Hemodynamic and neural responses to renal denervation of the nerve to the clipped kidney by cryoablation in two-kidney, one-clip hypertensive rats

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Submitted 15 July 2015; accepted in final form 11 November 2015

Rossi NF, Pajewski R, Chen H, Littrup PJ, Maliszewska-Scislo M. Hemodynamic and neural responses to renal denervation of the nerve to the clipped kidney by cryoablation in two-kidney, one-clip hypertensive rats. Am J Physiol Regul Integr Comp Physiol 310: R197–R208, 2016. First published November 18, 2015; doi:10.1152/ajpregu.00331.2015.—Renal artery stenosis is increasing in prevalence. Angioplasty plus stenting has not proven to be better than medical management. There has been a reluctance to use available denervation methodologies in this condition. We studied conscious, chronically instrumented, two-kidney, one-clip (2K-1C) Goldblatt rats, a model of renovascular hypertension, to test the hypothesis that renal denervation by cryoablation (cryo-DNX) of the renal nerve to the clipped kidney decreases mean arterial pressure (MAP), plasma and tissue Ang II, and contralateral renal sympathetic nerve activity (RSNA). Five-week-old male Sprague-Dawley rats underwent sham (ShC) or right renal artery clipping (2K-1C), placement of telemetry transmitters, and pair-feeding with a 0.4% NaCl diet. After 6 wk, rats were randomly assigned to cryo-DNX or sham cryotreatment (sham DNX) of the renal nerve to the clipped kidney. MAP was elevated in 2K-1C and decreased significantly in both ShC cryo-DNX and 2K-1C cryo-DNX. Tissue norepinephrine was ~85% lower in cryo-DNX kidneys. Plasma Ang II was higher in 2K-1C sham DNX but not in 2K-1C cryo-DNX vs ShC. Renal tissue Ang II in the clipped kidney decreased after cryo-DNX. Baseline integrated RSNA of the unclipped kidney was threefold higher in 2K-1C versus ShC and decreased in 2K-1C cryo-DNX to values similar to ShC. Maximum reflex response of RSNA to baroreceptor unloading in 2K-1C was lower after cryo-DNX. Thus, denervation by cryoablation of the renal nerve to the clipped kidney decreases not only MAP but also plasma and renal tissue Ang II levels and RSNA to the contralateral kidney in conscious, freely moving 2K-1C rats.

angiotensin; baroreflex; Goldblatt kidney; renovascular hypertension; sympathetic nerve activity

ACTIVATION OF THE SYMPATHETIC NERVOUS SYSTEM plays an important role in the development and maintenance of several forms of human hypertension (16, 23, 53) and animal hypertension (31, 42, 45, 46). Specifically, neuroexcitation contributes to the high arterial pressure and high plasma renin and angiotensin II (ANG II) levels in the two-kidney, one-clip (2K-1C) Goldblatt rat, a model of renovascular hypertension (17, 26, 39, 51). Early in the course of 2K-1C hypertension, renin secretion by the clipped kidney increases, and that of the contralateral kidney is suppressed by the elevated blood pressure. Approximately 6 wk after the renal artery was clipped, the elevated arterial pressure transitions from a primarily renin-independent to a more neurogenically mediated mechanism (40).

Stimulation of the renal sympathetic nerves results in renin secretion as well as renal tubular sodium reabsorption (4, 34). Inhibitory renorenal reflexes are impaired in 2K-1C rats, thereby leading to enhanced effluent renal sympathetic nerve activity (RSNA) and urinary sodium retention (30). Denervation of the clipped kidney by surgical transection of the nerve with application of phenol to the nerve and artery of the clipped kidney interrupts nerve activity to the ischemic kidney. In addition, physiological indices consistent with diminished RSNA to the contralateral kidney such as renin secretion and renal sodium reabsorption are reduced (7, 19, 26, 28, 30, 50). Potential decreases in other sympathetic outputs resulting from interruption of afferent signals from the kidney may result in vasodilatation of other vascular beds as well (32). Except for one study showing decreased RSNA in the contralateral kidney only 1.5 h after recovery from anesthesia (30), direct measurements of contralateral RSNA, certainly in fully awake and freely moving rats several days after recovery, have not been reported. Together, inhibition of the renin-angiotensin system, higher urinary sodium excretion, and vasodilatation of selective vascular beds contribute to the reduction in arterial pressure observed with renal denervation of the stenotic kidney.

Over the last few years, renal sympathetic denervation for uncontrolled essential hypertension in humans has become an area of intense study (6, 33, 53), but significant renal artery stenosis has typically been an exclusion criterion (24). Importantly, renovascular hypertension due to atherosclerotic disease is increasing, with 20–54% prevalence in high-risk groups with diabetes mellitus, heart failure, or peripheral vascular disease (1, 15). Many such patients suffer from hypertension resistant to multidrug therapy (8). Nearly one-third of these individuals die within 5 yr, even with current interventional modalities (2). Moreover, angioplasty with or without stenting of the renal arteries has proven to be of little benefit in controlling arterial pressure, decreasing cardiac or renal events, or reducing mortality (2, 13, 61). A recent study in a limited number of patients who had already undergone renal artery stenting reported some success in further decreasing systolic pressure after radio frequency denervation (3). Given technical considerations such as avoiding the area near the stenosis and delivery of lower-power radio frequency energies, there is still concern as to whether renovascular patients are suitable for current approaches for renal sympathetic denervation (60).

Cryotherapies are used to ablate aberrant cardiac conduction pathways (52), treat malignancies (14), and ameliorate peripheral vascular disease (35). Therefore, it is possible that emerging endovascular cryotechnologies using very low tempera-

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tasures may successfully ablate renal sympathetic nerves (36). The present studies were designed as proof-of-principle experiments to test the hypothesis that cryotreatment of the renal nerve to the clipped kidney will decrease systemic arterial pressure, reduce plasma ANG II levels, and decrease contralateral RSNA in conscious, chronically instrumented 2K-1C hypertensive rats. Since changes in baseline arterial pressure as well as alteration in afferent inputs from the kidney could very well modulate the arterial baroreflex, whenever possible, the baroreflex response of RSNA before and after cryotreatment was assessed in the 2K-1C rats.

METHODS

Male Sprague-Dawley rats (Harlan Sprague Dawley, Indianapolis, IN) were used in all protocols. Rats were permitted to acclimate after being placed in the vivarium for a minimum of 3 days. They were housed under controlled conditions (ambient temperature 21–23°C, lights on from 0700 to 0900). They were permitted free access to water and standard rat chow containing 0.4% NaCl, except where noted by protocol. All rats were cared for in compliance with the National Institutes of Health’s Guide for the Care and Use of Laboratory Animals (8th edition, 2011). All procedures and protocols were reviewed and approved by the Wayne State University Institutional Animal Care and Use Committee.

Renal artery clipping. Five-week-old rats were anesthetized with an intraperitoneal injection of ketamine (80 mg/kg) and xylazine (8 mg/kg). Additional doses (25–50% of the initial dose) were administered if needed to maintain a plane of anesthesia. The right renal artery was exposed via a right flank incision and visualized under a stereomicroscope. The tip of the cryoprobe was carefully held under the nerve such that the tip was isolated from the tip of the cryoprobe (Endocare, Austin, TX). Rats were anesthetized with ketamine and xylazine as before. A right flank incision was made along the flank. The electrode wires from the transmitter were passed through this tunnel for subsequent placement. First, the catheter with the arterial pressure transducer was inserted into the left femoral artery and secured with sutures. Then, the left renal nerve was identified under a stereomicroscope. The nerve was carefully placed onto the exposed ends of the electrode wires from the transmitter. The silicone casing of the proximal ends of the wires was then stabilized by anchoring it with 6-0 sutures to the adventitia of the aortic wall. Placement of the electrodes and quality of the nerve signal were established by evaluating the nerve sound using an audio monitor and verified using an oscilloscope (Hameg, New Meadow, NY). Then, the nerve and electrodes were encased with silicone gel (Kwik-Sil; World Precision Instruments, Sarasota, FL). The muscles were then sutured closed in layers, and the body of the transmitter was inserted subcutaneously over the lower abdomen. The skin was closed with surgical staples. The rat was then returned to its home cage and permitted to recover.

Cryotreatment of the renal nerve. Cryotreatment was performed using the argon-based CryoCare system with a PERC-15 Percryo cryoprobe (Endocare, Austin, TX). Rats were anesthetized with ketamine and xylazine as before. A right flank incision was made along the scar from the previous surgery. The right renal nerve was identified and isolated under a stereomicroscope. The tip of the cryoprobe was carefully held under the nerve such that the tip was isolated from other tissues as the nerve lay on the tip. Freezing was initiated at 100% power. Once the probe temperature reached −155 ± 5°C, it was held for 30 s, followed by a thawing cycle (maximum temperature not exceeding 7°C) of 1 min. The freeze-thaw cycle was repeated a total of three times per side, for a total of 9 min. The clip typically being placed more proximal to the aorta and avoiding the hilus of the kidney. Shams clipped rat (ShC) underwent identical surgery, but no clip was placed. The flank incision was closed with surgical staples.

Hemodynamic radiotelemetry transmitter placement. Immediately after renal artery clipping was completed, the femoral artery was exposed via a groin incision and the proximal end occluded briefly so that the gel-filled catheter attached to the radiotelemetry transducer (TA11PA-C40; Data Sciences International, St. Paul, MN) could be inserted into the artery and then advanced into the distal aorta. The catheter was secured with medical adhesive and the transmitter device placed subcutaneously and secured to the underlying muscle. The skin was closed with surgical staples. The rat then received a dose of buprenorphine SR (0.3 mg/kg ip) for analgesia. Each rat was returned to its home cage with its individual receiver and permitted to recover for 3 days prior to hemodynamic recordings being initiated.

Dual hemodynamic and renal nerve radiotelemetry transmitter placement. Rats were anesthetized with pentobarbital sodium (50 mg/kg ip). If required, supplemental doses were given as needed. The telemetry unit (Telemetry Research TR-463, Auckland, New Zealand), which has both blood pressure and nerve electrode components, was placed using a modification of the technique described by Stocker and Munzel (57). Briefly, two incisions were made: one over the left flank and the other in the left groin. A separate venous catheter was first inserted into the left femoral vein, secured, and then tunneled subcutaneously and exteriorized posteriorly at the base of the neck. To maintain patency, the catheter was filled with heparinized saline (100 U/ml). Then, a tunnel was made subcutaneously from the femoral area to the flank. The electrode wires from the transmitter were passed through this tunnel for subsequent placement. First, the catheter with the arterial pressure transducer was inserted into the left femoral artery and secured with sutures. Then, the left renal nerve was identified under a stereomicroscope. The nerve was carefully placed onto the exposed ends of the electrode wires from the transmitter. The silicone casing of the proximal ends of the wires was then stabilized by anchoring it with 6-0 sutures to the adventitia of the aortic wall. Placement of the electrodes and quality of the nerve signal were established by evaluating the nerve sound using an audio monitor and verified using an oscilloscope (Hameg, New Meadow, NY). Then, the nerve and electrodes were encased with silicone gel (Kwik-Sil; World Precision Instruments, Sarasota, FL). The muscles were then sutured closed in layers, and the body of the transmitter was inserted subcutaneously over the lower abdomen. The skin was closed with surgical staples. The rat was then returned to its home cage and permitted to recover.

Table 1. Body weights, kidney weights, and cortical NE content in the 4 groups of rats in protocol 1

<table>
<thead>
<tr>
<th>Group</th>
<th>Body Weight g</th>
<th>Left Kidney Weight, g</th>
<th>Right Kidney Weight, g</th>
<th>Left Kidney NE, ng/g</th>
<th>Right Kidney NE, ng/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>ShC sham cryo</td>
<td>442 ± 10</td>
<td>1.291 ± 0.098</td>
<td>1.278 ± 0.087</td>
<td>100 ± 6</td>
<td>92 ± 6</td>
</tr>
<tr>
<td>ShC cryo-DNX</td>
<td>446 ± 6</td>
<td>1.267 ± 0.024</td>
<td>1.273 ± 0.083</td>
<td>106 ± 6</td>
<td>16 ± 4*†</td>
</tr>
<tr>
<td>2K-1C sham cryo</td>
<td>415 ± 8</td>
<td>1.264 ± 0.030</td>
<td>1.146 ± 0.026*</td>
<td>88 ± 8</td>
<td>82 ± 8</td>
</tr>
<tr>
<td>2K-1C cryo-DNX</td>
<td>432 ± 15</td>
<td>1.369 ± 0.201</td>
<td>1.181 ± 0.038*</td>
<td>104 ± 11</td>
<td>24 ± 6*†</td>
</tr>
</tbody>
</table>

Values are means ± SE. NE, norepinephrine; ShC, sham clipped; 2K-1C, two-kidney, one-clip; DNX, denervated; cryo-DNX, cryotreatment; sham cryo, sham cryotreatment. *P < 0.05 vs. left kidney; †P < 0.001 vs. corresponding sham cryo-DNX group.
of three times (cryo-DNX). Then, the muscle and skin layers were closed. Sham-treated rats underwent the same procedures, but without freezing or thawing (sham DNX). Rats were returned to their home cages and received acetaminophen (6 mg/ml) in their drinking water for 3 days for analgesia to avoid potential effects of long-acting opioids on blood pressure.

**Protocol 1.** The experimental design in protocol 1 is depicted in Fig. 1. All protocol measurements were performed on conscious rats. After renal artery clipping or sham clipping completed, rats were returned to their home cages. Five and a half weeks later, each rat was equipped with a dual hemodynamic and renal nerve telemetry transmitter and a venous catheter for infusions. Arterial pressure, heart rate, and RSNA were recorded daily from 0800 to 1200 via a TR161 receiver. Data was digitized, recorded, and analyzed using an analog-to-digital converter and software platform (Power Lab 8/30 and LabChart Pro 7; ADInstruments, Colorado Springs, CO). Four days after placement of the transmitter, ShC and 2K-1C rats then underwent either cryotreatment or sham cryotreatment of the right renal nerve. This resulted in four groups: ShC cryo-DNX, ShC sham DNX, 2K-1C cryo-DNX, and 2K-1C sham DNX. Recording of hemodynamic and RSNA parameters continued for }\pm 10 days or until the nerve recording lost fidelity. Values for RSNA were used only for analysis from day 3 after surgery to permit full recovery from anesthesia. In addition, RSNA was monitored daily, and if the recording failed on a given day (e.g., day 6), values only from }\geq 24 h prior to the failure (day 4) were used to ensure validity. On average, our nerve activity lasted 5 days.

Baroreflex testing of the heart rate and RSNA responses was performed on unrestricted, conscious 2K-1C rats in their home cages 2 days prior to and 3 days after cryo or sham treatment of the renal nerve. Baroreflex curves were generated by inducing ramp decreases and increases in arterial pressure. Nitroprusside (200 }\mu g/ml; Ohmeda) was infused intravenously at an increasing rate of 7.5–100 }\mu g·kg}\(^{-1}\)·min\(^{-1}\) and phenylephrine at 5–50 }\mu g·kg}\(^{-1}\)·min\(^{-1}\) (200 }\mu g/ml; Sigma Aldrich, St. Louis, MO) so as to result in a ramp decrease or increase, respectively, over a 2-min period. Fifteen to 30 min were permitted between infusions for all parameters to return to baseline values. At the end of each experiment, trimethaphan camsylate (20 }\mu g/ml; Sigma Aldrich) was infused intravenously to stop the recording and stop any ongoing responses. After completion of the experiment, rats were sacrificed by an overdose of pentobarbital. Blood pressure was measured by telemetry 1 day prior to and daily for 7 days after cryo- or sham treatment of the renal nerve to the clipped kidney in 2K-1C and ShC rats. ShC sham DNX (n = 11), ShC cryo-DNX (n = 9), 2K-1C sham DNX (n = 9), and 2K-1C Cryo-DNX (n = 11). *P < 0.05 vs. baseline day –1.

**Fig. 2.** Changes in mean arterial pressure (MAP; A) and heart rate (HR; B) as measured by telemetry 1 day prior to and daily for 7 days after cryo- or sham treatment of the renal nerve to the clipped kidney in 2K-1C and ShC rats. ShC sham DNX (n = 11), ShC Cryo-DNX (n = 9), 2K-1C sham DNX (n = 9), and 2K-1C Cryo-DNX (n = 11). *P < 0.05 vs. baseline day –1.

For comparison with previously published data regarding renal tissue ANG II in 2K-1C rats (44), separate groups of sham clipped and 2K-1C rats were anesthetized as above, and renal cortical tissue was taken for assessment of tissue ANG II 1 wk after sham or renal artery clipping.

**Protocol 2.** After renal artery clipping or sham clipping was completed, rats were returned to their home cages. Five and a half weeks later, each rat was equipped with a dual hemodynamic and renal nerve telemetry transmitter and a venous catheter for infusions. Arterial pressure, heart rate, and RSNA were recorded daily from 0800 to 1200 via a TR161 receiver. Data was digitized, recorded, and analyzed using an analog-to-digital converter and software platform (Power Lab 8/30 and LabChart Pro 7; ADInstruments, Colorado Springs, CO). Four days after placement of the transmitter, ShC and 2K-1C rats then underwent either cryotreatment or sham cryotreatment of the right renal nerve. This resulted in four groups: ShC cryo-DNX, ShC sham DNX, 2K-1C cryo-DNX, and 2K-1C sham DNX. Recording of hemodynamic and RSNA parameters continued for }\pm 10 days or until the nerve recording lost fidelity. Values for RSNA were used only for analysis from day 3 after surgery to permit full recovery from anesthesia. In addition, RSNA was monitored daily, and if the recording failed on a given day (e.g., day 6), values only from }\geq 24 h prior to the failure (day 4) were used to ensure validity. On average, our nerve activity lasted 5 days.

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**Fig. 3.** MAP by telemetry averaged over the 3 days prior to cryotreatment (open bars) and 3 wk later averaged over the 3 days prior to euthanasia (black bars); sham treatment (sham DNX) or cryotreatment (Cryo-DNX) of the renal nerve to the clipped kidney in 2K-1C rats or the sham clipped kidney in ShC rats, respectively. Values are means }\pm SE; n = 11, 9, 9, and 11. *P < 0.01 vs. the corresponding ShC group; †P < 0.05 vs. before cryo-DNX (same group); §§P < 0.05 vs. 2K-1C sham DNX posttreatment.
mg/kg iv; Hoffman-La Roche) was administered as a bolus dose to assess background noise.

**Plasma and urinary measurements.** Urine volume was measured gravimetrically. Plasma and urinary sodium concentrations were measured by flame photometry (Model 2655-10; Cole-Parmer, Vernon Hills, IL). Creatinine in plasma and urine was measured using a gravimetric method. Plasma and urinary sodium concentrations were measured by flame photometry (Model 2655-10; Cole-Parmer, Vernon Hills, IL). Creatinine clearance (A), 24-h protein excretion on day 4 (B), and Na intake (C) and Na excretion (D) on days 1–4. Values are means ± SE.

**Analyses and statistics.** Heart rate and arterial pressure were averaged over 7 consecutive days unless specified otherwise. Resting integrated RSNA consisted of 1-s sequential averages over the 4-h recording period. Values were expressed as means ± SE. Protocol 1 was designed to assess a difference of 10 mmHg with a standard deviation of 5 mmHg, with 95% power at an α-level of 0.05, thus requiring nine rats per group. The study in protocol 2 was powered to assess a 50% change in resting integrated RSNA of the 2K-1C group (~4.5 μV/s with a standard deviation of 2 μV/s) 3 days after cryotreatment, with 95% power and an α-level of 0.05, thus requiring four rats per group. Comparison with baseline values in the same animal was accomplished by using the paired t-test. Comparisons among groups were made by one-way ANOVA followed by Tukey-Kramer analysis. Comparison with baseline over time among groups was done by two-way ANOVA followed by Dunnett’s test.

**Fig. 4. Renal parameters in ShC sham DNX (n = 11), ShC Cryo-DNX (n = 9), 2K-1C sham DNX (n = 9), and 2K-1C Cryo-DNX (n = 11) in metabolic cages.** Creatinine clearance (A), 24-h protein excretion on day 4 (B), and Na intake (C) and Na excretion (D) on days 1–4. Values are means ± SE.

**Fig. 5. Plasma ANG II values in ShC sham DNX (n = 11), ShC Cryo-DNX (n = 9), 2K-1C sham DNX (n = 9), and 2K-1C Cryo-DNX (n = 11) at the end of the protocol (week 9).** Values are means ± SE. *P < 0.001 vs. both ShC groups; †P < 0.001 vs 2K-1C sham DNX.
Body weights did not differ among the groups. The right kidney weights were significantly lower in the 2K-1C sham cryo-DNX rats compared with ShC rats. MAP averaged over days 18–21 after cryotreatment of the nerve to the clipped kidney decreased MAP significantly in 2K-1C rats. Notably, ShC cryo-DNX rats also displayed a significant decrease in MAP by the end of the 3 wk.

Three weeks after sham or cryotreatment, tissue norepinephrine values from the right kidney were significantly lower in both ShC and 2K-1C cryo-treated groups (Table 1). Thus, renal tissue norepinephrine content was ~85% lower in the cryo-treated kidney compared with either the corresponding sham cryo-treated kidney or the contralateral kidney in the same rat. In a separate set of rats, tissue norepinephrine content was 86 ± 3% lower at 1 wk (n = 5) and 81 ± 3% (n = 7) at 3 wk after cryotreatment of the renal nerve.

Creatinine clearance and protein excretion were similar among the groups (Fig. 4, A and B). Sodium intake and urinary sodium excretion did not change over the 4 days of measurement and were similar among the groups (Fig. 4, C and D). After completion of the metabolic studies, MAP remained significantly lower in the 2K-1C cryo-DNX rats compared with pretreatment MAP (~16 ± 5 mmHg, P < 0.05). No differences were evident in ShC sham DNx (~1.9 ± 3.9 mmHg) or 2K-1C sham cryo-DNX rats (~3.0 ± 3.0 mmHg). The ShC cryo-DNX group did display a decrease in MAP compared with pre-cryotreatment MAP (~7.0 ± 3.5 mmHg, P < 0.05).

Figure 5 shows that plasma ANG II values were approximately threefold greater in the 2K-1C sham cryo-DNX rats compared with either ShC group. Cryotreatment of the renal nerve to the clipped kidney decreased plasma ANG II values in both groups of 2K-1C rats; kidneys from ShC rats were of similar weight.

Figure 2 shows daily MAP and heart rate 1 day prior to cryo- or sham treatment and daily averages over the next 7 days. Although MAP declined in the 2K-1C cryo-DNX group as soon as 1 day after treatment, the decrease in MAP did not achieve significance until day 5. Thereafter, MAP tended to stabilize at this new level until euthanasia on day 21; MAP on day 7 was 129.8 ± 4.1 vs. 130.5 ± 5.6 mmHg on days 18–21 (see Fig. 3). MAP after cryo-DNX in the ShC group did not decrease over the first 7 days. Heart rate did not differ among the groups or over time (P > 0.05). The average MAP during the 3 days prior to sham cryotreatment or cryotreatment was significantly higher in both groups of 2K-1C rats compared with ShC rats. MAP averaged over days 18–21 after cryotreatment of the nerve to the clipped kidney decreased MAP significantly in 2K-1C rats. Notably, ShC cryo-DNX rats also displayed a significant decrease in MAP by the end of the 3 wk.

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Table 2. Mean arterial pressure, renal tissue NE content, and renal sympathetic nerve activity before and 3 days after cryotreatment in protocol 2

<table>
<thead>
<tr>
<th>Group</th>
<th>MAP, mmHg</th>
<th>Integrated RSNA, μV/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>Post-DNX</td>
</tr>
<tr>
<td>ShC sham DNx</td>
<td>105.0 ± 4.9</td>
<td>108.7 ± 6.7</td>
</tr>
<tr>
<td>ShC cryo-DNX</td>
<td>107.3 ± 2.6</td>
<td>105.0 ± 4.9</td>
</tr>
<tr>
<td>2K-1C sham DNx</td>
<td>161.0 ± 12.6*</td>
<td>168.0 ± 8.7*</td>
</tr>
<tr>
<td>2K-1C cryo-DNX</td>
<td>162.0 ± 5.4*</td>
<td>152.0 ± 5.4‡</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = 4 for each group. MAP, mean arterial pressure; RSNA, renal sympathetic nerve activity. *P < 0.05 vs. corresponding ShC group; †P < 0.001 vs. left kidney; ‡P < 0.001 vs. corresponding sham DNx group; §P < 0.05 vs. baseline, same group.
significantly in the 2K-1C rats to values no different from plasma ANG II concentrations in the ShC rats. Notably, renal tissue ANG II was similar in ShC rats at both 1 and 9 wk. Renal tissue ANG II content was increased significantly 2K-1C rats 1 wk after renal artery clipping; however, this elevation was not evident in the 2K-1C rats after 9 wk. Renal cortical tissue ANG II values were similar from both right and left kidneys of both groups of ShC rats. The clipped kidney of the 2K-1C sham cryo-treated rats displayed significantly higher tissue ANG II content compared with the nonclipped kidney; this increase was prevented by cryotreatment (Fig. 6).

Table 2 shows the values for MAP at baseline and 4 days after sham cryotreatment or cryotreatment in protocol 2. Cryotreatment lowered MAP significantly in the 2K-1C group; sham cryotreatment had no effect. As in protocol 1, sham cryotreatment did not change tissue norepinephrine

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Fig. 7. Representative recordings of MAP, renal sympathetic nerve activity (RSNA), integrated RSNA (RSNA), and HR 2 days (D−2) and 1 day (D−1) prior to treatment and then 1 (D+1), 3 (D+3), and 4 days (D+4) in individual 2K-1C rats after either cryotreatment (Cryo-DNX; A) or sham cryotreatment (sham DNX; B). Dotted line indicates injection of nitroprusside (+NP) to verify nerve response.
content of the right kidney, but cryotreatment decreased norepinephrine content of the right kidney in both ShC and 2K-1C rats.

Raw telemetry recordings of MAP, raw RSNA, integrated RSNA, and heart rate before and after cryotreatment from a freely moving 2K-1C are shown in Fig. 7A. Both MAP and RSNA decreased 1 day after cryotreatment and continued to decline up to day 4. The decrease in RSNA was not due to electrode malfunction or decreased nerve viability since a decrease in MAP induced by injection of nitroprusside 4 days after cryotreatment evoked increases in both heart rate and RSNA. Sham cryotreatment of a 2K-1C rat in Fig. 7B shows that MAP continued to rise over time and that RSNA was unchanged. Overall, integrated RSNA prior to cryotreatment was three- to fourfold higher in both groups of 2K-1C rats compared with the ShC groups. Integrated RSNA decreased significantly in the 2K-1C cryo-treated group to a value no different from that in the ShC groups (Table 2).

Examples of the integrity of the telemetric nerve recordings at baseline and after responses to nitroprusside or phenylephrine are depicted in Fig. 8. These recordings are from the same rat shown in Fig. 9, C and D, 9 days after cryotreatment. Background RSNA after ganglionic blockade with trimethaphan camsylate is also shown.

Typical baroreflex curves of RSNA expressed as percent maximum RSNA as well as in absolute units in a single 2K-1C rat before and after cryotreatment are presented in Fig. 9. In this rat, both upper and lower plateaus decreased. Baroreflex testing was not part of the original hypothesis and design but was performed as an addendum to the study. Thus, full baroreflex curves were completed on day 3 of four 2K-1C rats; these results are shown in Table 3. In one rat, were able to complete baroreflex curves after cryotreatment on day 3 (Fig. 9, A and B) and as late as day 9 (Fig. 9, C and D). The major difference was a further decrease in resting MAP and range and a shift in the curve to the left. The upper plateau decreased significantly after cryotreatment, resulting in a concurrent decrease in the range. In contrast, the upper plateau, if anything, displayed a tendency to rise in the sham cryo-treated 2K-1C rats (Table 3), but this did not achieve significance since the study was not powered to evaluate baroreflex parameters.

DISCUSSION

The present findings support the hypothesis that cryotreatment of the renal nerve to the clipped kidney in 2K-1C rats decreases systemic arterial pressure comparable with decreases in pressure observed with surgical denervation. Arterial pressure in sham clipped rats was also significantly decreased by unilateral cryoablation of the renal nerve. In addition, these studies demonstrate for the first time that denervation of the renal nerves by cryoablation reduces plasma ANG II levels, lowers renal tissue ANG II content of the clipped kidney, and decreases contralateral RSNA in conscious, chronically instrumented 2K-1C hypertensive rats. The decline in renal tissue norepinephrine content of the clipped kidney by as much as 85% provides proof of principle that cryotherapy may be used to effect sympathetic renal denervation comparable with that reported 2 wk after severing of the renal nerve and application of phenol in spontaneously hypertensive rats and suggests that reinnervation may be limited or delayed with this approach (43). Heart rate did not differ among the groups either before or after sham or cryoablative therapy. Moreover, a limited number of baroreflex observations suggests that denervation of the renal nerves by cryoablation results in a decreased reflex renal sympatoexcitatory response to a decline in arterial pressure.

Cryoablation of the renal nerve to the clipped kidney reproducibly decreased mean arterial pressure by $\sim 15$ mmHg in 2K-1C rats 6 wk after clipping in both protocols rats in both protocols. This decline in arterial pressure after cryoablation was comparable with that observed 6 days after standard surgical denervation of the ischemic kidney in this model (26). The decrease in pressure was sustained through the third week after cryoablation and is similar in magnitude to the attenuation seen with bilateral renal denervation in the development of hypertension in spontaneously hypertensive rats (27) and
DOCA salt rats (22) or after the nerve to the unclipped kidney is severed in 2K-1C rats (50). Arterial pressure also declined significantly in the sham clipped rats in protocol 1, which was powered to assess mean arterial pressure, but not in protocol 2, which was powered to evaluate RSNA. This is consistent with the findings of Jacob et al. (21) who found an ~10-mmHg difference in mean arterial pressure after standard denervation in normal rats. They were able to observe this difference as early as 7 days after bilateral renal denervation. In the present studies, mean arterial pressure in the sham clipped group was not different at 7 days (Fig. 2 and Table 2) but did achieve significance 3 wk after cryoablation of the renal nerve (Fig. 3). It may well be that unilateral denervation requires a longer period for its effect on normotensive rats. Moreover, the study in protocol 2 was powered to evaluate RSNA and not mean arterial pressure. Taken together, these observations in both 2K-1C and sham clipped rats show that cryoablation of the renal nerve is as effective as surgical denervation to decrease arterial pressure.

Just as with surgical denervation, several mechanisms contribute to the decrease in systemic pressure after cryoablation in the 2K-1C rats. Low renal perfusion pressure to the clipped kidney stimulates renin secretion via renal baroreceptor and macula densa mechanisms. Efferent renal sympathetic stimulation potentiates the renin secretory response to low perfusion pressure (56). Thus, whereas high-plasma ANG II would otherwise depress renin secretion by a feedback mechanism (9), the concurrent sympathetic activation and low perfusion pressure in the clipped kidney together result in high-circulating ANG II. The substantial decrease in plasma ANG II after cryotreatment of the 2K-1C rats to levels no different from in sham clipped rats is consistent with the absence of a renin secretory response to renal hypoperfusion in humans after preganglionic sympathetic blockade due to epidural anesthesia (20).

The potential mechanisms involving ANG II and renal nerves in 2K-1C hypertension are depicted in Fig. 10. Besides raising systemic pressure by producing direct vasoconstriction via activation of AT1 receptors on vascular smooth muscle cells (5), circulating ANG II also results in differential activation of regional sympathetic nerve activities (46). In contrast to chronic exogenous ANG II infusion, which typically results in

Fig. 9. Baroreflex curves of RSNA in a single 2K-1C rat before (baseline; •) and on days 3 (A and B) and 9 (C and D) after cryotreatment (cryo-DNX; ○) of the nerve to the clipped kidney. Values are plotted as %maximum RSNA (A and C) and as raw nerve activity (μV·s; B and D). Resting values are shown in red for pretreatment and green for posttreatment.
baroreflex inhibition of efferent RSNA (62), endogenous activation of the renin-angiotensin system in the 2K-1C model enhances cervical sympathetic nerve activity (59) and RSNA (7). Afferent inputs from the stenosed kidney in 2K-1C hypertension (30), as in other ischemic renal conditions (29), paradoxically exert an excitatory influence on contralateral efferent RSNA despite elevated endogenous ANG II. Studies have shown that inhibitory renorenal reflexes that occur in kidneys from normal rats (12) do not occur from the clipped kidney in 2K-1C rats but actually enhance efferent RSNA to the contralateral kidney (30). Moreover, afferent renal nerves also project to central structures that regulate sympathetic outputs to key vascular beds (55). Some of these nuclei, such as the subfornical organ and area postrema, lie outside the blood-brain barrier and possess abundant AT1 angiotensin receptors (49) so that plasma ANG II can then potentiate excitatory afferent renal nerve inputs, further enhancing efferent sympathetic activity (10, 11, 39). Cryotreatment performed in the present studies involved freezing the whole renal nerve so that afferent as well as efferent nerves from the stenosed kidney were interrupted. Thus, the combined decline in plasma ANG II and excitatory afferent inputs in awake, freely moving rats after cryotreatment contributed to the decrease in both systemic pressure and contralateral RSNA and confirm the earlier studies regarding surgical denervation by Kopp and Buckley-Bleiler (30) observed only 1.5 h after recovery from pentobarbital anesthesia.

The high levels of intrarenal ANG II content in both clipped and nonclipped kidneys 1 wk after clipping confirm the findings by Guan et al. (18), who also showed that by 25 days, tissue ANG II content, although significantly elevated, was not as pronounced. This present report is the first to show that there is no difference in renal tissue ANG II content between 2K-1C and sham clipped rats 9 wk after clipping. Nonetheless, similar to rats studied at 25 days (18), tissue ANG II content of the clipped kidney of 2K-1C rats was higher than that of the contralateral kidney and was significantly attenuated by cryotreatment of the nerve. Elevated intrarenal ANG II has been shown to decrease sodium excretion and may thereby further contribute to hypertension (48). The present data show that denervation decreases intrarenal ANG II in the stenosed kidney and confirm the earlier findings in anesthetized 2K-1C rats (30) that sympathetic inputs to the contralateral kidney are suppressed, leading to increased urinary sodium excretion. Thus, effects on sodium excretion by the reduced intrarenal ANG II and sympathetic drive may work in concert to lower systemic pressure and restore sodium balance chronically. We did not observe the increase in urinary sodium excretion that likely occurs early after renal denervation, as the metabolic studies were performed 10 days after denervation, at which time the rats were back into sodium balance. Since arterial pressure also declined in sham clipped rats, our findings are consistent with earlier studies that renal nerves influence basal arterial pressure even in the normotensive state (21). However, it is also apparent that in 2K-1C rats there is an additional decrease in pressure that is likely due to changes in systemic and intrarenal ANG II. Further studies are certainly warranted.

### Table 3. Arterial baroreflex parameters of renal sympathetic nerve activity before and 3 days after sham or cryotreatment of the renal nerve in 2K-1C rats

<table>
<thead>
<tr>
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<th>2K-1C</th>
<th>Cryo-DNX</th>
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<tbody>
<tr>
<td></td>
<td>Pretreatment</td>
<td>Posttreatment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper plateau, %</td>
<td>100 ± 0</td>
<td>142.8 ± 55.8*</td>
</tr>
<tr>
<td>Lower plateau, %</td>
<td>50.3 ± 13.0</td>
<td>41.0 ± 3.0</td>
</tr>
<tr>
<td>Range, %</td>
<td>49.5 ± 12.8</td>
<td>101.8 ± 53.7</td>
</tr>
<tr>
<td>BP50, mmHg</td>
<td>140.9 ± 21.7</td>
<td>139.7 ± 14.9</td>
</tr>
<tr>
<td>Slope coefficient, − 1/mmHg</td>
<td>0.17 ± 0.04</td>
<td>0.12 ± 0.02</td>
</tr>
<tr>
<td>Gmax, %/mmHg</td>
<td>2.45 ± 0.51</td>
<td>3.02 ± 1.17</td>
</tr>
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Values are means ± SE; n = 3 for each group. BP50, midrange of the baroreflex curve; Gmax, maximum gain. *P < 0.05 vs. pretreatment; †P < 0.05 vs. sham cryo posttreatment.

Fig. 10. Diagram of potential mechanisms involved in increased ANG II and efferent RSNA to the contralateral kidney in 2K-1C hypertension. Hypoperfusion of the stenotic kidney results in increased secretion of renin, thereby initiating a cascade leading to elevated plasma ANG II. Plasma ANG II can act to increase vascular resistance directly (not shown) but can also act on brain nuclei that lie outside the blood-brain barrier and possess AT1 receptors such as the subfornical organ (SFO) or area postrema (AP). Projections from the AP or the SFO via paraventricular nucleus (PVN) can then send signals either via the brainstem cardiovascular regulatory centers or directly to the spinal cord to enhance efferent RSNA. Notably, efferent RSNA may increase renin secretion from the contralateral kidney as well. Afferent renal nerves from the clipped kidney also project to SFO and to brainstem centers. These inputs, together with spinal cord renorenal reflexes initiating from afferent nerves of the clipped kidney, lead to increased efferent RSNA to the contralateral kidney.
to ascertain the role of renal nerves in normotensive rats as well.

The limited number of baroreflex observations suggests that cryoaiblation of the renal nerve decreases the reflex renal sympathoexcitatory response to baroreceptor unloading. The present data cannot distinguish whether this modulation of the baroreflex is due to interruption of direct neural inputs from renal afferent nerves, lowering of circulating ANG II, or both. Since both the neural and ANG II inputs converge on the subfornical organ, it is of interest that the attenuation of the maximal response to baroreceptor unloading here is similar to that seen with electrolytic lesioning of the subfornical organ (39) or chronic administration of a centrally acting sympatholytic agent (7). In addition, although this study was not a priori powered to assess baroreflex function, there was no detectable difference in the lower plateau. The latter observation would be consistent with previous studies suggesting that the baroreflex is already maximally active to suppress arterial pressure in secondary hypertension (7, 37, 59) and suggests that further studies are warranted.

Limitations. Cryotreatment resulted in a significant decrease in tissue norepinephrine content, but not to the extent reported with severing of the renal nerve and application of phenol, where tissue norepinephrine decreased by >95% (30). Without detailed longitudinal histological studies, it is not possible to distinguish definitively between lack of full denervation versus reinnervation. Previous studies with surgical denervation reported attenuation of the decrease in renal norepinephrine to 89% after 2 wk and 76% after 4 wk (27), whereas others have shown tissue norepinephrine to be only 50% of control values by 24 days (25). That the decrease in renal tissue norepinephrine was similar at 7 and 21 days post-cryotreatment is more consistent with cryoablation being initially less effective than surgical denervation. Nonetheless, if tissue norepinephrine is used as the index of denervation, reinnervation appears to be limited during the 3-wk course of the present experiments. This contrasts with studies after standard denervation showing ~40% reinnervation after 3–4 wk (43). Thus, cryoablation may be less effective initially but could conceivably be more long lasting. Corroboration of this finding as well as identification of the mechanism of the sustained decrease in norepinephrine would provide valuable information. Importantly, sodium intake was carefully controlled across groups in the present study. No differences were seen in creatinine clearance or sodium excretion at the time of the balance studies, but this does not exclude the possibility that sodium excretion differed acutely after sham or cryotreatment such that cumulative sodium excretion may have differed prior to balance being restored. Split renal function would have provided additional insights but also would have entailed anesthesia. Baroreflex testing was a post hoc addition to the studies and hence, not adequately powered for definitive interpretation. Nonetheless, the findings indicate that the availability of nerve telemetry will prove pivotal in ascertaining the relationship between the arterial baroreflex in freely moving rats after chronic manipulations in disease models.

Perspectives and Significance

In summary, these studies support the proof of principle that cryoablation alone to the renal nerve is able to effect substantial sympathetic renal denervation to the clipped kidney in conscious, chronically instrumented 2K-1C rats, leading to reductions in systemic arterial pressure, plasma ANG II levels, renal tissue ANG II and norepinephrine content of the clipped kidney, and contralateral RSNA. Given that renovascular hypertension due to atherosclerotic disease is increasing in prevalence (15), it is noteworthy that standard approaches using angioplasty and stenting of the renal artery have proven to be ineffective in lowering systemic pressure (13). Because the time of onset of stenosis in humans is impossible to judge, it is likely that the sympathetic mechanisms are engaged by the time the stenosis is addressed. Despite the early reports of successful treatment with radiofrequency denervation in resistant essential hypertension (33, 53), renal artery stenosis has generally been considered an exclusionary factor (60). Moreover, issues have more recently have come to light regarding the limited effectiveness of radio frequency denervation, such as proximity to the vessel wall, medication compliance, and operator experience, among others. Other radiofrequency-based technology for renal denervation may improve on these technical aspects, but balloon cryoplasty has already been applied to peripheral vascular disease (41). Emerging cryotechnology has shown sufficient power to effect endovascular approaches to the highest heat sink scenario of aberrant cardiac conduction pathways. Thus, cryoablation of the renal nerves with or without concurrent angioplasty appears to be increasingly feasible for future endovascular approaches and may be of benefit in individuals with renovascular hypertension to relieve both the stenosis as well as sympathoexcitation.

ACKNOWLEDGMENTS

We acknowledge the computer and technical assistance of Robert J. Pawlowicz.

GRANTS

This work was supported by a Department of Veterans Affairs Merit Award to N. F. Rossi.

DISCLOSURES

None of the authors have any conflicts of interest, financial or otherwise, to declare.

AUTHOR CONTRIBUTIONS

N.F.R. and P.J.L. conception and design of research; N.F.R., R.P., and M.M.-S. performed experiments; N.F.R., R.P., and M.M.-S. analyzed data; N.F.R. and M.M.-S. interpreted results of experiments; N.F.R. prepared figures; N.F.R. and P.J.L. performed experiments; N.F.R., R.P., and H.C. conceived and designed research; N.F.R. drafted manuscript; N.F.R. and M.M.-S. edited and revised manuscript; N.F.R., R.P., and H.C., P.J.L., and M.M-S. approved final version of manuscript.

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