Effects of the Inducible Nitric-Oxide Synthase Inhibitor L-\(N^6\)-(1-iminoethyl)-lysine on Microcirculation and Reactive Nitrogen Species Generation in the Kidney following Lipopolysaccharide Administration in Mice

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ABSTRACT

The mortality rate for septic patients with acute renal failure is approximately doubled compared with patients with sepsis alone. Unfortunately, the treatment for sepsis-induced renal failure has advanced little during the last several decades. Because sepsis is often caused by lipopolysaccharide (LPS), a mouse model of LPS challenge was used to study the development of kidney injury. We hypothesized that inducible nitric-oxide synthase (iNOS)-catalyzed nitric oxide production and the generation of reactive nitrogen species (RNS) might play a role in the microcirculatory defect and resulting tubular injury associated with LPS administration. Fluorescent intravital videomicroscopy was used to assess renal peritubular capillary perfusion and document RNS generation by renal tubules in real time. As early as 6 h after LPS administration (10 mg/kg i.p.), RNS generation (rhodamine fluorescence), redox stress [NAD(P)H autofluorescence], and the percentage of capillaries without flow were each significantly increased compared with saline-treated mice (\(p < 0.05\)). The generation of RNS was supported by the detection of nitrotyrosine-protein adducts in the kidney using immunohistochemistry. The iNOS inhibitor L-N6-(1-iminoethyl)-lysine (L-NIL; 3 mg/kg i.p.) completely blocked the increase in rhodamine fluorescence and NAD(P)H autofluorescence and prevented the capillary defects at 6 h after LPS administration. These results suggest that iNOS-derived RNS is an important contributor to the peritubular capillary perfusion defects and RNS generation that occur during sepsis and emphasize that pharmacological inhibition of iNOS may provide beneficial effects during sepsis by improving renal capillary perfusion and reducing RNS generation in the kidney.

Thus, a better understanding of the mechanism of kidney injury initiated by sepsis could lead to the uncovering of new therapeutic targets and more effective treatments for this serious condition.

Because sepsis is often caused by Gram-negative bacterial lipopolysaccharide (LPS), murine models of LPS challenge are frequently used to study the mechanisms of sepsis-induced renal failure. Studies suggest that the effects of LPS appear, at least in part, to be mediated by Toll-like receptor 4 and the initiation of the release of inflammatory cytokines, such as TNF-\(\alpha\) (Cunningham et al., 2002, 2004). Notably, in septic patients with ARF, cytokine levels are positively correlated with mortality (Simmons et al., 2004), supporting the importance of the inflammatory response in the prognosis of sepsis-induced ARF. Moreover, the levels of circulating adhesion molecules are increased in the septic patient, suggesting that vascular inflammation and endothelial activation may play a role in the development of organ failure (Boldt et

ABBREVIATIONS: ARF, acute renal failure; LPS, lipopolysaccharide; NO, nitric oxide; iNOS, inducible nitric-oxide synthase; RNS, reactive nitrogen species; ROS, reactive oxygen species; DHR, dihydrorhodamine 123; RBC, red blood cell; IVVM, intravital videomicroscopy; L-NIL, L-N6-(1-iminoethyl)-lysine; FITC-dextran, fluorescein isothiocyanate-dextran.
al., 1996). Cytokines and adhesion molecules are also elevated in the kidney following LPS challenge in the mouse, as is the generation of NO via another recognized inflammatory response, induction of inducible nitric-oxide synthase (iNOS) (Cunningham et al., 2004; Guo et al., 2004; Wu et al., 2007). Collectively, these inflammatory responses are probably contributors to renal injury during sepsis.

In models of ARF associated with iNOS induction, the contributions of reactive oxygen species (ROS) and reactive nitrogen species (RNS) are emerging as important mediators, particularly in ischemia/reperfusion injury (Nouri et al., 1996, 2001; Walker et al., 2000; Vinas et al., 2006). Recent studies also suggest that iNOS-derived NO/RNS may play a role in the pathogenesis of LPS-induced renal injury (Wang et al., 2003; Cuzzocrea et al., 2006). However, the dynamics of RNS generation in the kidney has never been examined.

The development of sepsis-induced renal injury is a complex process. Recently, we reported that peritubular capillary perfusion is severely disrupted following LPS administration in mice (Tiwari et al., 2005; Wu et al., 2007). Furthermore, this microcirculatory defect was positively correlated to the development of tubular cell stress (Wu et al., 2007). The aim of the present study was to examine the relationship between the decrease in peritubular capillary perfusion and the generation of RNS. We used intravital videomicroscopy (IVVM) to monitor peritubular capillary perfusion and RNS generation following LPS administration. The iNOS inhibitor N-(6-(1-iminoethyl)-lysine (L-NIL) was used to examine the role of iNOS. This study is the first to link early changes in renal microcirculation and tubular cell stress to iNOS-derived RNS generation by tubular epithelium.

Materials and Methods

Lipopolysaccharide (Escherichia coli 055:B5 strain) and fluorescein isothiocyanate-dextran (FITC-dextran; 150,000 Da) were purchased from Sigma-Aldrich (St. Louis, MO). Dihydrorhodamine 123 (DHR) was purchased from Invitrogen (Carlsbad, CA). Rabbit polyclonal antinitrotyrosine antibody was purchased from Upstate Cell (DHR) was purchased from Invitrogen (Carlsbad, CA). Rabbit polyclonal antinitrotyrosine antibody was purchased from Upstate Cell. 6-(1-iminoethyl)-lysine (L-NIL) was used to examine the role of iNOS. This study is the first to link early changes in renal microcirculation and tubular cell stress to iNOS-derived RNS generation by tubular epithelium.

Mouse Model of Endotoxin-Induced Renal Injury. All animals were housed and killed in accordance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals and with approval of the University of Arkansas for Medical Sciences Institutional Animal Care and Use Committee. Male C57BL/6 mice (8 weeks of age) were acclimated for 1 week with free access to food and water. At the start of the experiment, mice were injected with saline or LPS (10 mg/kg i.p.). At the indicated time after IVVM analysis, blood was collected via cardiac puncture under isoflurane anesthesia. Serum creatinine concentration was determined using a Roche Cobas Mira ClinicalChemiluminescent analyzer (Roche Diagnostics Systems, Inc., Branchburg, NJ).

Evaluation of Peritubular Capillary Dysfunction with IVVM. At 15 min before IVVM, mice were administered FITC-dextran (150,000 Da, 2 μmol/kg) and DHR (4 μmol/kg) via the tail vein. Mice were prepared for IVVM as described elsewhere (Tiwari et al., 2005). In brief, mice were anesthetized with isoflurane and underwent laparotomy to expose the left kidney. The kidney was positioned on a glass stage above an inverted fluorescent microscope (Zeiss Axiosvert 200; Carl Zeiss GmbH, Jena, Germany) equipped with a digitizing camera (Hamamatsu, Bridgewater, NJ) and kept moist with saline and covered. Core temperature was monitored and maintained at 36–37°C using an infrared heat lamp.

During IVVM, the renal intravascular space and red blood cell (RBC) movement were visualized with FITC-dextran using an excitation of 470 nm and an emission of 520 nm. From the left kidney of each animal, videos of 10 s each were captured at approximately 15 frames/s from five randomly selected fields of view (200×). Capillary function was analyzed as described previously (Tiwari et al., 2005; Wu et al., 2007). In brief, randomly selected vessels (approximately 150 per kidney) were classified into three categories of blood perfusion: “Continuous Flow”, where RBC movement in the vessel was not interrupted during the video; “Intermittent Flow”, where RBC movement stopped or reversed any time during the video; and “No Flow”, where no RBC movement was detected. Data were expressed as the percentage of vessels in each of the three categories.

Evaluation of Renal Tubular Epithelial Cell Stress Using IVVM. IVVM can be used to assess cellular redox stress by monitoring [NAD(P)H] autofluorescence (Paxian et al., 2004; Wunder et al., 2005). NAD(P)H autofluorescence was visualized at an excitation of 365 nm and an emission of 420 nm. To minimize photobleaching, a 3-s exposure was used to capture videos of five randomly selected fields of view per animal. Imaging settings were identical for all fields of view. The intensity of NAD(P)H autofluorescence was quantified using AxioVision Imaging Software (Carl Zeiss GmbH). Data were expressed as arbitrary units per micromolars.

Detection of ROS/RNS Using IVVM. DHR is oxidized to fluorescent rhodamine by hydroxyl radical, nitrogen dioxide, peroxynitrite, and peroxidase-derived species (Halliwell and Whitman, 2004). For each field of view captured for assessing capillary perfusion, additional images of rhodamine fluorescence were captured using an emission of 507 nm and an excitation of 530 nm. A 3-s exposure was used to minimize photobleaching. Imaging settings were identical for all fields of view. The intensity of rhodamine fluorescence was quantified using AxioVision Imaging Software (Carl Zeiss GmbH). Data were expressed as arbitrary units per micromolars.

Immunohistochemistry. Immunohistochemistry was used to identify the presence of nitrotyrosine-protein adducts, a biomarker of peroxynitrite generation (Beckman et al., 1990). Paraffin-embedded sections (3 μm) from the right kidney (not used for IVVM) were cleared in xylene and rehydrated with ethanol. Endogenous peroxidase activity and nonspecific protein binding were blocked using reagents supplied in the DakoCytoCytometry labeled streptavidin biotin + System-horseradish peroxidase kit was purchased from Dako North America Inc. (Carpinteria, CA). 1-N-(1-iminoethyl)-lysine-2HCl was purchased from Axxora (San Diego, CA).

Data were analyzed with Prism 4.0 software for Mac (GraphPad Software, San Diego, CA). Each “n” represents data or tissue obtained from one mouse. Data are expressed as means ± S.E.M. A one-way ANOVA followed by the Student-Newman-Keuls post test was used to determine differences between groups. A p value < 0.05 was considered significant.
Results

Real-Time Generation of ROS/RNS in the Kidney following LPS Administration. We recently reported that significant peritubular capillary dysfunction occurred at 2 h following LPS administration and that capillary dysfunction preceded tubular redox stress and renal failure (Wu et al., 2007). To examine the time course of ROS/RNS generation, rhodamine fluorescence was monitored at 0 (saline-treatment), 2, 6, 18, and 24 h after LPS administration. At 6 h, rhodamine fluorescence was elevated approximately 3-fold ($p < 0.05$ compared with saline) and remained elevated through 18 h (Fig. 1). Representative images of the kidney captured from saline and LPS-treated (18 h) mice are shown in Fig. 2. Capillary flow (visualized by FITC-dextran) and rhodamine fluorescence are shown for a saline-treated mouse (Fig. 2, A and B) and an LPS-treated mouse at 18 h (Fig. 2, C and D). These images show intense rhodamine fluorescence (ROS/RNS generation) in the kidney from the LPS-treated mouse. Tubules found in regions of decreased capillary perfusion, indicated by arrows in Fig. 2C, appeared to display the highest level of rhodamine fluorescence. Higher magnification images in Fig. 3, A (FITC-dextran) and B (rhodamine), suggested that rhodamine fluorescence intensity was highest in tubules bordered by capillaries with compromised flow.

Immunohistochemical Detection of Nitrotyrosine-Protein Adducts. The increase in rhodamine fluorescence suggested that RNS might have been generated in the kidney. To help confirm the generation of the RNS peroxynitrite, immunohistochemistry was used to detect nitrotyrosine-protein adducts, a marker of peroxynitrite generation. Little positive staining was observed in kidney sections from saline-treated mice (Fig. 4A). In contrast, kidney sections from LPS-treated mice at 18 h showed extensive positive staining for nitrotyrosine in tubules (Fig. 4B). A preincubation of the antibody with 10 mM 3-nitrotyrosine prevented staining (Fig. 4C), thus indicating that the antibody was specific for nitrotyrosine. These findings help to validate the IVVM findings that DHR can be used to detect RNS generation in real time.

Contribution of iNOS to Capillary Dysfunction, ROS/RNS Generation, and Cellular Redox Stress. To examine the effects of iNOS inhibition on LPS-induced events that could lead to renal failure, mice were studied before renal failure. Three groups of mice were studied: Saline, LPS, and LPS + L-NIL. At 6 h after dosing, mice underwent IVVM with FITC-dextran and DHR. Peritubular capillary perfusion

Fig. 1. Time course of ROS/RNS generation in the kidney following LPS administration. Rhodamine fluorescence was used to estimate ROS/RNS generation at the indicated time following LPS administration (10 mg/kg i.p.). Rhodamine fluorescence was significantly elevated at 6 and 18 h following LPS administration. Data are mean ± S.E.M. (n = 5–6 animals per group). *, $P < 0.05$ compared with time 0 (saline treatment).

Fig. 2. Representative images captured during IVVM following LPS administration. Shown are images captured from the same field of view from a Saline-treated mouse (A, capillary perfusion; B, rhodamine fluorescence) and an LPS-treated mouse (10 mg/kg i.p.) at 18 h (C, capillary perfusion; D, rhodamine fluorescence). Arrows indicate capillaries with intermittent or no flow. Rhodamine fluorescence was increased in regions of compromised flow. Magnification 200×.
was severely compromised in mice treated with LPS (Fig. 5). The percentage of capillaries with continuous flow was decreased from 89 ± 4% in Saline (n = 6) to 43 ± 7% in LPS (n = 6; p < 0.05 compared with Saline). The percentage of capillaries with intermittent and no flow was increased from 6 ± 2 and 5 ± 2% in Saline, respectively, to 43 ± 4 and 16 ± 4% in LPS, respectively (p < 0.05 for intermittent flow compared with Saline and p < 0.05 for no flow compared with Saline). Thus, all of the effects of LPS on peritubular capillary perfusion were completely blocked by l-NIL.

The effect of l-NIL treatment on LPS-induced ROS/RNS generation was determined using oxidation of DHR to rhodamine as in Fig. 2. Representative video images of rhodamine fluorescence from a saline-treated, LPS-treated (10 mg/kg i.p.), and l-NIL (3 mg/kg i.p.) + LPS-treated mouse captured at 6 h are shown in Fig. 6, A to C, respectively. LPS produced a significant (p < 0.05) increase in rhodamine fluorescence intensity compared with Saline at 6 h (Fig. 6D). The increase in rhodamine fluorescence was completely blocked by l-NIL. Thus, the ability of l-NIL to block the increase in LPS-induced rhodamine fluorescence suggests that iNOS-derived RNS was the major oxidative species generated at 6 h following LPS treatment.

IVVM was also used to assess cellular redox stress by measuring NAD(P)H autofluorescence (Fig. 7). Representative video images of NAD(P)H autofluorescence from a saline-treated, LPS-treated (10 mg/kg i.p.), and l-NIL (3 mg/kg i.p.) + LPS-treated mouse captured at 6 h are shown in Fig. 7, A to C, respectively. LPS caused a significant increase in NAD(P)H autofluorescence (p < 0.05 compared with Saline) that was completely blocked by coadministration of l-NIL (Fig. 7D). Taken together, these results indicate that iNOS-derived NO mediates the decrease in capillary perfusion, RNS generation, and tubular redox stress associated with LPS administration.

**Discussion**

It is becoming increasingly clear that endothelial injury and peritubular capillary dysfunction may initiate and extend the pathogenesis of chronic renal failure (O’Riordan et al., 2005) and also contribute to nephrotic and ischemic forms of acute renal failure (Brodsky et al., 2002; Yuan et al., 2003; Molitoris and Sutton, 2004) by compromising renal vascular responsiveness and tubule function (Linas and Repine, 1999; Piepot et al., 2003; O’Riordan et al., 2005). We have established that renal microcirculatory dysfunction is also a key feature of LPS-induced renal injury. Renal peritubular capillary perfusion is severely compromised as early as 2 h following LPS administration in mice, and tubular redox stress increases as perfusion decreases (Wu et al., 2007). In addition, induction of iNOS in the kidney parallels the time course of capillary dysfunction, raising the possibility that increased NO generation may participate in the development of renal injury (Tiwari et al., 2005; Wu et al., 2007). The present studies extend those studies to show the importance of iNOS in the early capillary defect. Furthermore, iNOS inhibition reduced tubular redox stress and

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**Fig. 3.** Relationship between capillary perfusion and ROS/RNS generation. Representative video images of capillary perfusion (A) and rhodamine fluorescence (B) from the same field of view were captured from an LPS-treated mouse (10 mg/kg i.p.) (A) and rhodamine fluorescence (B) from the same field of view captured from an LPS-treated mouse (10 mg/kg i.p.) are shown. Capillary perfusion was visualized using FITC-dextran and arrows indicate capillaries with intermittent or no flow (A). Image of rhodamine fluorescence was pseudo-colored to reveal differences in pixel intensity (B). Regions boarded by dysfunctional capillaries displayed higher relative pixel intensities.

**Fig. 4.** Immunohistochemistry of nitrotyrosine-protein adducts in the kidney. Representative photographs from the kidney of a saline-treated (A) and LPS-treated (10 mg/kg i.p.) (B and C) mouse 18 h following treatment are shown (representative of three animals per group). Positive staining, indicated by a brown color, was weak in saline-treated mice. In contrast, LPS treated mice displayed intense staining in the tubules. The specificity of the antinitrotyrosine antibody was confirmed by blocking antigen-binding sites with 10 mM 3-nitrotyrosine (C). Magnification 200×.
blocked the increase in rhodamine fluorescence, suggesting that the predominant oxidative species generated by the tubular epithelium in response to LPS were RNS.

Microcirculatory dysfunction is a common feature of several forms of renal injury. For example, IVVM has been used to document changes in peritubular capillary flow following renal ischemia (Sutton et al., 2005). However, the consequences of reduced peritubular capillary perfusion have never been studied in detail. IVVM is a powerful tool because it allows for real-time measurements of peritubular capillary perfusion and epithelial stress [NAD(P)H levels] and ROS/RNS generation in adjacent tubules. As early as 6 h following LPS administration, renal cortical RNS generation was significantly increased. Image analysis suggested that RNS generation was predominantly localized to the tubular epithelium and, in particular, those tubules bordered by capillaries with compromised flow. These findings suggest that RNS generation by the tubular epithelium may be regulated by capillary perfusion. Thus, reduced peritubular capillary perfusion may contribute to tubular epithelial oxidant generation. These data are the first to show the association between decreased capillary perfusion and increased tubular RNS generation. A significant decrease in capillary perfusion occurs as early as 2 h following LPS administration (Wu et al., 2007), preceding RNS generation. We also observed an early increase in tubular NAD(P)H levels, suggesting an increase in the redox state (Paxian et al., 2004; Wunder et al., 2005) of the tubular epithelium. The increase in NAD(P)H levels following LPS administration is likely a consequence of hypoxia caused by reduced capillary perfusion. For example, hepatic NAD(P)H levels are highly correlated with hypoxia in the liver (Paxian et al., 2004; Wunder et al., 2005). Thus, these data provide compelling evidence that localized decreases in peritubular capillary perfusion can result in a microenvironment that promotes oxidant generation and tubular injury. This type of cross-talk between the peritubular capillary and tubular epithelium may be important in other forms of renal injury as well.

Induction of iNOS results in overproduction of NO and increases the likelihood that RNS will be generated. NO reacts with superoxide to produce the RNS peroxynitrite, a highly reactive cytotoxic species (Szabo, 2003) that can be detected by DHR (Glebska and Koppenol, 2003). The finding that nitrotyrosine-protein adducts were present in the kidney following LPS administration indicated the generation of peroxynitrite. Furthermore, these findings supported the interpretation of the IVVM experiments with DHR that RNS was generated by the renal tubules. Whereas the precise source or superoxide is unknown, decreased capillary perfusion can lead to hypoxia and increased redox stress (Paxian et al., 2004; Wu et al., 2007), both of which can result in increased superoxide generation. This raises the possibility that compromised capillary perfusion could lead to ROS/RNS generation.

We reported previously that pharmacological inhibition of iNOS could achieve full protection in mice against LPS-induced peritubular capillary dysfunction and renal failure at 18 h (Tiwari et al., 2005). In the present study, we observed that i-NIL treatment prevented not only the early perfusion defects at 6 h but also prevented RNS generation and tubular redox stress. It is generally agreed that iNOS induction and the resulting overproduction of NO play an important role in the hemodynamic changes associated with sepsis and sepsis-induced renal failure (Schrier and Wang, 2004). The kidney is somewhat unique in that LPS produces a paradoxical renal vasoconstriction (Lugon et al., 1989) thought to be due, at least in part, to iNOS-derived NO-mediated inactivation of eNOS (Schwartz et al., 1997; Chauhan et al., 2003). The present findings show that, in addition to altering vascular reactivity, iNOS also serves as a major source of NO to generate RNS in kidney. Thus, these effects of NO could act synergistically to compromise renal function. Although these data provide compelling evidence for the role of iNOS, additional studies are required to fully establish cause-effect relationships that may exist between iNOS-derived NO and the decrease in peritubular capillary perfusion.

A unique feature of IVVM when applied to the kidney is the ability to directly monitor the effects of capillary flow on neighboring tubules. By determining capillary perfusion, RNS generation, and cellular redox stress in the same fields of view, we were able to uncover a previously unrecognized role for the peritubular capillary in regulating RNS generation. This study is the first to visualize RNS generation by renal tubules in response to LPS challenge in vivo. The data suggest that decreased capillary perfusion sets up a micro-
Fig. 6. Effects of l-NIL on LPS-induced ROS/RNS generation in the kidney. Representative video images of rhodamine fluorescence from a saline-treated (A), LPS-treated (10 mg/kg i.p.) (B), and l-NIL + LPS-treated mice (C) at 6 h are shown. LPS produced a significant increase in rhodamine fluorescence at 6 h, indicating the generation of ROS/RNS (*, $P < 0.05$ compared with Saline). Treatment with l-NIL (3 mg/kg i.p.) blocked this effect of LPS (D). Data are mean ± S.E.M. ($n = 6$). Magnification $200\times$.

Fig. 7. Effects of l-NIL on LPS-induced tubular cell stress at 6 h. NAD(P)H autofluorescence intensity was used as an indicator of tubular cell stress. Representative video images of NAD(P)H autofluorescence from a saline-treated (A), LPS-treated (10 mg/kg i.p.) (B), and l-NIL + LPS-treated mice (C) at 6 h are shown. LPS produced a significant increase in NAD(P)H autofluorescence at 6 h (*, $P < 0.05$ compared with Saline). Treatment with l-NIL (3 mg/kg i.p.) blocked this effect of LPS (D). Data are mean ± S.E.M. ($n = 6$). Magnification $200\times$. 
environment that may promote tubular RNS generation and cellular redox stress. Pharmacological inhibition of iNOS blocked the capillary perfusion defects, tubular RNS generation, and tubular cellular stress. This dependence on iNOS supports the notion that iNOS should be further evaluated as a potential therapeutic target in sepsis-induced renal injury.

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