Immunohistochemical Localization of Hepatic Nitric Oxide Synthase in Normal and Transgenic Sickle Cell Mice: The Effect of Hypoxia

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Nitric oxide (NO) generated from L-arginine and molecular oxygen by nitric oxide synthase (NOS) has been shown to influence hepatocellular function and pathology in response to ischemia and certain hepatotoxins. In the present study, we examined the liver of a transgenic line of sickle cell mice for hepatocellular injury and localization of two isoforms of NOS, the endothelial constitutively expressed isoform (ECNOS) and the inducible isoform (iNOS) by immunohistochemistry. Diffuse expression of ECNOS was observed in hepatocytes of control and sickle cell animals maintained under room air conditions. In contrast, iNOS was observed only in the sickle cell mice, well-localized to hepatocytes surrounding the central veins of the lobules. When normal mice were exposed to hypoxic conditions for 4 to 5 days, iNOS immunostaining appeared de novo in a patchy distribution throughout the liver lobules. In the sickle cell mice, hypoxia appeared to increase the subjective intensity of pericentral staining of iNOS. Liver histology was normal in the sickle cell mice maintained under room air conditions, but showed multifocal areas of necrosis when sickling was exacerbated by chronic hypoxic conditions. However, a pericentral zone of preserved architecture was present, corresponding to the region of iNOS staining. We postulate that pericentral induction of iNOS under ambient conditions occurs in transgenic sickle cell mice in response to particularly intense hypoxic conditions near the central veins of the liver. Increases in NO synthesis may occur in this region, which would serve to protect these cells from ischemic damage either directly or by maintaining blood flow. These findings could be relevant to liver pathophysiology in patients with sickle cell disease.

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3583
two constructs each containing the locus control region (LCR) of the human β-globin gene and either the a2-gene or β2-globin gene into fertilized eggs of the Friend virus strain B (FVB) mouse. The mice with stable cointegration of αβ and ββ were then bred onto the C57Bl/6J background for seven or more generations. Higher levels of human ββ were achieved by breeding the transgenic mice with C57Bl mice bearing a spontaneous deletion of the mouse β major-globin gene. When the β<sup>MM</sup> deletion was bred to homozygosity, expression of ββ averaged 72.7%.<sup>2</sup> These mice are designated α<sup>β</sup>β<sup>[β<sub>MM</sub>]</sup> indicating a homozygous deletion of mouse β<sup>MM</sup> globin. Normal mice of the strain C57Bl/6J were purchased from Jackson Laboratories (Bar Harbor, ME). The mice (n = 4 per treatment group) were housed in individual cages under room air or in glass environmental chambers (Braintree Scientific, Braintree, MA) filled with constantly flowing 10% O<sub>2</sub>/0.5% CO<sub>2</sub>/95% N<sub>2</sub> gas for 4 to 5 days. Animals were allowed free access to water and mouse pellet diet up to the day they were killed. The mice were anesthetized, and transcardiac perfusion was performed with cold phosphate-buffered saline (PBS) pH 7.6 for 10 minutes followed by perfusion fixation with paraformaldehyde-lysine-periodate<sup>26</sup> for 10 minutes. Livers were dissected, blocks of tissue taken from similar regions, postfixed in the same fixative for 12 hours at room temperature, and then postfixed for embedding in paraplast. Serial four micron-thick sections were cut on a microtome and stored until use.

**Immunohistochemistry and microscopy.** Tissue sections selected from similar lobes of the liver of the four groups of mice were selected and processed simultaneously on the same day for immunostaining of NOS isoforms. Because all reagents and timing of staining was the same in the four groups, a qualitative comparison of staining intensity could be made. The specimens were dewaxed twice in xylene for 10 minutes each, rehydrated in ethanol, and washed in distilled water for 1 minute and PBS for 10 minutes. Endogenous peroxidase was blocked by immersion in 0.03% hydrogen peroxide in methanol for 20 minutes and washed twice in PBS for 10 minutes each. Nonspecific binding was blocked and sections were permeabilized with a mixture of 0.3% Triton X-100, 0.2% normal goat serum, and 0.5% bovine serum albumin in PBS (PBA) for 20 minutes. After blotting to remove excess serum, tissue sections were then incubated with PBA containing antisera to NOS isoforms (Transduction Labs, Lexington, KY). These antisera were generated against specific peptide sequences of NOS isoforms, and their tissue specificity has been determined by previous studies in our laboratory.<sup>11</sup> In preliminary experiments, the absence of immunostaining for INOS and ECNOS in the liver; BNOS was not observed in the liver. Therefore, for the study, tissue sections were incubated with either anti-INOS or anti-ECNOS at an optimum dilution of 16 µg per mL for 1 hour at room temperature. Adjacent sections, which served as controls, were incubated with preimmune serum, or the primary antibody was omitted in the staining procedure.

After washing the sections twice in PBS for 5 minutes each, NOS immunostaining was detected with the Vectastain peroxidase kit (Vector Labs, Burlingame, CA). Optimum color reaction was developed with diaminobenzidine tetrahydrochloride for 5 minutes. Sections were then counterstained with hematoxylin, rehydrated with ethanol, cleared with xylene and coverslipped. For routine histological analysis, adjacent sections were stained with hematoxylin-eosin (H&E). Sections from similar lobes of normal and α<sup>β</sup>β<sup>[β<sub>MM</sub>]</sup> mice housed under room air were compared with sections from mice exposed to chronic hypoxia. The sections were coded and analyzed by two observers blinded to the results with a Nikon Optiphot microscope equipped with a Nikon FX35A camera (Yokohama, Japan). The following parameters were evaluated: iNOS and ECNOS immunostaining within zones of the hepatic lobule, ie, in relation to the central veins and portal areas, and intracellular location. The relative intensity of immunostaining within cells was also scored as absent, similar, or increased in comparison to coded standards from normal and α<sup>β</sup>β<sup>[β<sub>MM</sub>]</sup> mice housed under room air and processed simultaneously under the same conditions.

**Aspartate amino transferase.** Plasma samples were obtained from C57Bl/6J, and α<sup>β</sup>β<sup>[β<sub>MM</sub>]</sup> mice by collecting blood from a tail incision in heparinized microhematocrit tubes. The samples were centrifuged to obtain the plasma. They were analyzed using the Technicon Chem-1 system (Technicon, Tarrytown, NY) and results for aspartate amino transferase were expressed in units/mL. Samples were collected under both ambient and chronic hypoxic conditions, using the same protocol as for the histology studies.

**RESULTS**

**Histology.** H&E-stained liver sections of control and α<sup>β</sup>β<sup>[β<sub>MM</sub>]</sup> mice maintained under room air showed normal histology. In contrast, under chronic hypoxic conditions, the liver of the α<sup>β</sup>β<sup>[β<sub>MM</sub>]</sup> mice manifested multifocal infarcts characterized by coagulative necrosis, hepatocytes lacking nuclei, and loss of outlines of hepatic plates and dilated sinusoids. A typical example is shown in Fig 1A. Normal mice maintained under hypoxic conditions did not show any histological abnormalities.

**Immunohistochemistry.** Control sections of the liver incubated with preimmune serum or absent the primary antisera did not show specific staining. In animals housed under room air conditions, immunohistochemistry of the liver showed a diffuse distribution of ECNOS immunostaining scattered throughout the hepatic lobules of both normal (Fig 1B) and α<sup>β</sup>β<sup>[β<sub>MM</sub>]</sup> mice. There was no change in the pattern of ECNOS staining in either normal or α<sup>β</sup>β<sup>[β<sub>MM</sub>]</sup> mice when they were exposed to chronic hypoxia. iNOS immunoreactivity was absent in liver sections of normal mice housed under room air conditions (Fig 1C). However, when normal mice were exposed to chronic hypoxia, iNOS immunostaining was observed scattered throughout the hepatic lobules (Fig 1D). In the α<sup>β</sup>β<sup>[β<sub>MM</sub>]</sup> transgenic mice, iNOS immunostaining was present even under room air conditions, and was sharply localized to pericentral hepatocytes (Fig 1D). This zonal distribution of iNOS immunostaining persisted after exposure to chronic hypoxia, although the relative intensity of staining appeared to be increased (compare Fig 1E with 1F).

**Aspartate amino transferase.** In control (C57Bl/6J) mice maintained under room air conditions, the level of aspartate amino transferase was 51.2 ± 3.4 U/mL (mean ± SE, n = 10). In the α<sup>β</sup>β<sup>[β<sub>MM</sub>]</sup> mice, the level was 61.0 ± 4.3 (n = 20). Although the mean value was higher in the α<sup>β</sup>β<sup>[β<sub>MM</sub>]</sup> mice than in the controls, the difference was not statistically significant. When two C57Bl/6J mice were exposed to hypoxia for 5 days, there was no apparent change in plasma amino transferase levels. In contrast, when α<sup>β</sup>β<sup>[β<sub>MM</sub>]</sup> mice were subjected to hypoxia for 5 days, their plasma level of aspartate amino transferase rose to an average value of 125.7 ± 9.3 U/mL, respectively (Fig 2). This value is statistically different from that found for the α<sup>β</sup>β<sup>[β<sub>MM</sub>]</sup> mice under room air (P < .00002). These elevated enzyme levels presumably relate to the abnormal histology found in separate α<sup>β</sup>β<sup>[β<sub>MM</sub>]</sup> mice exposed to hypoxia (Fig 1A).
Fig 1. (A) Hematoxylin and eosin-stained section of liver from transgenic sickle cell mouse reared under chronic hypoxia. Note area of infarct, loss of outline of hepatic plate, and dilated sinusoids. (B) Diffuse EcNOS-immunostaining of hepatocytes in a normal mouse under room air. (C) Absence of iNOS in liver of a normal mouse under room air. The background staining was similar to adjacent control sections incubated with preimmun serum or when primary antisera were omitted. (D) iNOS immunostaining in scattered hepatocytes in a normal mouse exposed to chronic hypoxia (arrows). (E) Moderate iNOS-immunostaining in pericentral hepatocytes of αβ[β(HB)] mouse under room air. (F) Increase in pericentral iNOS in transgenic mouse exposed to hypoxia. Scale bar = 100 μm in A, C, D; 50 μm in B, E, F.
patchy liver necrosis and elevation of plasma aspartate aminotransferase concentrations when exposed to a low oxygen environment. The hepatocellular damage is presumed to be caused by vasooclusion-mediated tissue hypoxia resulting from HbS polymerization and sickle. These results are consistent with a previous study performed in a different strain of transgenic sickle cell mice, a strain expressing both βS and βS-α1antu. These mice, which have a more severe phenotype, have prominent liver necrosis and elevated aspartate amino transferase (AST) even under ambient conditions. The hepatocellular necrosis in these two transgenic mouse strains of sickle cell disease is most likely similar to that which occurs in some sickle cells patients during crises.

To determine whether nitric oxide synthases are expressed in the liver of the sickle cell mice, we performed immunohistochemistry using antibodies directed against endothelial cell constitutive NOS (EcNOS) and inducible NOS (iNOS). We found differences in the expression of these two isoforms of NOS in hepatocytes of normal versus transgenic sickle cell mice. EcNOS was seen diffusely in hepatocytes of both normal and transgenic sickle cell mice. Hypoxia is known to induce iNOS mRNA in rat kidney cells and to increase the gene product and NO release. Hypoxia is also known to upregulate the constitutive isoforms of NOS in endothelial cells and brain. Whether hypoxia leads to iNOS expression in the liver has not been previously reported. Our finding of scattered immunostaining of iNOS in hepatocytes of normal mice exposed to a low oxygen environment suggests that hypoxia also induces liver iNOS.

Histologic studies in isolated hypoperfused normal rat livers have shown differences in the susceptibility of various zones of the hepatic lobules to hypoxic injury. The liver has a high oxygen extraction ratio and an oxygen gradient, with pericentral hepatocytes being exposed to lower oxygen tensions than periportal hepatocytes. Various markers of cell death such as mitochondrial dysfunction, histologic abnormalities, and enzyme release have shown that hepatocytes closest to the central veins are the first to manifest a loss of viability, followed by extension of hypoxic damage towards the periportal areas. In the present study, exposure of normal mice to chronic hypoxia did not lead to any gross or histologic abnormalities in the liver, in contrast to the above-mentioned studies in isolated perfused livers. On the other hand, in the αHβN[βMDD] mice, hypoxia resulted in multifocal areas of necrosis scattered throughout the liver lobules, with sparing of the pericentral zones. This pattern of liver necrosis, including protection of cells around the central vein, is similar to that previously reported in a more severe phenotypic transgenic mouse model. Because the direction of blood flow in the hepatic sinusoids is from the periportal region toward the central veins, PO2 and pH are most likely lowest near the central veins. These conditions would predispose to sickling and adherence of red blood cells to the endothelium. Vasoocclusion occurring in
the sinusoids is expected to reduce oxygen tension even more severely in the region of the central veins. Paradoxically, liver necrosis was not observed in this region in the αββ[βMEDS] mice. It has been proposed that NO produced by hepatocytes plays a protective role in the liver by reducing the level of free-oxygen radicals. The balance between NO synthesis and free-oxygen radical formation is thought to determine the degree of hepatocellular toxicity. If NO production is increased in the cells that showed positive iNOS staining, this may account for the absence of necrosis in this region. An alternative explanation is that increased NO production protects hepatocytes by maintaining local blood flow.

Weidenbach et al demonstrated that L-arginine infusions prevent the fall in blood flow in perfused rat livers exposed to endotoxin and PGF2α. Improved blood flow in the region of the central veins might account for protection of the hepatocytes in the αββ[βMEDS] mice. Of course, in humans the capacity to induce iNOS expression might be under genetic control, opening the possibility that individual susceptibility involving the NOS system could underlie the interpatient variability in liver damage and propensity to acute hepatic complications.

The colocalization of iNOS immunostaining in the same region showing preserved hepatocytes (Fig 1E & F) is consistent with a protective role of iNOS in the pericentral zone. These observations may have significant implications for clinical liver involvement in patients with sickle cell disease and may lead to improved therapy in the future.

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