Load Versus Humoral Activation in the Genesis of Early Hypertensive Heart Disease

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Background—The role of load versus angiotensin II (Ang II) and endothelin-1 (ET) in the pathogenesis of hypertensive heart disease is controversial. We sought to determine whether alterations in cardiac structure and function due to hypertension (HTN) were dependent on Ang II or ET activation.

Methods and Results—Bilateral renal wrapping to produce HTN (n=12) or sham surgery (n=6) was performed in adult dogs. Weekly blood pressure, plasma renin activity, Ang II, ET, and catecholamines were measured. Systolic (end-systolic elastance, Ees) and diastolic (τ) function were assessed in sham and HTN dogs at 5 (HTN-5wk) or 12 (HTN-12wk) weeks. Ang II and ET were assayed in the left ventricle (LV) and kidney. Mean arterial pressure was higher in renal wrap dogs at week 1 (*P<0.05 versus controls: 139±4* versus 124±2 mm Hg), week 5 (174±7* versus 124±4 mm Hg), and week 12 (181±12* versus 124±4 mm Hg). LV mass index was increased in HTN-5wk (22%*) and HTN-12wk (39%*). LV fibrosis was increased in HTN-12wk. Ees was preserved in HTN-5wk and HTN-12wk. τ was increased in HTN-5wk (50±10* ms) and HTN-12wk (62±10* ms) dogs compared with sham (41±2 ms). Plasma Ang II, ET, catecholamines, and plasma renin activity were unchanged during the progressive HTN. Ang II and ET in LV and kidney were not different from controls.

Conclusions—Systemic HTN induces LV hypertrophy, myocardial fibrosis, and isolated diastolic dysfunction in the absence of local or systemic activation of Ang II or ET. These findings suggest that load is the prevailing stimulus for the structural and functional changes associated with early hypertensive heart disease. (Circulation. 2001;104:215-220.)

Key Words: hypertension ■ hypertrophy ■ hemodynamics ■ angiotensin ■ endothelin

Epidemiological studies document that hypertension (HTN) accounts for 39% of heart failure (CHF) cases in men and 59% of cases in women. The effects of systemic HTN on the heart are complex but include left ventricular hypertrophy (LVH), myocardial fibrosis, and impairment in diastolic function. The degree of LVH observed in patients with HTN correlates poorly to blood pressure. This observation has led to speculation that humoral factors modulate the hypertrophic response to pressure overload. Local activation of the renin-angiotensin system (RAS) and endothelin (ET) have been reported in models of pressure overload. Furthermore, angiotensin II (Ang II) and ET are antilusitropic and profibrotic. In contrast, others have asserted that the LVH and diastolic impairment in early hypertensive heart disease are exclusively related to load. Few studies, however, have measured LV load, structure, function, and hemorul status to address this controversy.

Our objective was to use a large-animal model of systemic HTN to explore the role of load versus humoral function in early hypertensive heart disease. We hypothesized that systemic HTN would produce LVH and diastolic dysfunction in the absence of local activation of Ang II or ET. This is based on observations in the rapid-pacing model, in which progressive LV remodeling and dysfunction are not associated with local activation of Ang II or ET until end-stage CHF. The present study extends these observations to the study of hypertensive heart disease.

Methods
All experimental procedures were designed in accordance with NIH guidelines and approved by the Mayo Institutional Animal Care and Use Committee.

Model of HTN
The Page renal wrap model of inducing HTN was used. Adult male dogs (20 to 26 kg) were studied (1) 5 weeks after sham surgeries (controls, n=6), (2) 5 weeks after renal wrap (HTN-5wk, n=7), and (3) 12 weeks after renal wrap (HTN-12wk, n=5). Dogs were anesthetized with methohexital sodium 4% solution (12.5 mg/kg) and isoflurane (0.5% to 2.5%) and ventilated (15 mL/kg of 100% Fio2). Via a midline abdominal incision, kidneys were wrapped with silk without constriction of renal vessels. A femoral arterial catheter and port were placed. In controls, the arterial catheter was placed without renal wrap. Torbugesic (0.2 to 0.4 mg/kg every 4 to 6 hours)
was used for postoperative analgesia. Antibiotics (Ceph tabs 500 mg BID×10 days) were given. Blood pressure was measured weekly.

**Echocardiography**

2D targeted M-mode echocardiography (Acuson 128XP/10) was performed in conscious dogs before surgery. Echocardiography was repeated 5 weeks after surgery in controls and HTN-5wk and 5 and 12 weeks after surgery in HTN-12wk dogs. LV end-diastolic (LVDd) and end-systolic (LVDs) internal dimensions, septal wall end-diastolic (Sth d) and end-systolic (Sth s) thickness, and posterior wall end-diastolic (PWth d) and end-systolic (PWth s) thickness were measured. LV mass was calculated and indexed to body weight as: 

\[
\text{LV mass} = \left[ \text{LVDd} + \text{Sth d} + \text{PWth d} \right] - \left[ \text{LVDs} + \text{Sth s} + \text{PWth s} \right] \times 1.04 \times 0.80.
\]

Ejection fraction was calculated as: 

\[
\text{EF} = 100 \times \left[ \frac{\text{LVDd} - \text{LVDs}}{\text{LVDd}} \right].
\]

LV end-diastolic wall stress was estimated by a cylindrical model: 

\[
\text{WSS} = \frac{\text{SBP}}{\text{hes}} \times \frac{\text{PWth d} + \text{PWth s}}{2}.
\]

**Acute Experimental Protocol**

Fasted dogs were anesthetized with fentanyl 0.25 mg/kg (Johnson Matthey, Inc) and midazolam 0.75 mg/kg IV (Roche) and ventilated (Harvard Respirator) with room air and O2. Infusion of fentanyl 0.18 mg · kg⁻¹ · h⁻¹ and midazolam 0.59 mg · kg⁻¹ · h⁻¹ was titrated to effect. Via a left thoracotomy, an LV pressure transducer (Koningsberg Instruments, Inc) was inserted in the apex. A fluid-filled pigtail catheter (USCI) was used to calibrate the transducer. Piezoelectric crystals (2.0 mm) (Sonometrics Corp) were implanted on anterior and posterior endocardial surfaces at the mid-LV level, the endocardial LV apex, and basal epicardial surfaces. An occluder was placed around the inferior vena cava. Dogs were atrial-paced at 20 bpm above sinus rate.

Steady-state data were collected over 5 minutes. A 250-mL IV bolus of warmed saline was given. Three inferior vena cava occlusions producing reduction of peak LV systolic pressure of ≥30 mm Hg were obtained. Steady-state and variable preloaded measurements were repeated after administration of propranolol (2 mg/kg IV).

Dogs were killed by removal of the heart under anesthesia, consistent with guidelines of the Panel on Euthanasia of the American Veterinary Medical Association. The LV mass index at autopsy (Figure 2) was higher in HTN than in controls. The LV log[cBNP], a marker of LVH, was increased in HTN-5wk and HTN-12wk dogs without change in LVDd or ejection fraction. Afterload, assessed by end-systolic wall stress (Es) and end-diastolic pressure-volume relationship was fitted monexponentially, and the chamber stiffness constant, βc, was derived.

**Statistical Analysis**

Data were averaged and reported as mean±SEM. Comparisons of control and HTN groups were made by Student’s t tests. Statistical significance was achieved at a value of \(P<0.05\).

**Results**

**Model of Systemic HTN**

The development of HTN is shown in Figure 1. Mean arterial pressure progressively increased in renal-wrapped dogs. At autopsy, a dense fibrous rind surrounded the renal capsule immediately under the silk. Grossly, the renal capsule and parenchyma were uninvolved in the fibrotic reaction. Histological assessment of renal cortex and medulla revealed no significant interstitial fibrosis, tubular atrophy, or vascular sclerosis in control or hypertensive animals at 5 or 12 weeks. Blood urea nitrogen and creatinine did not change after renal wrapping and were not different from controls at any point (data not shown).

**LV Structure, Function, and Load in the Conscious State**

LV structure, function, and load as assessed at echocardiography in conscious dogs are shown in Table 1. LV mass index increased in HTN-5wk and HTN-12wk dogs without change in LVDd or ejection fraction. Afterload, assessed by end-systolic wall stress (Es) tended to be increased in both HTN groups.

**LV Structure: Autopsy and Histology**

The LV mass index at autopsy (Figure 2) was higher in HTN dogs than in controls. The LV log[cBNP], a marker of LVH, was increased in HTN (0.03±0.11 pmol/mg controls versus 1.07±0.32 pmol/mg HTN-5wk, \(P<0.05\), and 0.80±0.26 pmol/mg HTN-12wk, \(P<0.05\). The fibrosis score (Figures 2 and 3) was higher in HTN-12wk than in controls or HTN-5wk.

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**Figure 1.** Mean arterial pressure after sham surgery (control) or renal wrapping (HTN). Values are mean±SEM. \(\dagger P<0.05\), \(\ddagger P<0.01\), \(\spadesuit P<0.001\) vs controls.

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**Figure 3.** Fibrosis score in control and HTN dogs. A: Masson’s trichrome. B: Oil red O. C: Alcian blue. D: Picrosirius red.
Systolic and Diastolic Function

Systolic and diastolic function assessed under anesthesia are shown in Table 2. LV peak systolic pressure was increased in HTN. The load-independent index, Ees, was not different between HTN groups and controls. Although LVEDP was higher in HTN-12wk, the coefficient of chamber stiffness (LVEDP) was increased in HTN-12wk. Although LVEDP was shown in Table 2. LV peak systolic pressure was increased in HTN. The load-independent index, Ees, was not different between HTN groups and controls. Although LVEDP was higher in HTN-12wk, the coefficient of chamber stiffness (LVEDP) was increased in HTN-12wk. Although LVEDP was significantly higher in HTN dogs (58±3 ms HTN-5wk, P<0.001 versus control; 62±4 ms HTN-12wk, P<0.01 versus control) than in controls (43±2 ms).

Circulating and Local Humoral Activation

Circulating Ang II, ET (Figure 5), catecholamines, and plasma renin activity in the HTN groups were not increased. Plasma cBNP tended to be slightly higher in HTN dogs, significantly so at 2 weeks (data not shown). Cardiac humoral function is shown in Figure 6. In HTN dogs, Ang II levels were lower in the left atrium and tended to be lower in the LV than in controls. Cardiac ET levels were not different between control and HTN dogs. Renal cortex Ang II (0.48±0.05 pmol/mg controls versus 0.95±0.15 pmol/mg HTN-5wk versus 1.66±0.51 pmol/mg HTN-12wk, P=NS) and ET (1.36±0.26 pmol/mg controls versus 0.95±0.61 pmol/mg HTN-5wk versus 1.92±1.29 pmol/mg HTN-12wk, P=NS) were not significantly activated in HTN dogs. Renal medulla Ang II (0.51±0.08 pmol/mg controls versus 0.63±0.11 pmol/mg HTN-5wk versus 1.78±1.26 pmol/mg HTN-12wk, P=NS) and ET (3.99±0.95 pmol/mg controls versus 3.99±0.72 pmol/mg HTN-5wk versus 1.26±0.52 pmol/mg HTN-12wk, P=NS) were also not activated in HTN dogs.

Discussion

The present study demonstrates that renal wrapping produces sustained HTN without renal parenchymal inflammation or renal insufficiency. Furthermore, the development of HTN is unassociated with systemic or renal activation of the vasoconstrictor hormones Ang II or ET. This model displayed the hallmarks of early hypertensive heart disease: LVH, myocardial fibrosis, and diastolic dysfunction without systolic dysfunction. These changes occurred in the absence of systemic or myocardial activation of prohypertrophic, profibrotic, and antilusitropic neurohormones, Ang II or ET. These data advance our understanding of the effects of HTN on LV structure and function and support the concept that load

![Figure 2](http://circ.ahajournals.org/)

*Figure 2.* LV mass index (g/kg) (A) in controls, HTN-5wk, and HTN-12wk. *P<0.05 vs controls. LV fibrosis score (B) in controls, HTN-5wk, and HTN-12wk. *P<0.01 vs controls; †P<0.001 versus control.

**TABLE 1. Conscious Assessment of LV Structure, Function, and Load by Echocardiography**

<table>
<thead>
<tr>
<th></th>
<th>Body Weight, kg</th>
<th>LVDD, cm</th>
<th>EF, %</th>
<th>LVMI, g/kg body wt</th>
<th>SBP, mm Hg</th>
<th>Ees, g/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controls (n=6)</td>
<td>23±0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Baseline</td>
<td></td>
<td>4.2±0.0</td>
<td>63±3</td>
<td>4.5±0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week 5</td>
<td>24±0.6</td>
<td>4.1±0.1</td>
<td>58±4</td>
<td>4.6±0.3</td>
<td>174±4</td>
<td>220±16</td>
</tr>
<tr>
<td>HTN-5wk (n=7)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>23±0.5</td>
<td>4.0±0.1</td>
<td>58±2</td>
<td>4.2±0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week 5</td>
<td>24±0.4</td>
<td>3.9±0.1</td>
<td>61±2</td>
<td>6.0±0.4*</td>
<td>231±4†</td>
<td>253±7‡</td>
</tr>
<tr>
<td>HTN-12wk (n=5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>22±0.4</td>
<td>4.2±0.2</td>
<td>57±1</td>
<td>4.9±0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week 5</td>
<td>4.1±0.2</td>
<td>58±2</td>
<td>7.0±0.6*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Week 12</td>
<td>22±0.6</td>
<td>3.8±0.2*</td>
<td>54±2</td>
<td>6.9±0.6*</td>
<td>250±11†</td>
<td>276±28</td>
</tr>
</tbody>
</table>

EF indicates ejection fraction; LVMI, LV mass index; SBP, systolic blood pressure; and Ees, end-systolic wall stress.

*P<0.05 vs baseline; †P<0.05, ‡P=0.07 vs control.
predominates in the genesis of hypertensive heart disease, at least in this early, yet clearly established phase.

Although RAS antagonism is effective in controlling blood pressure and causing regression of LVH in human and experimental HTN, the role of Ang II activation in the pathophysiology of hypertensive heart disease remains controversial. “Subpressor” doses of Ang II were reported to induce hypertrophy in the rat, although alterations in load cannot be excluded in such studies. Studies in aortic-banded rats reported activation of local RAS as evidenced by increases in myocardial ACE mRNA and ACE activity in vitro. Myocardial Ang II, however, was not measured to document that enhanced ACE mRNA resulted in higher levels of active peptide. In the spontaneously hypertensive rat, plasma and myocardial levels of Ang II are low in the early-compensated stage, although LV Ang II does increase late in the natural history of this model, when systolic dysfunction and CHF develop. Although Page HTN was presumed to be a model of RAS activation, the humoral profile of this model has not been well studied. We found no systemic or local activation of the RAS in this model. Furthermore, we found no activation of myocardial Ang II to suggest that the RAS contributes to the LVH, fibrosis, or

### TABLE 2. Invasive Hemodynamic Assessment of LV Function

<table>
<thead>
<tr>
<th></th>
<th>Controls (n=8)</th>
<th>HTN-5wk (n=7)</th>
<th>HTN-12wk (n=5)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Systolic function</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LVPSP, mm Hg</td>
<td>113±4</td>
<td>144±5*</td>
<td>139±6*</td>
</tr>
<tr>
<td>LV+dp/dt, mm Hg/s</td>
<td>1871±114</td>
<td>2168±124</td>
<td>2399±206*</td>
</tr>
<tr>
<td>SV, mL</td>
<td>25±2</td>
<td>22±4</td>
<td>24±5</td>
</tr>
<tr>
<td>CO, L/min</td>
<td>2.4±0.3</td>
<td>2.4±0.4</td>
<td>2.3±0.3</td>
</tr>
<tr>
<td>Ees, mm Hg/mL</td>
<td>5±1</td>
<td>7±1</td>
<td>10±4†</td>
</tr>
<tr>
<td>Ea, mm Hg/mL</td>
<td>3±0.3</td>
<td>6±1*</td>
<td>6±1*</td>
</tr>
<tr>
<td><strong>Diastolic function</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LVEDP, mm Hg</td>
<td>7±0.3</td>
<td>7±1</td>
<td>11±2*</td>
</tr>
<tr>
<td>Tau dp/dt, ms</td>
<td>41±2</td>
<td>50±3*</td>
<td>61±9*</td>
</tr>
<tr>
<td>$\beta_0$</td>
<td>0.10±0.03</td>
<td>0.11±0.04</td>
<td>0.09±0.02</td>
</tr>
</tbody>
</table>

LVPSP indicates LV peak systolic pressure; SV, stroke volume; CO, cardiac output; Ea, end-arterial elastance; and $\beta_0$, LV chamber stiffness constant. Values are mean±SEM.

*P<0.05 vs control.
†Not statistically significant; mean contains an outlying value.
Hayashida et al28 found variable levels of circulating Ang II in hypertensive dogs. Although we were unable to demonstrate an increase in the LV stiffness constant, LVEDP was higher, suggesting early decreases in LV compliance or altered distensibility. This finding is consistent with those of Abrahams et al,30 who found altered LV collagen matrix in monkeys as early as 4 weeks after unilateral renal wrap. In contrast, other investigators using bilateral or unilateral renal wrapping have not observed significant fibrosis by use of morphometric techniques31 and hydroxyproline analysis.14

Our findings suggest that fibrosis starts early in hypertensive heart disease, that it can occur in the absence of profibrotic humoral factors, and that it is associated with hemodynamic abnormalities (increases in LVEDP).

The mechanism responsible for the development of HTN in this model is unclear and deserves comment. When Page and colleagues (Kohlstaedt et al32) described this model, they demonstrated that the tail artery of a normal dog constricted when perfused with blood from a hypertensive dog, suggesting that a circulating factor was involved. We speculate that the renal manipulation may induce production of an as yet uncharacterized circulating vasoconstrictive factor. This hypothesis is suggested by studies in the pancreas, in which cellophane wrapping induces production of a growth factor that stimulates islet-cell formation and insulin production.33 We are using kidney medulla and cortex extracts to search for possible differential protein expression in the renal-wrap dog. Because of limited canine genomic data, however, further studies in a renal-wrap murine model will be required in identifying differential protein expression. Although at present we are still unable to determine the mechanism of HTN in this model, its hemodynamic features are similar to those of the human condition and thus provide a useful large-animal model of systemic HTN.

In summary, the absence of local or systemic activation of Ang II or ET in this model suggests that load is the primary determinant of the early ventricular remodeling and diastolic dysfunction associated with systemic HTN. These findings, along with those of the SHEP study, in which control of blood pressure without humoral modulation had a profound effect to reduce progression to CHF,34 suggest aggressive treatment of high blood pressure as the primary means to prevent progression of hypertensive heart disease.

Acknowledgments

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Figure 5. Circulating humoral response. Ang II (A) and ET-1 (B) concentrations measured weekly after surgeries until week 5 in controls and HTN-5wk and again at 12 weeks in HTN-12wk (n=5).

Figure 6. Cardiac humoral response. Tissue concentrations of Ang II (A) and ET-1 (B) are normalized to tissue protein content for controls, HTN-5wk, and HTN-12wk groups. Values are mean±SEM. LA indicates left atrium. *P<0.05 vs controls, †P<0.05 vs HTN-5wk.
References


