Renalase Protects against Ischemic AKI

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ABSTRACT

Elevated levels of plasma catecholamines accompany ischemic AKI, possibly contributing the inflammatory response. Renalase, an amine oxidase secreted by the proximal tubule, degrades circulating catecholamines and reduces myocardial necrosis, suggesting that it may protect against renal ischemia reperfusion injury. Here, mice subjected to renal ischemia reperfusion injury had significantly lower levels of renalase in the plasma and kidney compared with sham-operated mice. Consistent with this, plasma NE levels increased significantly after renal ischemia reperfusion injury. Furthermore, renal tubular inflammation, necrosis, and apoptosis were more severe and plasma catecholamine levels were higher in renalase-deficient mice subjected to renal ischemia reperfusion compared with wild-type mice. Administration of recombinant human renalase reduced plasma catecholamine levels and ameliorated ischemic AKI in wild-type mice. Taken together, these data suggest that renalase protects against ischemic AKI by reducing renal tubular necrosis, apoptosis, and inflammation, and that plasma renalase might be a biomarker for AKI. Recombinant renalase therapy may have potential for the prevention and treatment of AKI.


Ischemic AKI is a major problem for patients subjected to major surgical procedures involving the kidney, liver, heart, or aorta. Renal ischemia reperfusion (IR) injury is a frequent cause of clinical AKI, with the incidence of AKI exceeding 50% after major cardiac, hepato-biliary, or aortic surgery. Furthermore, ischemic AKI is frequently complicated by multi-organ dysfunction, systemic inflammation, sepsis, and death. Unfortunately, there are no proven therapies to prevent or treat AKI in the perioperative setting.

Renalase is a 38-kD, flavin adenine dinucleotide–dependent amine oxidase synthesized and secreted by the renal proximal tubules. Renalase degrades circulating catecholamines and regulates systemic BP in rodents and humans. Plasma catecholamines and systemic BP are elevated in patients with chronic kidney dysfunction or end stage renal insufficiency. Recent studies suggest that renalase deficiency in patients with chronic renal insufficiency leads to increased plasma catecholamine levels and systemic BP. However, the effect of ischemic AKI on kidney renalase and plasma catecholamine levels remains to be determined.

In addition to regulating BP, renalase may protect against inflammatory tissue injury by metabolizing catecholamines. Catecholamines via activation of leukocyte α-adrenergic receptors directly cause inflammation in sepsis and multi-organ dysfunction. Indeed, patients with chronic renal insufficiency show increased markers of inflammation that contribute directly to increased morbidity and mortality. In mice, renalase deficiency resulted in exacerbated cardiac IR injury and exogenous renalase administration reduced myocardial necrosis.

In this study, we hypothesized that ischemic AKI in mice leads to renalase deficiency and this renalase...
deficiency directly exacerbates ischemic AKI. We performed experiments to test the following: (1) whether ischemic AKI leads to reduced kidney and plasma renalase levels, (2) whether ischemic AKI-induced renalase deficiency leads to elevated plasma catecholamine (NE) levels, (3) whether renalase-deficient mice exhibit increased renal IR injury, and (4) whether exogenous administration of recombinant human renalase directly protects against ischemic AKI in mice.

RESULTS

Renalase Is Selectively Expressed in Renal Proximal Tubules
Figure 1A shows coimmunolocalization analyses of pig kidney tissue incubated with antibodies against megalin (a marker for proximal renal tubules; red) or renalase (green). Renalase and megalin stain perfectly overlap indicating that renalase is expressed in renal proximal tubules. We also performed coimmunolocalization studies with renalase (green) and E-cadherin (a marker for distal renal tubules; red) (Figure 1B). Unlike megalin, E-cadherin does not colocalize with renalase in pig kidneys. These data indicate selective expression of renalase in renal proximal tubules. Our renalase antibody also detected renalase in mouse proximal tubules (data not shown).

Plasma NE Levels after Sham Operation or Renal IR in Mice
We show that plasma NE concentration increased 24 hours after renal IR in renalase wild-type (WT) mice (>2-fold compared with sham-operated renalase WT mice) (Figure 2; n=3–5). The increase in plasma NE concentration was even higher in renalase-deficient mice after renal IR (>5-fold compared with sham-operated renalase knockout [KO] mice).

Plasma and Kidney Renalase Expression after Renal IR
Immunoblotting for plasma renalase revealed significant reductions in plasma renalase 5 hours and 24 hours after renal IR (Figure 3A; n=4–5). Consistent with this decrease in plasma renalase, kidney renalase mRNA expression was significantly attenuated 24 hours after renal IR (Figure 3B; n=4).

Renalase-Deficient Mice Have Increased Ischemic AKI after Renal IR
Baseline plasma creatinine values were similar between renalase WT and renalase KO subjected to sham operation (anesthesia, laparotomy, right nephrectomy, and recovery) (Figure 4A). Plasma creatinine increased significantly in renalase WT and renalase KO mice subjected to moderate (20 minutes) or severe (30 minutes) renal IR compared with sham-operated mice (Figure 4A; n=4–6). However, renalase KO mice had significantly increased renal injury indicated by higher plasma creatinine levels compared with renalase WT mice after both moderate and severe renal IR injury.

Renal Protective Effects of Exogenous Human Recombinant Renalase Administration
We next tested whether exogenous human recombinant renalase pretreatment protects against renal IR injury in mice. Plasma creatinine significantly increased in vehicle (saline)-treated mice subjected to 30 minutes of renal IR compared with sham-operated mice (Figure 4B; n=4–6).
Pretreatment with human recombinant renalase (0.5, 1.5, or 4.5 mg/kg subcutaneously 10 minutes before renal ischemia) significantly attenuated the increases in plasma creatinine in mice. However, a higher dose of human recombinant renalase (4.5 mg/kg) provided reduced renal protection compared with the recombinant renalase dose of 1.5 mg/kg. We also determined that exogenous renalase (1.5 mg/kg) decreased plasma NE levels in mice subjected to renal IR injury (vehicle-injected mice plasma NE, 2.4±0.13 ng/ml, n=4, versus renalase injected mice plasma NE, 1.6±0.2 ng/ml, n=4; P<0.05) consistent with its renal protective effects.

We also tested whether recombinant renalase treatment after renal reperfusion (after completion of renal ischemia) protected against renal IR injury. Figure 4C shows that recombinant renalase (1.5 mg/kg) given 30 minutes after reperfusion was protective against renal IR injury (n=4–6). Administration of recombinant renalase 60 minutes did not provide renal protection against IR injury.

Renal Protective Effects of α-Adrenergic Receptor Blockade
We also tested whether blocking α-adrenergic receptors mimics the renal protective effects of human recombinant renalase administration. Phentolamine, a nonspecific but selective α-adrenergic receptor antagonist (5 mg/kg, intraperitoneally), produced significant renal protection in renalase WT mice subjected to renal 30 minutes of IR injury (Figure 4D). Furthermore, phentolamine also protected renalase KO mice against 30 minutes of renal IR injury (Figure 4D).

Renalase Modulates Renal Tubular Necrosis after IR
Renalase-deficient mice subjected to moderate renal IR injury (20 minutes of renal ischemia) developed exacerbated renal histologic injury compared with the renalase WT mice, including increased tubular necrosis and/or proteinaceous casts with increased congestion (Figure 5A, top panels, representative of four to six experiments). In contrast to and consistent with the plasma creatinine data, renalase WT mice treated with human recombinant renalase
(1.5 mg/kg) had dramatically reduced injury compared with vehicle-treated renalase WT mice (Figure 5A, bottom panels). The Jablonski scale16 renal injury score (0–4) was used to grade renal tubular necrosis 24 hours after renal IR (Figure 5B; n=4–6). Renalase KO mice subjected to moderate renal IR injury (20 minutes of renal ischemia) showed severe acute tubular necrosis (with renal injury scores >3) unlike renalase WT mice subjected to 20 minutes of renal IR injury. In contrast, renalase WT mice treated with human recombinant renalase had significantly lower renal injury scores compared with vehicle-treated renalase WT mice subjected to 30 minutes of renal IR injury.

**Exogenous Renalase Decreases Renal Apoptosis, Neutrophil Infiltration, and Macrophage Infiltration after IR**

Terminal deoxynucleotidyl transferase–mediated digoxigenin–deoxyuridine nick-end labeling (TUNEL) staining detected apoptotic renal cells in kidney of mice subjected to renal IR with predominant proximal tubule cell apoptosis (Figure 6A; magnification, ×100; representative of four experiments). Unlike the kidneys of sham-operated mice, 30 minutes of renal ischemia and 24 hours of reperfusion resulted in severe apoptosis in the kidneys of vehicle (saline)–treated mice (Figure 6A). Recombinant renalase (1.5 mg/kg, subcutaneously) given 10 minutes before renal ischemia significantly reduced the number of apoptotic TUNEL-positive cells in the kidney (Figure 6B, n=4).

Figure 7A shows representative images of neutrophil immunohistochemistry of kidneys (magnification, ×200; representative of four experiments) from mice subjected to 30 minutes of renal ischemia and 24 hours of reperfusion or to sham operation. There was significant neutrophil infiltration (dark brown) in the kidneys of mice treated with saline and subjected to 24 hours renal IR. In sham-operated mice, we were unable to detect any neutrophils in the kidney. Mice treated with recombinant before renal ischemia had significantly reduced number of neutrophils infiltrating the kidney after IR (Figure 7B, n=4). Figure 7C shows representative images of macrophage (F4/80) immunohistochemistry of kidneys (magnification, ×400; representative of three to four experiments) from mice subjected to 30 minutes of renal ischemia and 24 hours of reperfusion or to sham operation. There was significantly increased macrophage infiltration (brown stain) in the kidneys of mice treated with saline and subjected to 24 hours of renal IR. Mice treated with recombinant renalase before renal ischemia had a
A significantly reduced number of macrophages infiltrating the kidney after IR (Figure 7D).

**Renalase Deficiency Increases Proinflammatory Gene Expression in the Kidney after IR**

We measured the expression of proinflammatory cytokine mRNAs in the kidney 24 hours after renal IR with RT-PCR: TNF-α, intercellular adhesion molecule 1 (ICAM-1), monocyte chemoattractive protein 1 (MCP-1), and macrophage inflammatory protein 2 (MIP-2). The primer sequences are listed in Table 1. Renalase WT mice significantly increased the expression of all proinflammatory mRNAs examined compared with the sham-operated renalase WT mice (Figure 8). Moreover, renalase-deficient mice had even greater increases in TNF-α, MCP-1, and MIP-2 expression without any changes in ICAM-1 expression compared with renalase WT mice.

**DISCUSSION**

Ischemic AKI is complicated by intrarenal recruitment of proinflammatory leukocytes and systemic inflammation. Recent studies have demonstrated that renal IR is not a single organ disease but involves multiple extrarenal organs including the liver, intestine, and lung. Although many advances have been made detailing the mechanisms of renal tubular cell death after ischemic AKI, the trigger that orchestrates renal and systemic inflammation after ischemic AKI remains unknown. Extrarenal effects of ischemic AKI may explain the disproportionately high mortality in patients with AKI. Therefore, ways to prevent these systemic, extrarenal complications from AKI would contribute greatly to improved patient care and survival.

Renalase is a renal tubule-secreted, flavin adenine dinucleotide-dependent amine oxidase that degrades catecholamines including epinephrine, NE, and dopamine without effects against other physiologic amines including serotonin, tyramine, or spermidine. Administration of recombinant renalase decreases cardiac output and BP by regulating plasma catecholamine levels. In contrast, plasma renalase levels are reduced in patients with chronic renal insufficiency. Deficiencies in plasma renalase in these patients are most likely due to increased plasma catecholamine levels. Reduction in circulating levels of renalase would increase circulating plasma catecholamine levels. Consistent with this, patients with CKD or end stage renal failure suffer from hypertension due to increased plasma catecholamine levels. Deficiencies in plasma renalase in these patients are most likely due to the direct reduction in renal tubular renalase synthesis. In rats, plasma and kidney renalase levels are decreased after subtotal nephrectomy. Moreover, unilateral renal artery stenosis causes drastic reductions in renalase expression and secretion compared with the nonstenotic kidney. These studies strongly suggest that the kidney is the major source of steady state renalase secretion to plasma.

We show in this study that renal tubular cell death and acute reduction in renal function after ischemic AKI led to drastic

Figure 5. Renalase modulates renal tubular necrosis after IR. (A) Representative photomicrographs for hematoxylin and eosin staining of kidney sections of renalase WT or renalase-deficient (KO) mice subjected to 20 minutes or 30 minutes of renal ischemia and 24 hours of reperfusion. Some renalase WT mice are pretreated with 1.5 mg/kg of human recombinant renalase 10 minutes before renal ischemia. Photographs are representative of three to five independent experiments. (B) Summary of Jablonski scale renal injury scores (n=4), graded from hematoxylin and eosin staining (scale 0–4) for mice subjected to renal IR. We show that renalase KO mice have worse renal tubular necrosis after IR and recombinant renalase provides significant renal tubular protection against necrosis in renalase WT mice. *P<0.05 versus WT mice subjected to 20 minutes of renal IR. †P<0.05 versus vehicle-treated WT mice subjected to 30 minutes of renal IR. Error bars represent 1 SEM. Original magnification, ×200 in A.
reductions in renal and plasma renalase levels with a resultant increase in plasma NE. These findings are consistent with the hypothesis that kidney proximal tubule is a major source of circulating renalase. Moreover, our data suggest that secreted renalase is degraded rapidly in plasma and constant new renalase synthesis and release by the kidney must occur to maintain normal plasma renalase levels. Furthermore, because kidney and plasma renalase levels rapidly decreased after ischemic AKI in mice, urine and plasma renalase may also serve as a novel and sensitive biomarker for the early detection of ischemic AKI.

Recombinant renalase therapy may provide a novel therapeutic tool for the prevention and treatment of AKI, because we showed powerful protective effects of recombinant renalase against renal IR injury in mice. Specifically, exogenous recombinant renalase attenuated renal tubular necrosis (Jablonski renal injury score). Furthermore, we demonstrate reduced influx of proinflammatory neutrophils and macrophages into the kidney and renal tubular apoptosis after renal IR in recombinant renalase–treated mouse kidneys. Therefore, we conclude that exogenous administration of human recombinant renalase provides powerful renal protection against ischemic AKI by targeting all three pathways (necrosis, apoptosis, and inflammation) of renal cell injury. Similar to our findings, exogenous human recombinant renalase significantly protected against myocardial necrosis and decreased plasma catecholamine levels in renalase-deficient mice.

We noted that recombinant renalase (1.5 mg/kg) provided significant but partial renal protection (creatinine decreasing from approximately 2.4 mg/dl to 1.4 mg/dl), most likely due to the severity of our ischemic AKI model (30 minutes of warm ischemia). Thirty minutes of renal ischemia would have caused significant renal tubular necrosis during ischemia that may not be rescued with renalase treatment. We also discovered that renalase does not provide dose-dependent protection and there was some reversal of protection at doses of 4.5 mg/kg. We believe that the high dose (4.5 mg/kg) failed to provide increased renal protection because renalase causes dose-dependent reduction in systemic BP. A previous study showed that a 4 mg/kg renalase dose reduced mean arterial pressure by approximately 40%. This reduction in systemic BP may have negated the renal protective effects of high-dose recombinant renalase.

Recombinant renalase therapy was also partially protective when administered 30 minutes after renal ischemia. This is highly exciting as recombinant renalase therapy may be effective for a diverse group of patients at risk for ischemic AKI. Although renal ischemia can be anticipated in many surgical procedures, a significant number of patients present to the hospital after renal ischemic injury has already occurred. Postischemic therapy for AKI will increase the translational as well as clinical significance because not all ischemic AKI can be anticipated in advance. However, we noted significant differences in the efficacy of renalase administered 10 minutes before renal ischemia and 30 minutes after reperfusion. We believe

![Figure 6. Exogenous recombinant human renalase reduces renal tubular apoptosis in mice after IR. (A) Representative photomicrographs for TUNEL staining (representing apoptotic nuclei) of kidney sections of mice subjected to sham operation or to 30 minutes of renal ischemia and 24 hours of reperfusion. Mice are pretreated with saline vehicle or with 1.5 mg/kg human recombinant renalase 10 minutes before renal ischemia. Photographs are representative of four independent experiments. (B) Quantifications of apoptotic cells per \( \times 100 \) field in the kidneys of mice after renal IR. *P<0.05 versus vehicle-treated mice subjected to renal IR. Error bars represent 1 SEM. Recombinant renalase treatment significantly decreases renal tubular apoptosis in mice after renal IR injury. Original magnification, \( \times 100 \) in A.](image-url)
that this is because of the severity of early reperfusion injury that occurs after 30 minutes of warm kidney ischemia. It appears that recombinant renalase must be present in the circulation to counteract the significant renal injury that occurs during 30 minutes after reperfusion.

We show in this study that increases in plasma NE levels were greater in renalase KO mice compared with the renalase WT mice after renal IR injury. Wu et al. have also demonstrated that plasma levels of catecholamines, including epinephrine, dopamine, and NE, are increased in renalase KO mice. We also showed in this study that renalase KO mice suffered increased renal tubular injury after renal IR. Furthermore, we demonstrate increased TNF-α, MCP-1, and MIP-2 after renal IR in renalase-deficient mice. In particular, MIP-2 is a chemokine involved in inflammation and immunoregulation and is a potent regulator of neutrophil chemotaxis. Consistent with our findings, renalase KO mice have exacerbated myocardial necrosis due to IR. Taken together, renalase deficiency appears to exacerbate ischemic organ injury and results in higher plasma catecholamine levels.

We hypothesize that the renal protective effects of recombinant renalase are, at least in part, due to increased metabolisms of plasma and tissue catecholamines. Consistent with this hypothesis, we show that recombinant renalase–mediated renal protection also resulted in significantly reduced plasma catecholamine levels. Increased catecholamine levels after ischemic AKI may exacerbate kidney injury by decreasing renal blood flow as well as by direct effects on renal tubules and immune cells. Catecholamines have been implicated in promoting tissue and organ injury in sepsis and systemic inflammatory response syndrome. For example, gut-derived NE has been implicated in causing hepatic injury and systemic inflammation in sepsis. Previous studies have shown that intestine-derived NE activates hepatic Kupffer cell α2-adrenoceptors to increase TNF-α generation and release. In septic rats, α2-adrenergic receptors upregulate in Kupffer cells to potentiate inflammatory response and organ injury. Furthermore, α1-adrenergic receptors increase LPS-mediated induction of proinflammatory cytokines in human monocytes and macrophages. Therefore, both α1- and α2-adrenergic receptors are implicated in proinflammatory effects of increased circulating catecholamines. Supporting a pathogenic role of α-adrenergic receptors against ischemic AKI, we found that blockade of α-adrenergic receptors provided significant renal protection in renalase WT as well as renalase KO mice.

Renal sympathetic nerves may play an important role in regulating ischemic AKI by modulating catecholamines released from the kidney. Indeed, increased renal sympathetic nerve activity during and after ischemic AKI increases renal

Figure 7. Exogenous recombinant human renalase reduces renal neutrophil infiltration in mice after IR. (A and C) Representative photomicrographs for immunohistochemistry for neutrophil infiltration or macrophages (F4/80 staining) of kidney sections of mice subjected to sham operation or to 30 minutes of renal ischemia and 24 hours of reperfusion. Mice were pretreated with saline vehicle or with 1.5 mg/kg of human recombinant renalase 10 minutes before renal ischemia. Photographs are representative of three to five independent experiments. (B and D) Quantifications of infiltrated neutrophils (per ×200 field) and macrophages (per ×400 field) in the kidneys of mice after renal IR. *P<0.05 versus sham-operated group; #P<0.05 versus vehicle-treated mice subjected to renal IR. Error bars represent 1 SEM. Recombinant renalase treatment significantly reduced renal neutrophil as well as macrophage infiltration in mice after renal IR injury. Original magnification, ×200 in A; ×400 in C.
vein catecholamines released to systemic circulation and directly contributes to increased renal injury after IR.\textsuperscript{33} Furthermore, a previous study by Jiang \textit{et al}. showed that renal denervation increased plasma and kidney renalase levels.\textsuperscript{34} Therefore, renal sympathetic nerve activation may negatively modulate kidney and plasma renalase levels. Taken together, we propose that increased renal sympathetic nerve activity during and after renal IR exacerbates ischemic AKI by increasing plasma catecholamine levels and downregulating kidney/ plasma renalase levels.

Given the robust protective effects of recombinant renalase, it is possible that renalase may protect against AKI \textit{via} additional mechanisms beyond degradation of catecholamine. It would be extremely interesting to demonstrate in future studies whether renalase protects against other models of AKI (e.g., cisplatin nephrotoxicity) as well as whether recombinant renalase protects against necrosis and/or apoptosis in proximal tubule cells in culture. These experiments would significantly broaden the translational aspect of recombinant renalase and could provide further mechanistic insight to the observed beneficial properties of renalase against ischemic AKI.

In summary, our findings that exogenous recombinant renalase rescues against ischemic AKI and plasma renalase levels falls rapidly after ischemic AKI represent a novel approach to combat ischemic AKI. Our studies may lead to new therapeutic approaches with a drug that can reduce all three pathways of renal cell death (necrosis, apoptosis, and inflammation) to lessen the clinical perils from AKI and have implications in organ protection strategies beyond the kidney.

### CONCISE METHODS

**Synthesis of Recombinant Human Renalase**

Human recombinant renalase was synthesized as described.\textsuperscript{35} The complete methods are available in the Supplemental Material.

**Murine Model of Renal IR Injury**

After Columbia University Institutional Animal Care and Use Committee approval, we subjected adult male renalase-deficient (KO) mice\textsuperscript{15} on a C57BL/6 background to renal IR as described.\textsuperscript{36,37} Renalase KO or WT mice (C57BL/6 from Harlan Laboratories, Indianapolis, IN) were subjected to sham operation or to 20 minutes (moderate) or 30 minutes (severe) of renal ischemia and 24 hours of reperfusion. To test the renal protective effects of recombinant human renalase, we pretreated mice with saline (vehicle) or with recombinant renalase (0.5, 1.5, or 4.5 mg/kg, subcutaneously) 10 minutes before 30 minutes of renal ischemia. In addition, we tested whether renalase treatment after completion of renal ischemia also provides renal protection. Separate cohorts of mice were treated with saline or with renalase (1.5 mg/kg, subcutaneously) 30 minutes or 60 minutes after reperfusion of the ischemic kidney. To test whether blocking \( \alpha \)-receptors would mimic the renal protective effects of human recombinant renalase administration, we administered phentolamine, an \( \alpha \)-receptor antagonist (5 mg/kg, intraperitoneally), in some mice 15 minutes before renal ischemia.

**Measurement of Renal Function**

Plasma creatinine was measured as described, with an enzymatic creatinine reagent kit according to the manufacturer’s instructions (Thermo Fisher Scientific, Waltham, MA).\textsuperscript{38}

**Measurement of Plasma NE**

Plasma NE in mice subjected to sham operation or to renal IR was measured with a commercial ELISA kit according to the manufacturer’s instructions (Rocky Mountain Diagnostics, Colorado Springs, CO).

**Histologic Detection of Necrosis, Apoptosis, and Neutrophil Infiltration**

An established grading scale of necrotic injury (renal injury score: 0–4) to the proximal tubules was used for the histopathological assessment of IR-induced damage as outlined by Jablonski \textit{et al}.\textsuperscript{16} and as described previously in our studies.\textsuperscript{39,40} We detected apoptosis after

### Table 1. Primers used to amplify cDNAs based on published GenBank sequences for mice

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<th>Sequence (Sense/Antisense)</th>
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ICAM-1, intercellular adhesion molecule-1; MCP-1, monocyte chemotactic protein-1; MIP-2, macrophage inflammatory protein 2; GAPDH, glyceraldehyde 3-phosphate dehydrogenase.
renal IR with TUNEL staining as described\textsuperscript{19} using a commercially available \textit{in situ} cell death detection kit (Roche, Indianapolis, IN) according to the instructions provided by the manufacturer. Kidney neutrophil and macrophage infiltrations were assessed with immunohistochemistry 24 hours after IR as described previously.\textsuperscript{19} Neutrophils and macrophages infiltrating the kidney were quantified in five to seven randomly chosen $\times 200$ (neutrophils) or $\times 400$ (macrophages) microscope image fields in the corticomedullary junction and results were expressed as neutrophils counted per $\times 200–400$ field.

**RT-PCR and Immunoblotting Analyses for Mouse Renalase**

We measured mRNA encoding mouse renalase with RT-PCR as described.\textsuperscript{41} Glyceraldehyde 3-phosphate dehydrogenase mRNA was also measured to control for equal RNA input. In addition, mouse kidney cortex was also collected for immunoblotting analyses of renalase (Abcam, Cambridge, MA) and $\beta$-actin (internal protein loading control; Sigma) as described previously.\textsuperscript{41}

**Measurement of Proinflammatory mRNA Expression after Intestinal IR**

Kidney inflammation after renal IR in mice were additionally determined by measuring mRNA encoding markers of inflammation, including IL-17A, ICAM-1, MCP-1, MIP-2, and TNF-$\alpha$ and IL-6 (liver and kidney only) (Table 1). RT-PCR was performed as described.\textsuperscript{19}

**Coimmunolocalization of Endogenous Renalase with E-Cadherin or Megalin in Pig Kidney**

Our renalase antibody was synthesized against human renalase sequence. We performed renalase immunohistochemistry in pig kidneys because we felt that the human renalase sequence would be best conserved in pigs. Pig kidney slices were fixed, permeabilized, and incubated with anti-renalase 28–4 (raised against renalase peptide EAGTKIDVPWAGQYITSNPC) and with either anti-E-cadherin (BD Biosciences) or anti-megalin primary antibody (kind gift of Dr. D. Biemesderfer, Yale University School of Medicine, New Haven, CT) for 2 hours. Secondary antibodies (Alexa488-goat anti-rabbit for detecting renalase) and Alexa555-goat anti-mouse (Molecular Probes, for detecting E-cadherin or megalin) were then applied. Slides were imaged with a fluorescence microscope (Carl Zeiss Inc) and photographed using SPOT camera software (Diagnostic Instruments Inc).

**Statistical Analyses**

The data were analyzed with the $t$ test when comparing means between two groups or with one-way ANOVA plus the Tukey’s post \textit{hoc} multiple comparison test when comparing multiple groups. Two-way ANOVA plus Bonferroni post-test was used to test the effects of sham operation or renal IR injury on different mouse strains or treatment groups. The ordinal values of the renal injury scores were analyzed by the Mann–Whitney nonparametric test. In all cases, $P<0.05$ was
taken to indicate significance. All data are expressed throughout the text as mean ± SEM.

ACKNOWLEDGMENTS

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DISCLOSURES

G.V.D. has two issued patents on renalase discovery.

REFERENCES


This article contains supplemental material online at http://jasn.asnjournals.org/lookup/suppl/doi:10.1681/ASN.2012090943/-/DCSupplemental.
**Complete Methods**

**Synthesis of recombinant human renalase**

Human recombinant renalase was synthesized as described\(^1\). The gene sequence of human Renalase1 (hRenalase1) was subjected to codon optimization to facilitate expression in *E. coli*. Untagged, recombinant hRenalase1 (amino acids 1-342) was generated by cloning the coding region into the Ned1/XhoI sites of the pET27b+ vector (Novagen, Madison, WI). *E. coli* BL21 were transformed and grown at 37°C for 16 hr with 0.1μM flavin adenine dinucleotide (FAD). Isopropyl β-D-1-thiogalactopyranoside was added for the last 3.5 hr of culture. Recombinant renalase was purified from inclusion bodies and refolded by dilution in the presence of FAD. Refolded hRenalase1 (0.1mg/ml) was analyzed on a HPLC molecular sizing column (Agilent 1100 series HPLC, Biorad Gel filtration (300mm x 7.8mm) column, Cat. # 125-0062), and activity was assessed by monitoring NADH oxidation to NAD. Absorbance at 340 nm was measured in a plate reader at 37°C, and recorded every 4 min. for up to 60 min. The amount of NADH oxidized to NAD was calculated from the decrease in absorbance at 340nm using a molar extinction coefficient of 0.00622 μM/cm at 340nm. All studies were carried out with a single batch of recombinant renalase.

**Murine model of renal IR injury**

After Institutional Animal Care and Use Committee approval at Columbia University, we subjected adult male renalase deficient (KO) mice\(^12\) on a C57BL/6 background to renal IR as described\(^3\). We used C57BL/6 from Harlan Labs (Indianapolis, IN) as wild type (WT) controls. Renalase KO or WT mice were subjected
to sham-operation or to 20 min (moderate) or 30 min (severe) renal ischemia and 24 hr reperfusion. To test the renal protective effects of recombinant human renalase, we pretreated mice with saline (vehicle) or with recombinant renalase (0.5, 1.5 or 4.5 mg/kg, s.c.) 10 min prior to 30 min renal ischemia. We also tested whether renalase treatment after completion of renal ischemia also provides renal protection. Separate cohorts of mice were treated with saline or with renalase (1.5 mg/kg, s.c.) 30 min or 60 min after reperfusion of the ischemic kidney. To test whether blocking alpha receptors would mimic the renal protective effects of human recombinant renalase administration, phentolamine (an alpha receptor antagonist, 5 mg/kg, i.p.) were given in some mice 15 min before renal ischemia. We collected kidney (cortex and cortico-medullary junction) and plasma 24 hr after IR injury to examine the severity of renal dysfunction (plasma creatinine, renal tubular necrosis, apoptosis and neutrophil infiltration).

Measurement of renal function

Plasma creatinine was measured as described with an enzymatic creatinine reagent kit according to the manufacturer’s instructions (Thermo Fisher Scientific, Waltham, MA). Unlike the Jaffé method, this method of creatinine measurement largely eliminates the interferences from mouse plasma chromagens.

Measurement of plasma norepinephrine

Plasma norepinephrine in mice subjected to sham-operation or to renal IR was measured with a commercial ELISA kit according to the manufacture’s instructions (Rocky Mountain Diagnostics, Colorado Springs, CO).
Histological detection of necrosis and apoptosis

Morphological assessment of hematoxylin and eosin (H&E) staining was performed by an experienced renal pathologist (V.D.A.) who was unaware of the treatment that each animal had received. An established grading scale of necrotic injury (0-4, Renal Injury Score) to the proximal tubules was used for the histopathological assessment of IR-induced damage as outlined by Jablonski et al.\(^2\) and as described previously in our studies\(^6,7\). We detected apoptosis after renal IR with TUNEL staining as described elsewhere\(^9\) using a commercially available in situ cell death detection kit (Roche, Indianapolis, IN) according to the instructions provided by the manufacturer. Apoptotic TUNEL positive cells were quantified in 5-7 randomly chosen 100X microscope images fields in the corticomedullary junction and results were expressed as TUNEL positive cells counted per 100X field.

Histological detection of kidney neutrophil and macrophage infiltration

Kidney neutrophil and macrophage infiltration was assessed by immunohistochemistry 24 hr after IR as described previously\(^10\). Fixed mouse kidney sections were deparaffinized in xylene and rehydrated through a graded ethanol series to water. After blocking in 10% normal rabbit serum in PBS, the slides were stained for neutrophils or macrophage with rat anti-mouse primary antibodies (Ly-6B.2 for neutrophils and F4/80 for macrophages, Serotec, Raleigh, NC) for 12 hr at 4°C, horseradish peroxidase-conjugated rabbit anti-rat IgG (1/100 dilution, Vector Laboratories, Burlingame, CA) for 1 hr at room temperature and diaminobenzidine
reagent (Vector Laboratories, Burlingame, CA) for 2 min to 10 min. Neutrophils or macrophages infiltrating the kidney were quantified in 5-7 randomly chosen 200X (neutrophils) or 400X (macrophages) microscope images fields in the corticomedullary junction and results were expressed as neutrophils or macrophages counted per 200X or 400X field.

Reverse transcription polymerase chain reaction and immunoblotting analyses for mouse renalase

We measured mRNA encoding mouse renalase with RTPCR as described\(^4\). GAPDH mRNA was also measured to control for equal RNA input. Amplification of the mouse renalase cDNA was performed using the primer sequences listed in Table 1. In addition, mouse kidney cortex (including corticomedullary junction) were also collected for immunoblotting analyses of renalase (Abcam, Cambridge, MA) and β-actin (internal protein loading control, Sigma) as described previously\(^4\).

Measurement of pro-inflammatory mRNA expression after intestinal IR

Kidney inflammation after renal IR in mice were additionally determined by measuring mRNA encoding markers of inflammation, including IL-17A, intercellular adhesion molecule 1 (ICAM-1), monocyte chemoattractive protein 1 (MCP-1), macrophage inflammatory protein 2 (MIP-2) and tumor necrosis factor-α (TNF-α) and IL-6 (liver and kidney only) (Table 1). RT-PCR was performed as described\(^8\).
Coimmunolocalization of endogenous renalase with megalin or with E-cadherin in pig kidney

Pig kidney slices (5 µm, obtained from discarded surgical practice specimens at Yale University) were fixed (with 4% paraformaldehyde), permeabilized (with 0.1% Triton-X) and incubated with anti-renalase 28-4 (raised against renalase peptide EAGTKIDVPWAGQYITSNPC) and with either anti-E-cadherin (BD Biosciences) or anti-megalin primary antibody (kind gift of Dr. D. Biemesderfer, Yale University School of Medicine) for 2 hr. Secondary antibodies (Alexa488-goat anti-rabbit for detecting renalase and Alexa555-goat anti-mouse for detecting E-cadherin or megalin, Molecular Probes) were then applied. Slides were images with a fluorescence microscope (Carl Zeiss, Inc.) and photographed using a SPOT camera software (Diagnostic Instruments, Inc.).

Statistical analysis

The data were analyzed with Student's t-test when comparing means between two groups or one-way ANOVA plus Tukey’s post hoc multiple comparison test when comparing multiple groups. Two-way ANOVA plus Bonferroni posttest was used to test the effects of sham operation or renal IR injury on different mouse strains or treatment groups. The ordinal values of the renal injury scores were analyzed by the Mann–Whitney nonparametric test. In all cases, a probability statistic < 0.05 was taken to indicate significance. All data are expressed throughout the text as means ± SEM.
References


