Interleukin 6 Underlies Angiotensin II–Induced Hypertension and Chronic Renal Damage

Weiru Zhang, Wei Wang, Hong Yu, Yujin Zhang, Yingbo Dai, Chen Ning, Lijian Tao, Hong Sun, Rodney E. Kellems, Michael R. Blackburn, Yang Xia

Abstract—Chronic kidney disease (CKD) is a prevalent life-threatening disease frequently associated with hypertension, progression to renal fibrosis, and eventual renal failure. Although the pathogenesis of CKD remains largely unknown, an increased inflammatory response is known to be associated with the disease and has long been speculated to contribute to disease development. However, the causative factors, the exact role of the increased inflammatory cascade in CKD, and the underlying mechanisms for its progression remain unidentified. Here we report that interleukin 6 (IL-6) expression levels were significantly increased in the kidneys collected from CKD patients and further elevated in CKD patients characterized with hypertension. Functionally, we determined that angiotensin II is a causative factor responsible for IL-6 induction in the mouse kidney and that genetic deletion of IL-6 significantly reduced hypertension and key features of CKD, including renal injury and progression to renal fibrosis in angiotensin II–infused mice. Mechanistically, we provide both human and mouse evidence that IL-6 is a key cytokine functioning downstream of angiotensin II signaling to directly induce fibrotic gene expression and preproendothelin 1 mRNA expression in the kidney. Overall, both the mouse and human studies reported here provide evidence that angiotensin II induces IL-6 production in the kidney, and that, in addition to its role in hypertension, increased IL-6 may play an important pathogenic role in CKD by inducing fibrotic gene expression and ET-1 gene expression. These findings immediately suggest that the IL-6 signaling is a novel therapeutic target to manage this devastating disorder affecting millions worldwide. (Hypertension. 2012;59:136-144.) ● Online Data Supplement

Key Words: renin-angiotensin system ■ cytokines ■ hypertension ■ chronic kidney disease ■ endothelin 1

Chronic kidney disease (CKD) is a life-threatening condition frequently associated with hypertension, renal dysfunction, progression to renal fibrosis, and eventual chronic renal failure. It affects 26 million American adults and is the ninth leading cause of mortality in the United States. Available strategies used to manage CKD are poor and currently limited to dialysis or kidney transplantation, thus making chronic renal failure one of the most expensive diseases to treat on a per-patient basis. Despite improvement in the knowledge of diverse aspects related to CKD, the pathogenesis and the initial molecular events leading to the chronic renal fibrosis and eventual chronic renal failure remain elusive. By understanding the molecular basis of the pathogenesis of CKD, we will identify novel therapeutic targets to treat this harmful disease and prevent its progression.

It has been long speculated that pathogenesis of chronic renal fibrosis likely results from a combination of prolonged hypoxia, ischemic-mediated inflammatory response, vascular damage, and attempted tissue repair. A growing body of evidence supports a novel concept that elevated inflammation contributes to the pathogenesis of CKD. For example, several recent studies have shown that patients with hypertension and CKD exhibit high levels of diverse proinflammatory cytokines. Some hypothesize that the activation of leukocytes and upregulation of certain cytokines propagate a state of chronic inflammation in CKD patients that likely contributes to progression of the disease. Among the cytokines identified, interleukin (IL) 6 is a multifunctional proinflammatory cytokine that is associated with a number of cardiovascular disorders including CKD with or without hypertension and pulmonary vascular disease. Thus, IL-6 is now considered a major biomarker for cardiovascular risk. A critical role of IL-6 in pathogenesis of various forms of CKD was suggested by both human and animal studies. Of note, elevated IL-6 levels in the serum of patients with CKD with or without hypertension have been reported. Significantly, angiotensin II (Ang II)–induced hypertension is atten-

Received March 15, 2011; first decision April 1, 2011; revision accepted October 13, 2011.

From the Departments of Biochemistry and Molecular Biology (W.Z., W.W., Y.Z., C.N., R.E.K., M.R.B., Y.X.), University of Texas-Houston Medical School, Houston, TX; Nephrology (W.Z., W.W., L.T.), Urology (C.N.), and Otorhinolaryngology (H.S.), The First Xiangya Hospital of Central South University, Changsha, Hunan, China; Pathology (H.Y.), Hunan Provincial People’s Hospital, Changsha, Hunan, China; Urology (Y.D.), The Third Xiangya Hospital of Central South University, Changsha, Hunan, China.

Correspondence to Yang Xia, Departments of Biochemistry and Molecular Biology, University of Texas-Houston Medical School, Houston, TX. E-mail yang.xia@uth.tmc.edu

Hypertension is available at http://hyper.ahajournals.org

DOI: 10.1161/HYPERTENSIONAHA.111.173328
IL-6 in Hypertension and Chronic Renal Damage

Zhang et al

**Table. Information of Control Individuals and CKD Patients**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control (N=15)</th>
<th>CKD Without Hypertension (N=28)</th>
<th>CKD With Hypertension (N=38)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>41.7±14.1</td>
<td>46.4±13.5</td>
<td>49.8±12.5</td>
</tr>
<tr>
<td>Sex, male/female</td>
<td>9/6</td>
<td>16/12</td>
<td>24/14</td>
</tr>
<tr>
<td>SBP, mm Hg</td>
<td>106.1±12.6</td>
<td>109.3±14.3</td>
<td>155.4±19.5*</td>
</tr>
<tr>
<td>DBP, mm Hg</td>
<td>74.1±13.5</td>
<td>72.3±10.5</td>
<td>95.4±12.3*</td>
</tr>
<tr>
<td>SUN, mmol/L</td>
<td>4.56±1.07</td>
<td>5.82±1.13</td>
<td>8.29±2.47*</td>
</tr>
<tr>
<td>Bcr, µmol/L</td>
<td>70.2±23.3</td>
<td>69.36±28.84</td>
<td>117.67±29.50*</td>
</tr>
<tr>
<td>eGFR, ml/min</td>
<td>84.73±19.65</td>
<td>78.32±16.51</td>
<td>53.77±19.78*</td>
</tr>
<tr>
<td>UA, µmol/L</td>
<td>287.86±88.79</td>
<td>278.67±93.86</td>
<td>348.16±111.70</td>
</tr>
</tbody>
</table>

CKD indicates chronic kidney disease; SBP, systolic blood pressure; DBP, diastolic blood pressure; SUN, serum urea nitrogen; Bcr, blood creatinine; eGFR, estimated glomerular filtration rate; UA, uric acid.

*Compared with controls, P<0.05. Kidneys of controls with normal kidney function and blood pressure were collected after 3 h of acute kidney rupture.

Intravenously injected in IL-6-deficient mice,17–19 and knocking down IL-6 by RNA interference blocks cold-induced hypertension.20 Notably, elevated IL-6 also contributes to hypertension in pregnant rats with chronic reductions in uterine perfusion.21 These findings strongly support the essential role of IL-6 in hypertension. However, specific factors to induce IL-6 elevation in CKD are unknown, the exact contribution of this cytokine to the disease features remains unclear, and the molecular mechanisms underlying progression to renal fibrosis in CKD is still elusive. Here we sought to investigate causative factors responsible for the elevation of IL-6, the role of IL-6 in the pathogenesis of CKD, underlying mechanisms for the disease, and potential therapeutic strategies.

**Materials and Methods**

An expanded Methods section is available in the online Data Supplement (please see http://hyper.ahajournals.org).

**Human Subjects**

IL-6 expression levels were measured in kidney biopsies collected from normal control individuals (n=15), CKD patients associated with hypertension (n=38), and those without hypertension (n=28). CKD patients admitted to First XiangYi Hospital were identified by the nephrologists of the Central South University at Changsha (Hunan, China). Normal individuals were selected on the basis of having normal blood pressure and kidney function with acute kidney rupture. The research protocol was approved by the Central South University Ethics Committee for the Protection of Human Subjects. The normal individuals and patient clinical data are listed in the Table.

**Animals**

Wide-type 8- to 10-week-old C57BL/6 mice were purchased from Harlan Laboratories (Indianapolis, IN). IL-6-deficient mice (IL-6−/−) congenic on a C57BL/6 background were generated and genotyped as described.22 The mice were housed in the animal care facility of the University of Texas-Houston and had access to food and water ad libitum. All of the protocols involving animal studies were reviewed and approved by the institutional animal welfare committee of the University of Texas Houston Health Science Center. Six to 10 mice for each group were used.

**Immunohistochemistry for IL-6 in Kidney Biopsies of Humans and Quantification**

Immunohistochemistry for IL-6 was carried out similar to ET-1 (for details see the online Data Supplement) except that the slides were incubated with rabbit antihuman IL-6 antibody (Lifespan, 1:100 dilution) in a humidified chamber at 4°C overnight. After the primary antibody incubation, antirabbit IgG avidin-biotin-alkaline phosphatase complex (ABC-AP) staining system kit (Vector Labs) was used. Slides were stained with Vector Red alkaline phosphatase substrate (Vector Labs) after being washed in PBS for 5 minutes, washed in PBS and diaminobenzidine (Bios) for 5 minutes, and counterstained with hematoxylin. Vector Red produces a red reaction product that can be seen using either bright field or fluorescent microscopy. For negative controls, the primary antibody was replaced with the corresponding affinity-purified preimmune IgG. Quantification of the immunohistochemical staining was performed using the Image-Pro Plus software (Media Cybernetics, Bethesda, MD). The density of the red staining (positive for IL-6) was measured. The average densities of 25 areas per kidneys were determined, and the SEM is indicated (n=6 for each group).

**Chronic Ang II Infusion**

Mice were infused with vehicle (saline) or Ang II at a rate of 1.5 mg/kg of body weight per day into the mice by osmotic micropumps (ALZET model 201; Alza, Palo Alto, CA) subcutaneously for 2 weeks as described.23

**Blood Pressure**

We used 2 methods to measure systolic blood pressure. First, systolic blood pressure was measured by a carotid catheter-calibrated tail-cuff system (CODA, Kent Scientific, Torrington, CT) before and after micropump implantation as described.23–25 In addition to the tail-cuff system to measure blood pressure in live animals, we also measured blood pressure in anesthetized animals.21 Specifically, on the final day of Ang II infusion, the intracarotid mean arterial blood pressure was measured in the mice after anesthesia with isoflurane (2%). The carotid artery was isolated and cannulated with a PE-50 microtip catheter. The intracarotid mean artery blood pressure was measured with a pressure transducer connected to a Grass Model 7B chart recorder (AD Instrument Co). Blood pressure was recorded and averaged over a 10-minute period.

**Urine Analysis**

Twenty-four-hour urine was collected on different days from mice with or without Ang II infusion using a metabolic cage (Nalgene) as described previously.23–25

**Enzyme Immunometric Assay for Mouse Kidney Endothelin 1**

The kidneys were homogenized with an Ultrasonic homogenizer (model W-220F, Heat Systems Ultrasorics) for 60 seconds in 10 volumes of Nonidet P-40 lysis buffer containing protease inhibitor mixture (Roche Diagnostics). The homogenate was centrifuged at 12,000g for 15 minutes at 4°C, and the supernatant was stored at −80°C until it was used. The protein concentration was measured by BCA assay. Approximately 400 µL of kidney protein were placed into a microcentrifuge tube containing the same volume of 20% acetic acid, the mixture was centrifuged at 3000g for 10 minutes at 4°C, and the supernatant was kept. Subsequently, ET-1 was extracted with a Sep-Pak C-18 cartridge (Honeywell). Finally, the eluates were reconstituted with 0.25 mL of assay buffer and subjected to sensitive enzyme immunometric assay for endothelin 1 (ET-1; Life Science). The ET-1 level was normalized to protein concentration.

**Statistical Analyses**

All of the data were expressed as the mean±SEM. Data were analyzed for statistical significance using GraphPad Prism 4 software (GraphPad Software, San Diego, CA). Student t tests (paired or unpaired as appropriate) were applied in 2-group analysis. Differences between the means of multiple groups were compared by the 1-way ANOVA, followed by a Tukey multiple comparisons test. A value of P<0.05 was considered significant and was the threshold to reject the null hypothesis.
Results

IL-6 Expression Levels Are Increased in the Kidneys of CKD Patients and Further Elevated in CKD Patients With Hypertension

To determine whether IL-6 is increased in the kidneys of CKD patients, we examined IL-6 expression profiles in kidney biopsies collected from normal controls (n=15) and CKD patients with (n=38) and without hypertension (n=28; see Table for detailed information of human subjects). We found that the IL-6 expression level was low in the kidneys of normal control individuals. However, IL-6 levels were elevated in both glomeruli and tubules of kidney biopsies isolated from CKD patients with or without hypertension (Figure 1A). Quantitative image analysis demonstrates that increased IL-6 staining in the kidneys of CKD patients was significantly higher than controls and that IL-6 levels were further elevated in CKD patients with hypertension (Figure 1B). These studies show that elevated IL-6 is associated with CKD.

IL-6 Deficiency Attenuates Ang II–Induced Proteinuria in Mice

Because it is difficult to determine the role of increased IL-6 in CKD patients, we took advantage of IL-6–deficient mice. To assess the significance of increased IL-6 in the pathophysiology of CKD associated with hypertension, we chose to infuse Ang II, a potent vasoconstrictor known to induce hypertension and renal damage and dysfunction,26,27 key features seen in humans with CKD, into both wild-type and IL-6–deficient mice. First, we found that IL-6 mRNA expression levels were significantly elevated in the kidneys of mice after a 2-week Ang II infusion compared with controls with saline infusion (Figure 2A). Next, we assessed renal injury in each group during the 2-week Ang II infusion by measuring albumin content in 24-hour collected urine. We found that the ratio of urinary albumin:creatinine in 24-hour collected urine was elevated in the Ang II–infused mice compared with that of the controls by day 7 and reached a significantly higher level by day 14 of continuous Ang II infusion (Figure 2B). In contrast, the increased proteinuria was significantly attenuated in IL-6–deficient mice on day 14 of Ang II infusion (Figure 2C). Thus, these findings provide the in vivo evidence that IL-6 is a mediator of Ang II–induced kidney damage featured with proteinuria in an intact animal.

IL-6 Contributes to Progression of Renal Fibrosis in Ang II–Infused Mice

One of the major features associated with CKD is renal fibrosis. To determine the critical role of elevated IL-6 in the

Figure 1. Interleukin 6 (IL-6) expression level is elevated in the kidneys of chronic kidney disease (CKD) patients and is further increased in CKD patients with hypertension. A, Immunohistochemistry study of IL-6 expression in control individuals with acute kidney rupture and CKD patients without and with hypertension. Microscopic examination revealed that IL-6 expression was significantly elevated in glomeruli and tubules of kidneys of CKD patients without hypertension and additionally elevated in CKD patients with hypertension. Scale bar=400 μm. B, Semi-quantitative analysis of IL-6 expression levels in the kidney biopsies from controls and CKD patients with or without hypertension. The average densities ±SEM of 25 areas per kidney were determined. n=15 to 48 kidneys for each category. *P<0.05 vs control with acute kidney rupture, **P<0.05 vs CKD without hypertension.

Figure 2. Elevated interleukin 6 (IL-6) mRNA in the kidneys contributes to proteinuria in angiotensin II (Ang II)–infused mice. Wild-type (WT) and IL-6–deficient mice were infused with Ang II for 2 weeks. A, IL-6 mRNA was elevated in the kidneys of Ang II–infused mice after 2 week of Ang II infusion. B and C, Albumin and creatinine concentrations were measured in 24-hour collected mouse urine of the WT and IL-6–deficient mice on day 7 (B) and day 14 (C) with or without Ang II infusion. Data are expressed as mean±SEM (n=6). *P<0.05 vs WT mice. **P<0.05 vs Ang II–infused WT mice.
progression of renal fibrosis, histological studies were conducted to characterize the renal fibrosis in each group of mice described above on day 14 of Ang II infusion. Analysis of hematoxylin-eosin–stained sections from Ang II–infused mice revealed extensive renal damage (Figure 3A). The majority of the glomeruli seen in these mice demonstrated decreased Bowman space, decreased capillary lumen, and mesangial hypercellularity (Figure 3A, top). Masson trichrome staining showed significant fibrosis in both glomeruli and interstitial areas between tubules (Figure 3A, bottom). Quantitative image analysis showed significantly increased collagen staining in kidneys of Ang II–infused mice (Figure 3B). Consistent with histological studies, total collagen measurements of the kidneys of Ang II–infused mice were significantly elevated (Figure 3C). In contrast, the Ang II–induced renal fibrosis, collagen staining, and total collagen content were significantly reduced in IL-6–deficient mice (Figure 3). Taken together, these results demonstrate that increased IL-6 contributes to Ang II–induced renal fibrosis.

**Ang II–Induced Hypertension Depends on IL-6 and Occurs Before Proteinuria and Kidney Fibrosis**

In addition to renal injury and fibrosis, we also monitored hypertension (a key feature associated with CKD) in the Ang II–infused mice. We found that in wild-type mice systolic blood pressure began to increase by day 3, increased significantly by day 7, reached a peak by day 10, and continuously maintained high blood pressure through the end of 2-week Ang II infusion (Figure 4A). Thus, these findings demonstrate that Ang II–induced hypertension occurred before proteinuria and subsequent renal fibrosis, which were significantly induced in wild-type mice after 14 days of Ang II infusion (Figure 2B). Next, we found that genetic deletion of IL-6 in mice led to a significant reduction of Ang II–induced hypertension (Figure 4A). Consistent with tail-cuff measurements, we showed that IL-6 deficiency significantly attenuated Ang II–induced intracarotid mean arterial pressure in anesthetized mice on day 14 of infusion with Ang II (Figure 4B). Taken together, these results provide direct evidence that increased IL-6 plays an important role in Ang II–induced hypertension and the associated proteinuria and progression to renal fibrosis.

**Elevated IL-6 Is Responsible for Increased Fibrotic Mediator Gene Expression in the Kidneys of Ang II–Infused Mice**

To determine whether IL-6–mediated renal fibrosis in Ang II–infused mice is associated with an induction of genes encoding fibrotic mediators, we measured gene expression profiles of the renal tissue of both wild-type and IL-6–deficient mice with or without Ang II infusion. We found that the expression of fibrotic marker genes, including procollagen I, transforming growth factor-β, and plasminogen activator inhibitor-1 mRNAs, were significantly increased in the kidneys of Ang II–infused mice (Figure 5). In contrast,
genetic deficiency in IL-6 significantly decreased the elevated profibrotic gene expression in the kidneys of Ang II–infused mice (Figure 5). These results reveal that Ang II–induced renal fibrosis is associated with increased expression of fibrotic marker genes in the kidney.

IL-6 Underlies Increased PreproET-1 mRNA Levels and ET-1 Production in the Kidneys of Ang II–Infused Mice

ET-1 is a 21-amino acid peptide and a key mediator of vascular tone and renal function. Elevated ET-1 signaling is associated with hypertension, proteinuria, and kidney fibrosis,28–32 and Ang II is known to induce its production.33,34 However, the molecules functioning downstream of Ang II responsible for ET-1 induction and subsequent hypertension and kidney damage are largely unidentified. Because we found that IL-6 played an important role in Ang II–induced hypertension, renal injury, and fibrosis, it is possible that elevated IL-6 in the kidney may underlie the induction of ET-1 by Ang II. To test this hypothesis, we first measured preproET-1 mRNA levels in the kidneys of both wild-type mice and IL-6–deficient mice with or without Ang II infusion. We found that the expression of preproET-1 was significantly increased in the kidneys of Ang II–infused mice (Figure 6A). In addition, using a sensitive ELISA, we confirmed that Ang II–induced preproET-1 mRNA led to an elevated ET-1 production in the mouse kidneys with Ang II (Figure 6B). Consistently, immunostaining revealed that ET-1 was highly expressed in endothelial cells and epithelial cells of renal tubules (Figure 6C). Image quantification indicated that ET-1 levels were significantly elevated in both glomeruli and tubules of Ang II–infused mice (Figure 6D). Strikingly, genetic deletion of IL-6 significantly decreased preproET-1 mRNA levels and ET-1 levels in the kidneys of Ang II–infused mice (Figure 6A). These results demonstrate that IL-6 is a downstream signaling molecule that contributes to Ang II–mediated induction of elevated ET-1 production in the kidney.

IL-6 Contributes to Ang II–Induced Expression of Profibrotic Marker Genes and the PreproET-1 Gene in Cultured Mouse Kidney Explants

To determine whether IL-6 is a potential mediator of Ang II–induced fibrosis and preproET-1 gene expression in the kidney, we performed experiments using kidney organ cultures. Specifically, we isolated kidneys from wild-type mice and IL-6–deficient mice and incubated renal explants in the presence or absence of Ang II for 24 hours. We found that Ang II directly induced plasminogen activator inhibitor-1, procollagen I, transforming growth factor-β, and preproET-1 mRNA levels (Figure 7). Consistent with in vivo findings, we found that genetic deletion of IL-6 significantly abolished the Ang II–induced procollagen I, plasminogen activator inhibitor-1, transforming growth factor-β, and preproET-1 mRNA production in the kidney cultures (Figure 7). Consistent with these genetic studies, we found that blockade with neutralizing antibodies for IL-6 or gp130 (coreceptor for IL-6 receptor activation), but not isotype control antibodies, significantly attenuated Ang II–induced fibrotic gene expression.
and preproET-1 mRNA levels in the cultured kidney explants isolated from wild-type mice (Figure 7). Taken together, the studies demonstrate that the IL-6 directly contributes to Ang II–induced expression of profibrotic genes and the preproET-1 gene in cultured mouse kidneys.

**IL-6 Is Essential for Ang II–Induced PreproET-1 mRNA Production in Cultured Human Endothelial Cells**

We found that IL-6 is significantly elevated in the kidneys of CKD patients (Figure 1) and that elevated IL-6 contributes to ET-1 production in Ang II–infused mice. Furthermore, ET-1 expression was significantly elevated in the endothelial cells of the capillary lumens of kidneys of Ang II–infused mice (Figure 6B), suggesting that endothelial cells are a major cell type responsible for Ang II–induced ET-1 production. To determine whether Ang II can induce ET-1 production in endothelial cells, we selected human microvascular endothelial cells as a model in vitro system. We found that Ang II was capable of inducing IL-6 gene expression in cultured human microvascular endothelial cells (Figure 8A). Importantly, we found that Ang II–induced preproET-1 mRNA expression was significantly attenuated by either anti–IL-6 or anti-gp130 (IL-6 coreceptor) neutralizing antibodies but not by isotype control antibodies (Figure 8B). Thus, we provide human evidence that Ang II can directly induce IL-6 expression and that elevated IL-6 is essential for Ang II–induced preproET-1 mRNA production in cultured human endothelial cells.

**Discussion**

In this study, we showed that IL-6 is elevated in the kidneys of CKD patients, and its level is further elevated in CKD patients with hypertension. We provided in vivo mouse evidence that IL-6 is an important cytokine that contributes to hypertension and multiple features of CKD including proteinuria and renal fibrosis in Ang II–infused mice. Additional studies show that IL-6 functions downstream of Ang II and contributes to upregulating the expression of multiple profibrotic genes ($\alpha_2$-procollagen, transforming growth factor-$\beta$, and plasminogen activator inhibitor-1) and the preproET-1 gene in the mouse kidney. Thus, in addition to the role of IL-6 in Ang II–induced hypertension, we have provided both in vivo and in vitro evidence that IL-6 contributes to Ang II–induced gene expression in the kidney. Overall, both the mouse and human studies reported here provide strong evidence that Ang II stimulates increased IL-6 production and that, in addition to its role in hypertension, increased IL-6 may play an important pathogenic role in CKD by inducing
fibrotic gene expression and ET-1 gene expression in the kidney. The increased inflammatory response associated with CKD is speculated to contribute to the pathogenesis of the disease.\textsuperscript{6, 9} For example, multiple in vitro studies have demonstrated that increased IL-6 production may lead to mesangial cell proliferation, leukocyte proliferation and infiltration, epithelial cell apoptosis, and endothelial cell damage that are relevant to the pathophysiology of the disease.\textsuperscript{35–37} However, the direct cause of the increased IL-6 production is unknown, and the pathogenic role of this cytokine in CKD is undetermined.\textsuperscript{17} The renin-angiotensin system is elevated in CKD patients,\textsuperscript{2, 38, 39} and infusion of Ang II into multiple species leads to hypertension, renal injury, and progression to renal fibrosis.\textsuperscript{26, 27} Here, using an Ang II infusion mouse model of hypertension and CKD, we have shown that Ang II leads to increased IL-6 production in the mouse kidney. Next, we found that genetic deletion of IL-6 significantly attenuates Ang II–induced hypertension and multiple features associated with CKD, including proteinuria, renal injury, and kidney fibrosis. In agreement with our mouse studies, we found that IL-6 levels were also elevated in the kidneys of CKD patients and that IL-6 levels were additionally elevated in the kidneys of CKD patients with hypertension. Finally, we provide evidence that Ang II can directly induce IL-6 expression in human endothelial cells and in mouse kidney explants. Thus, we have shown here for the first time that Ang II is a key mediator to induce IL-6 production in the kidney and that elevated IL-6 contributes to the enhanced expression of specific genes in the kidney that may directly contribute to the pathophysiology of CKD and progression to renal fibrosis.

The increased inflammatory response associated with CKD is speculated to contribute to the pathogenesis of the disease.\textsuperscript{6, 9} For example, multiple in vitro studies have demonstrated that increased IL-6 production may lead to mesangial cell proliferation, leukocyte proliferation and infiltration, epithelial cell apoptosis, and endothelial cell damage that are relevant to the pathophysiology of the disease.\textsuperscript{35–37} However, the direct cause of the increased IL-6 production is unknown, and the pathogenic role of this cytokine in CKD is undetermined.\textsuperscript{17} The renin-angiotensin system is elevated in CKD patients,\textsuperscript{2, 38, 39} and infusion of Ang II into multiple species leads to hypertension, renal injury, and progression to renal fibrosis.\textsuperscript{26, 27} Here, using an Ang II infusion mouse model of hypertension and CKD, we have shown that Ang II leads to increased IL-6 production in the mouse kidney. Next, we found that genetic deletion of IL-6 significantly attenuates Ang II–induced hypertension and multiple features associated with CKD, including proteinuria, renal injury, and kidney fibrosis. In agreement with our mouse studies, we found that IL-6 levels were also elevated in the kidneys of CKD patients and that IL-6 levels were additionally elevated in the kidneys of CKD patients with hypertension. Finally, we provide evidence that Ang II can directly induce IL-6 expression in human endothelial cells and in mouse kidney explants. Thus, we have shown here for the first time that Ang II is a key mediator to induce IL-6 production in the kidney and that elevated IL-6 contributes to the enhanced expression of specific genes in the kidney that may directly contribute to the pathophysiology of CKD and progression to renal fibrosis.

The increased inflammatory response associated with CKD is speculated to contribute to the pathogenesis of the disease.\textsuperscript{6, 9} For example, multiple in vitro studies have demonstrated that increased IL-6 production may lead to mesangial cell proliferation, leukocyte proliferation and infiltration, epithelial cell apoptosis, and endothelial cell damage that are relevant to the pathophysiology of the disease.\textsuperscript{35–37} However, the direct cause of the increased IL-6 production is unknown, and the pathogenic role of this cytokine in CKD is undetermined.\textsuperscript{17} The renin-angiotensin system is elevated in CKD patients,\textsuperscript{2, 38, 39} and infusion of Ang II into multiple species leads to hypertension, renal injury, and progression to renal fibrosis.\textsuperscript{26, 27} Here, using an Ang II infusion mouse model of hypertension and CKD, we have shown that Ang II leads to increased IL-6 production in the mouse kidney. Next, we found that genetic deletion of IL-6 significantly attenuates Ang II–induced hypertension and multiple features associated with CKD, including proteinuria, renal injury, and kidney fibrosis. In agreement with our mouse studies, we found that IL-6 levels were also elevated in the kidneys of CKD patients and that IL-6 levels were additionally elevated in the kidneys of CKD patients with hypertension. Finally, we provide evidence that Ang II can directly induce IL-6 expression in human endothelial cells and in mouse kidney explants. Thus, we have shown here for the first time that Ang II is a key mediator to induce IL-6 production in the kidney and that elevated IL-6 contributes to the enhanced expression of specific genes in the kidney that may directly contribute to the pathophysiology of CKD and progression to renal fibrosis.

The increased inflammatory response associated with CKD is speculated to contribute to the pathogenesis of the disease.\textsuperscript{6, 9} For example, multiple in vitro studies have demonstrated that increased IL-6 production may lead to mesangial cell proliferation, leukocyte proliferation and infiltration, epithelial cell apoptosis, and endothelial cell damage that are relevant to the pathophysiology of the disease.\textsuperscript{35–37} However, the direct cause of the increased IL-6 production is unknown, and the pathogenic role of this cytokine in CKD is undetermined.\textsuperscript{17} The renin-angiotensin system is elevated in CKD patients,\textsuperscript{2, 38, 39} and infusion of Ang II into multiple species leads to hypertension, renal injury, and progression to renal fibrosis.\textsuperscript{26, 27} Here, using an Ang II infusion mouse model of hypertension and CKD, we have shown that Ang II leads to increased IL-6 production in the mouse kidney. Next, we found that genetic deletion of IL-6 significantly attenuates Ang II–induced hypertension and multiple features associated with CKD, including proteinuria, renal injury, and kidney fibrosis. In agreement with our mouse studies, we found that IL-6 levels were also elevated in the kidneys of CKD patients and that IL-6 levels were additionally elevated in the kidneys of CKD patients with hypertension. Finally, we provide evidence that Ang II can directly induce IL-6 expression in human endothelial cells and in mouse kidney explants. Thus, we have shown here for the first time that Ang II is a key mediator to induce IL-6 production in the kidney and that elevated IL-6 contributes to the enhanced expression of specific genes in the kidney that may directly contribute to the pathophysiology of CKD and progression to renal fibrosis.

The increased inflammatory response associated with CKD is speculated to contribute to the pathogenesis of the disease.\textsuperscript{6, 9} For example, multiple in vitro studies have demonstrated that increased IL-6 production may lead to mesangial cell proliferation, leukocyte proliferation and infiltration, epithelial cell apoptosis, and endothelial cell damage that are relevant to the pathophysiology of the disease.\textsuperscript{35–37} However, the direct cause of the increased IL-6 production is unknown, and the pathogenic role of this cytokine in CKD is undetermined.\textsuperscript{17} The renin-angiotensin system is elevated in CKD patients,\textsuperscript{2, 38, 39} and infusion of Ang II into multiple species leads to hypertension, renal injury, and progression to renal fibrosis.\textsuperscript{26, 27} Here, using an Ang II infusion mouse model of hypertension and CKD, we have shown that Ang II leads to increased IL-6 production in the mouse kidney. Next, we found that genetic deletion of IL-6 significantly attenuates Ang II–induced hypertension and multiple features associated with CKD, including proteinuria, renal injury, and kidney fibrosis. In agreement with our mouse studies, we found that IL-6 levels were also elevated in the kidneys of CKD patients and that IL-6 levels were additionally elevated in the kidneys of CKD patients with hypertension. Finally, we provide evidence that Ang II can directly induce IL-6 expression in human endothelial cells and in mouse kidney explants. Thus, we have shown here for the first time that Ang II is a key mediator to induce IL-6 production in the kidney and that elevated IL-6 contributes to the enhanced expression of specific genes in the kidney that may directly contribute to the pathophysiology of CKD and progression to renal fibrosis.

The increased inflammatory response associated with CKD is speculated to contribute to the pathogenesis of the disease.\textsuperscript{6, 9} For example, multiple in vitro studies have demonstrated that increased IL-6 production may lead to mesangial cell proliferation, leukocyte proliferation and infiltration, epithelial cell apoptosis, and endothelial cell damage that are relevant to the pathophysiology of the disease.\textsuperscript{35–37} However, the direct cause of the increased IL-6 production is unknown, and the pathogenic role of this cytokine in CKD is undetermined.\textsuperscript{17} The renin-angiotensin system is elevated in CKD patients,\textsuperscript{2, 38, 39} and infusion of Ang II into multiple species leads to hypertension, renal injury, and progression to renal fibrosis.\textsuperscript{26, 27} Here, using an Ang II infusion mouse model of hypertension and CKD, we have shown that Ang II leads to increased IL-6 production in the mouse kidney. Next, we found that genetic deletion of IL-6 significantly attenuates Ang II–induced hypertension and multiple features associated with CKD, including proteinuria, renal injury, and kidney fibrosis. In agreement with our mouse studies, we found that IL-6 levels were also elevated in the kidneys of CKD patients and that IL-6 levels were additionally elevated in the kidneys of CKD patients with hypertension. Finally, we provide evidence that Ang II can directly induce IL-6 expression in human endothelial cells and in mouse kidney explants. Thus, we have shown here for the first time that Ang II is a key mediator to induce IL-6 production in the kidney and that elevated IL-6 contributes to the enhanced expression of specific genes in the kidney that may directly contribute to the pathophysiology of CKD and progression to renal fibrosis.

Figure 7. Direct effects of interleukin 6 (IL-6) on angiotensin II (Ang II)–induced fibrotic and prepro-endothelin (ET)-1 gene expression in cultured mouse kidney explants. Analysis of \( \alpha_2 \)-procollagen (A), transforming growth factor (TGF)-\( \beta \) (B), plasminogen activator inhibitor-1 (pai-1) (C), and preproET-1 (D) by quantitative RT-PCR in cultured kidney explants isolated from wild-type (WT) and IL-6–deficient mice in response to Ang II treatment. Some of the kidney explants from WT mice were treated with or without Ang II in the presence or absence of neutralizing antibodies to IL-6, gp130 (IL-6 coreceptor), or isotype control antibody. Data are expressed as mean±SEM. *\( P<0.05 \) vs without Ang II treatment. **\( P<0.05 \) vs WT treated with Ang II (\( n=4–6 \)).
Although earlier studies showed that IL-6 deficiency attenuated Ang II–induced hypertension, the pathogenic mechanisms underlying these effects have not been clearly identified. Here, we showed that Ang II–induced preproET-1 mRNA expression and ET-1 protein levels in mouse kidney were significantly reduced in IL-6–deficient mice. Similarly, we found that Ang II–induced preproET-1 gene expression was significantly attenuated by IL-6 and gp-130 neutralizing antibodies in cultured human microvascular endothelial cells. Thus, both in vivo mouse studies and in vitro human studies revealed a previously unrecognized role for IL-6 in Ang II–induced ET-1 production. ET-1 is a downstream mediator known to be responsible for Ang II–induced hypertension. Therefore, our findings lead to a novel hypothesis that IL-6–mediated ET-1 elevation in the kidney contributes to Ang II–induced hypertension and renal injury seen in CKD. Our studies are supported by earlier findings showing that IL-6 deficiency attenuated Ang II–induced hypertension in nonpregnant mice, and knocking down IL-6 by RNA interference ameliorated cold-induced hypertension in non-pregnant rats. Consistently, earlier studies using pregnant rats showed that chronic infusion of IL-6 led to hypertension and reduced renal function. However, these effects mediated by IL-6 infusion were only seen in the pregnant rats but not in virgin rats and did not involve induction of ET-1 in the kidneys of pregnant rats, suggesting that IL-6–induced preeclamptic features in the rats are pregnancy dependent and ET-1 independent. Nevertheless, our studies in mice provide strong genetic evidence that IL-6 is a key cytokine stimulating ET-1 production from the kidney and contributes to Ang II–induced hypertension and kidney injury.

In addition to hypertension and kidney injury, renal fibrosis is a common progressive feature seen in CKD. Without interference, it will eventually lead to chronic renal failure. Thus, understanding the molecular basis of progression of renal fibrosis in CKD is extremely important. Using both intact animals and isolated kidney cultures, we provide new evidence for mechanisms that may underlie Ang II–induced renal fibrosis. Our in vivo and in vitro studies reveal an important role for IL-6 in Ang II–mediated induction of multiple fibrotic genes in the mouse kidney. Overall, our findings show that IL-6 is an important downstream mediator of Ang II signaling and contributes not only to hypertension but also to Ang II–mediated induction of gene expression in the kidney. Specifically, IL-6 contributes to Ang II–mediated induction of multiple fibrotic genes and ET-1 production in the kidneys, and in this way may contribute to renal injury and renal fibrosis (Figure 8C). The research reported here provides new insight regarding the pathogenesis of CKD and provides a foundation for future clinical trials to treat CKD, a life-threatening disorder with limited therapeutic options.

**Perspectives**

Taken together, our studies identified Ang II as a candidate responsible for the elevated expression of IL-6 in the kidneys of patients with CKD. Both human and mouse studies demonstrated that this inflammatory cytokine plays an important role in the pathogenesis of Ang II–induced hypertension and CKD and its progression. Of significant importance, genetic deletion or pharmacological neutralization of IL-6 reduces hypertension and renal impairment in Ang II–infused mice. In addition, Ang II–induced ET-1 production is significantly inhibited by blockade of IL-6 and its coreceptor antigp130 in human endothelial cells. Taken together, these findings support a central role of IL-6 in Ang II–induced hypertension and kidney injury.

Figure 8. Interleukin 6 (IL-6) functions via its receptor responsible for angiotensin II (Ang II)–induced prepro-endothelin (ET)-1 mRNA elevation in culture human endothelial cells. A, Ang II increased the expression of IL-6 mRNA in cultured human microvascular endothelial cells (HMECs). B, Ang II–mediated induction of preproET-1 mRNA in HMECs was inhibited by neutralizing antibodies to IL-6 or gp130 but not isotype control antibodies. C, A model depicting the potential role of elevated IL-6 signaling in Ang II–induced chronic kidney disease (CKD). Ang II stimulates increased production of IL-6. In addition to its role in hypertension, increased IL-6 may play an important pathogenic role in CKD by directly stimulating fibrotic gene expression and preproET-1 mRNA levels via IL-6 receptor activation.
hypertension and draw attention to a potentially direct contribution of IL-6 to renal dysfunction and subsequent development of renal fibrosis resulting from the induction of profibrotic genes and increased production of ET-1. These findings have revealed novel therapeutic possibilities by targeting these signaling pathways.

Sources of Funding
This work was supported by National Institutes of Health grants DK077748 (to Y.X.), DK083559 (to Y.X.), and RC4HD067977 (to Y.X. and R.E.K.); American Heart Association grant 10GRNT3760081 (to Y.X.); and China Scholarship Council 2009637520 (to W.Z.).

Disclosures
None.

References
Interleukin 6 Underlies Angiotensin II–Induced Hypertension and Chronic Renal Damage
Weiru Zhang, Wei Wang, Hong Yu, Yujin Zhang, Yingbo Dai, Chen Ning, Lijian Tao, Hong Sun, Rodney E. Kellems, Michael R. Blackburn and Yang Xia

Hypertension. 2012;59:136-144; originally published online November 7, 2011;
doi: 10.1161/HYPERTENSIONAHA.111.173328
Hypertension is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2011 American Heart Association, Inc. All rights reserved.
Print ISSN: 0194-911X. Online ISSN: 1524-4563

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://hyper.ahajournals.org/content/59/1/136

Data Supplement (unedited) at:
http://hyper.ahajournals.org/content/suppl/2011/11/04/HYPERTENSIONAHA.111.173328.DC1

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Hypertension can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Hypertension is online at:
http://hyper.ahajournals.org//subscriptions/
Online Supplementary Methods for

Interleukin-6 Underlies Angiotensin II-induced Hypertension and Chronic Renal Damage

By

Weiru Zhang\textsuperscript{1,2}, Wei Wang\textsuperscript{1,2}, Hong Yu\textsuperscript{3}, Yujin, Zhang\textsuperscript{1}, Yingbo Dai\textsuperscript{4}, Chen Ning\textsuperscript{1,5}, Lijian, Tao\textsuperscript{2}, Hong Sun\textsuperscript{6}, Rodney E. Kellems\textsuperscript{1}, Michael R. Blackburn\textsuperscript{1}, and Yang Xia\textsuperscript{1*}

Departments of \textsuperscript{1}Biochemistry and Molecular Biology, The University of Texas - Houston Medical School, Houston, TX, \textsuperscript{2}Nephrology, \textsuperscript{5}Urology and \textsuperscript{6}Otorhinolaryngology, The First Xiangya Hospital of Central South University, \textsuperscript{3}Pathology, Hunan Provincial People’s Hospital, \textsuperscript{4}Urology, The Third Xiangya Hospital of Central South University, Changsha, Hunan

Running title:
IL-6 in hypertension and chronic renal damage

*Correspondence: Dr. Yang Xia,
Tel: 713-500-5039; Fax: 713-500-0652; Email: yang.xia@uth.tmc.edu
**Histological analysis**

Kidneys were harvested from the mice, fixed in 4% formaldehyde, dehydrated, and embedded in paraffin. Sections of 4 µm were cut, stained with haematoxylin and eosin (H&E) or Masson’s trichrome, according to the manufacturer’s instructions (Shardon-Lipshaw) as described. 1,2

**Morphometric analysis of the renal fibrosis in Masson's trichrome stained sections**

Ten consecutive non-overlapping fields of a mouse kidney stained with the Trichrome were analyzed. The fibrotic areas stained in light blue were picked up on the digital images using a computerized densitometry (ImagePro Plus, version 6.0, Media Cybernetics, Silver Spring, MD, USA) coupled to a microscope equipped with a digital camera as described.1-3 The percentage of the fibrotic area relative to the whole area of the field was calculated (percent fibrosis area). The average densities of ten areas per kidney were averaged and the SEM is indicated and n = 4-6 kidneys for each category.

**ET-1 Immunohistochemistry in the mouse kidneys and quantification.**

Immunohistochemistry for ET-1 was carried out with the formalin fixed tissues. Sections of 4µm were cut and mounted on glass slides, deparaffinized through serial baths in xylene and rehydrated in a graded series of alcohol and distilled water. Endogenous peroxidase activity was quenched by 10 min of incubation in a 3% hydrogen peroxide/methanol buffer. Antigen retrieval was enhanced by autoclaving slides in sodium citrate buffer (pH 6.0) at 95°C for 15 min. Next, endogenous avidin and biotin blocking was performed with a Biotin Blocking System (Dako). The slides were then incubated with rabbit anti human ET-1 antibody (Sigma, 1:100 dilution) in a humidified chamber at 4°C overnight. After the primary antibody incubation, anti-rabbit IgG ABC staining system kit (VECTOR LAB, USA) was used. For negative controls, the primary antibody was replaced with the corresponding affinity-purified pre-immune IgG. Quantification of the immunohistochemical staining was performed using the Image-Pro Plus software (Media Cybernetics, Bethesda, MD). The density of the brown staining (positive for ET-1) was measured. The average densities of 25 areas per kidneys were averaged and the SEM is indicated. n=6 for each group.

**Collagen Quantification**

Soluble collagen levels were quantified in kidney tissues using the Sircol collagen assay (Biocolor, Belfast, N. Ireland) according to the manufacturer’s instructions.4

**Total RNA isolation and Real-time RT-PCR analysis**

Total RNA was isolated using TRIzol reagent (Invitrogen). RNase-free DNase (Invitrogen) was used to eliminate genomic DNA contamination. Transcript levels were quantified using real-time quantitative RT-PCR. Syber green was used for analysis of α2 (I) procollagen, plasminogen activator inhibitor-1 (Pai-1), TGF-β1, IL-6, ET-1 and β-actin using the following primers: mouse α2 (I) procollagen, forward, 5’- AGA CAT GCT CAG CTG TGT GGA TAC-3’ and reverse, 5’- GTACTGATCCCAGATTGCAAT-3’; mouse PAI-1, forward, 5’- AGTGATGGAGCCTGACAG- 3’ and reverse, 5’- AGGAGGAGTTGCCTTCTCTT-3’; mouse TGF-β1, forward, 5’- CCC CAC TGA TAC GCC TGA TAC GAG TGA -3’ and reverse, 5’- AGC CCT GTA
TTC CGT CTC CTT-3'; mouse IL-6, forward, 5’- TGG GAA ATC GTG GAA ATG AG-3’ and reverse, 5’-CTC TGA AGG ACT CTG GCT TTG -3’; mouse preproET-1, forward,5’-CTG CAC TCC ATT CTC AGC TCC-3’ and reverse, 5’-TTC CCG TGA TCT TCT CTC TGC -3’; mouse β-actin, forward, 5'- GGG AAT GGG TCA AAA CT-3’ and reverse, 5’- CTT CTC CAT GTC GTC CCA GT-3’; human preproET-1, forward,5’- CAG CAG TCT TAG GCG CTG AG-3’ and reverse, 5’- ACT CTT TAT CCA TCA GGG AGC AG-3’; human IL-6, forward,5’- AAATTCCGTACATCCTCGACGG-3’ and reverse, 5’- GGAAGTTACAGGTTGTTTTCTGC-3’; human β-actin, forward, 5’-TGA CCG GGT CAC CCA CAC TGT GCC CAT CTA-3’ and reverse, 5’-CTA GAA GCA TTT GCG GTG GAC GAT GGA GGG-3’

Isolation of kidney and organ culture

Kidneys were surgically isolated from wild type mice and IL-6-deficient mice. The isolated kidneys were washed in PBS, minced into 2-3 mm³ pieces and suspended in Dulbecco’s modified Eagle Medium (DMEM) containing 10% fetal bovine serum (FBS) and cultured in a humidified atmosphere of 5% CO2 at 37°C. After 24 hours in culture, tissues were serum-starved in DMEM without FBS and treated with various reagents including Ang-II (100nM) (Sigma), neutralizing antibodies for IL-6, gp130 (0.25 μg/ml, R&D Systems) and isotype antibodies. After 24-hour treatment, total RNA was isolated and quantitative RT-PCR was conducted as described above.

Cell culture

Human microvascular endothelial cell line (HMEC-1) was derived from dermal tissues and were harvested and cultured by a modification of methods described previously.5 HMEC-1 cells were passaged in 25 cm² culture flasks in 5% CO2 humidified air at 37°C in MCDB131 medium supplemented with 10% heat-inactivated fetal bovine serum (FBS), 100 U/ml penicillin, 100 U/ml streptomycin, 10ng/ml epidermal growth factor, 1ug/ml hydrocortisone and 2 mM L-glutamine (Invitrogen ,USA). Cells at Passages 10–15 were used for all experiments. Before experimental intervention, cultured cells at 85% confluency were switched to serum free medium and subsequently treated without or with Ang II at 100nM. Some of cells were treated with neutralizing antibodies for IL-6, gp130 or control isotype antibodies (0.25μg/ml, R&D Systems). After 24-hour treatment, total RNA was isolated and quantitative RT-PCR was conducted as described above.
References


