an impaired production of NO that acts in...
the liver as an endogenous vasodilator (2). In experimental models of liver cirrhosis, as well as in cirrhotic patients, simultaneously with the excessive synthesis of NO in the systemic vasculature there is an impaired enzymatic function of liver eNOS despite the fixed expression of eNOS mRNA and protein (11, 13). In endothelial cells eNOS catalytic activity is modulated by dynamic regulatory processes including posttranslational protein modifications, interactions with regulatory proteins, and availability of essential cofactors (13). It is well established that the binding of eNOS with the ubiquitous calcium-regulatory protein calmodulin promotes NO production, whereas caveolin-1, the coat protein of nonclathrin-coated transport vesicles and putative signaling molecule, decreases the catalytic activity of the enzyme (31). Liver expression of caveolin-1 is increased in cirrhotic rats, suggesting that an abnormal protein–protein interaction is responsible for the defective eNOS function (13). Moreover, because the cirrhotic liver is unable to respond to incremental shear stress with an increased generation of NO, a defect of mechanotransduction pathways responsible for flow-mediated activation of eNOS also has been postulated (12, 13, 21). Whatever mechanism is responsible for presumed defect in posttranslational handling of eNOS, transfecting cirrhotic rats with a recombinant adenovirus carrying the neuronal NOS gene, which undergoes lesser posttranslational modifications than eNOS, leads to liver neuronal NOS overexpression and intrahepatic resistance reduction (21).

NCX-1000 is a NO-releasing derivative of UDCA generated by adding a nitroxybutyl moiety to UDCA (25). We have previously demonstrated that this compound, but not UDCA, protects against liver damage induced by Con A in mice by directly modulating liver resident immune system (25). Indeed in comparison with currently available NO donors, NCX-1000 has several potential advantages: (i) it is stable and releases NO very slowly in the blood stream, a property that should minimize its effect on arterial pressure, a major drawback of currently available nitrates; and (ii) it is almost exclusively metabolized in the liver, a property that should allow delivery of NO directly to hepatic cells.

In the present study we have provided evidence that NCX-1000 protects against development of portal hypertension in an animal model of liver cirrhosis by reducing intrahepatic resistance. Several of our results indeed support the concept that NCX-1000 modulates both anatomical and dynamic component of portal hypertension. First, UDCA and NCX-1000 exert similar antifibrotic effects, but only NCX-1000 protects against portal hypertension and ascite development induced by CCl4, thereby demonstrating that NCX-1000 reverses the dynamic component of portal hypertension, i.e., HSC contraction. Second, similarly to UDCA, NCX-1000 has no effect on liver eNOS expression and activity (Fig. 2), demonstrating that its effect is unrelated to change in endogenous NO production. Third,
NCX-1000 administration significantly increases liver content of nitrite/nitrate, demonstrating that liver cells are able to use NCX-1000 as a source of NO despite a defect in posttranslational handling of eNOS. Fourth, as a further index of its ability to protect against development of portal hypertension, NCX-1000 reduces the nitrite/nitrate content in the ascitic fluid and prevents iNOS expression induction in the thoracic aorta, suggesting that similar to other compounds generated with the same technology (i.e., NO-NSAIDs), the NO-UDCA derivative modulates iNOS expression (32). Fifth, NCX-1000 has no effect on mean arterial pressure, both in control and cirrhotic rats, indicating that it releases a low amount of NO in the blood stream (33). Sixth, NCX-1000 directly modulates HSC functions as demonstrated by our in vitro experiments. Indeed NCX-1000 reduces HSC contraction as well as MCP-1 release induced by TNF-α and IFN-γ (30). The finding that SNAP also inhibits HSC contraction (31) and that both compounds increase nitrate/nitrite release in cell supernatants as well as intracellular fluorescence in cells loaded with the NO-reactive fluorochrome 4,5-diaminofluorescein diacetate, whereas UDCA itself has no effect, strongly supports the view that NCX-1000 inhibits HSC functions through an NO-dependent mechanism (25).

The results of the present study are important for another reason, which is the demonstration that HSCs are able to directly metabolize NCX-1000 to generate NO. This result is relevant because hematogenous compounds must traverse the sinusoidal endothelium as well as the sinusoidal space of Disse (wherein reside stellate cells) before coming into contact with hepatocytes, making it possible for NCX-1000 to directly reach HSCs from the perisinusoidal space (i.e., independently of hepatocyte handling). If this is the case it cannot be excluded that hepatic sinusoidal cells can use NCX-1000 as a source of NO.

In summary, the results presented in this study are consistent with previous data indicating that nitrogenous compounds are capable of affecting portal vascular resistance. Moreover, it establishes that whatever mechanism is responsible for presumed eNOS dysfunction it is possible to restore normal intrahepatic resistance by a compound that selectively releases NO in the liver. Finally, our data demonstrated that UDCA can be used as a carrier to transport other biologically active molecules to the liver with minimal systemic effects.

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