The extent to which chronic hypertension alters autonomic regulation of the heart remains to be established. One approach to understanding this problem is to determine if a change occurs in autonomic receptors. Several studies have examined changes in β-adrenergic receptor density in rodents with hypertension, while changes in muscarinic, cholinergic receptors have been investigated less extensively. The results of these studies on β-adrenergic receptors have been conflicting, perhaps because of differences in experimental models of hypertension. It is also conceivable that there are differences due to species and, potentially, to the degree of left ventricular (LV) hypertrophy that develops as a consequence of systemic hypertension. In regard to this latter point, it is not clear whether changes occurring in the heart during chronic hypertension are due to alterations induced by hypertrophy or to the various metabolic and hormonal factors that are associated with chronic systemic hypertension. Accordingly, the goal of the present investigation was to examine the extent to which chronic hypertension alters the density of β-adrenergic and cholinergic receptors in a large mammalian model. In addition, the changes in β-adrenergic receptor density and affinity were compared with those in another group of dogs studied previously with similar levels of pressure overload hypertrophy, but in which LV hypertrophy was induced by long-term aortic banding and did not involve systemic hypertension.
Methods
Preparation of Model

After recording baseline levels of arterial pressure in the conscious state for 3 consecutive days by either a catheter implanted in the aorta or a catheter acutely introduced into the femoral artery using local anesthesia with 2% lidocaine HCl, perinephric hypertension was induced with a modification of the method of Page 10. Mongrel dogs of either sex were anesthetized with sodium pentobarbital (30 mg/kg) and ventilated with a respirator. The left kidney was exposed through a left flank incision and stripped of fat and fascia. Raw, unbleached silk was wrapped around the kidney and sutured in place. Care was taken to avoid constriction of the renal pedicle and parenchyma. Plastic wrap (Saran Wrap, Dow Chemical Company, Indianapolis, IN) was placed over the silk to prevent the formation of adhesions with other tissues in proximity to the kidney. The animals were allowed to recover for 1 week before the second operation. Pressure again was recorded in the conscious dog, which then underwent anesthesia (sodium pentobarbital, 30 mg/kg). The right kidney was then removed through a right flank incision. Two sham-operated dogs underwent similar operations in which the kidney was stripped of fascia and plastic wrap was laid down beside it during the first operation and nephrectomy was performed 1 week later. In addition, 13 normal dogs were used for the remainder of the control group.

Arterial pressures were measured weekly with the implanted catheter and Statham P23ID strain gauge manometers (Statham Instruments Inc., Oxnard, CA). Blood samples for plasma catecholamine levels were drawn from the implanted catheters in conscious dogs. The data were recorded on a tape recorder (Honeywell Inc., Denver, CO) and displayed on a direct-writing oscillograph (Gould, Cleveland, OH). The experiment was terminated. LV pressure was measured in conscious dogs by catheterization with the use of local anesthesia with lidocaine. The LV tissue catecholamine levels were obtained when the animals were killed. The animals were killed 2 weeks (n = 1), 5 weeks (n = 3), 11 weeks (n = 2), and 21 weeks (n = 1) after nephrectomy.

Biochemical Studies

After arterial pressure had been recorded for the final time, the dogs were killed with sodium pentobarbital, 30 mg/kg, and their hearts were immediately excised and placed into iced normal saline. All subsequent procedures were carried out at 4°C. Approximately 1 mm of epicardium and endocardium was trimmed with scissors and discarded. The LV myocardium was minced coarsely in buffer A (0.25 M sucrose, 1 mM MgCl₂, and 1 mM KHCO₃) and homogenized with a PT-10ST Polytron (Brinkmann Instruments, Inc., Westbury, NY) tissue disruptor. The homogenate was filtered through one layer of Japanese silk screen, size 12, and centrifuged (Sorvall RC-2, DuPont Instruments, DuPont Co., Wilmington, DE) at 1000g for 15 minutes. The supernatant was centrifuged at 45,000g for 15 minutes, and the pellet was resuspended in buffer B (100 mM Tris, 5 mM MgCl₂, 1 mM EDTA, pH 7.2, 4°C) with a glass homogenizer. The homogenization and 45,000g centrifugation were repeated twice. The pellet was resuspended to a protein concentration of 2 to 3 mg/ml and stored at −70°C until assayed. At the time of assay, the membranes were again washed in buffer B and centrifuged at 45,000g for 15 minutes. All studies were performed in triplicate.

For the determination of β-adrenergic receptor density, 100 μL of the cardiac membrane preparation (2–3 mg of protein/ml) was incubated at 37°C for 30 minutes with increasing concentrations (10–300 nM) of [³H](-)dihydroalprenolol (³H-DHA; New England Nuclear, Boston, MA), with or without unlabeled d,l-propranolol (10 μM), in a final reaction volume of 150 μL. A concentration of 10 μM propranolol was required to inhibit specific binding of ligand competing at the higher concentration of ³H-DHA. Following incubation, the 150 μL of reaction mixture was rapidly filtered under vacuum onto Whatman GF/C glass fiber filters (Whatman, Inc., Clifton, NJ). The filters were quickly washed (<10 seconds) three times with 4 ml of buffer B, 4°C. The filters were counted for 5 minutes in 10 ml of Hydrofluor (New England Nuclear) in a Delta 300 scintillation counter (Searle Analytic Inc., Des Planes, IL) with a counting efficiency of 45%. Analysis of saturation binding assays was performed according to the method of Scatchard. 11 The data were also analyzed with the iterative curve-fitting program Ligand of Munson and Rodbard. 12

The muscarinic, cholinergic receptors were analyzed with binding studies with increasing concentrations (0.05–6.0 nM) of [³H]-quinuclidinyl benzilate ([³H]-QNB, New England Nuclear), with or without atropine, 1 μM. 9 Methacholine, 100 μM, provided results similar to those obtained with atropine. Assay conditions were the same as for the [³H]-DHA binding studies.

The Na-K-ATPase activity was determined by the method of Harris and Popat. 13 This is a colorimetric method that measures the hydrolysis of inorganic phosphate from adenosine triphosphate.

Plasma epinephrine and norepinephrine levels in the conscious dogs, as well as tissue norepinephrine levels obtained from LV samples before the animals were killed, were measured using the method of DaPrada and Zurcher. 14 The protein concentrations for each membrane assay were determined by the method of Lowry et al. 15

Comparison with Left Ventricular Hypertrophy Induced by Aortic Banding

A previous study from this laboratory 16 found that LV hypertrophy induced by banding the aorta in puppies resulted in an increase in β-adrenergic receptor density but a decreased receptor affinity (a larger dissociation constant, i.e., Kᵦ); however, the degree of hypertrophy was greater in that group. Accordingly, a subset of these dogs was selected for comparison in
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which the ratio of LV free wall weight to body weight increased by 61%, a value similar to that observed in the current study with LV hypertrophy induced by perinephritic hypertension. The data for the subgroup of dogs with LV hypertrophy induced by aortic banding are compared with data from the dogs with perinephritic hypertension in Table 1.

Statistical Analysis
Data are expressed as means ± SEM. Data were stored in a digital computer (PDP-11/34, Digital Equipment Corp., Maynard, MA), and statistical evaluation was performed by Student's *t* test for grouped comparisons.

**Results**

**Hemodynamic Studies**

The increases in mean arterial pressure over the course of the development of renal hypertension are shown in Figure 1. Mean arterial pressure rose from control values of 104 ± 3 mm Hg to 129 ± 5 mm Hg following the wrapping of one kidney. There was a further increase in mean arterial pressure to 142 ± 9 mm Hg 1 week after nephrectomy. After 4 weeks, the mean arterial pressure stabilized at 156 ± 11 mm Hg. Mean arterial pressure did not change significantly with time in the control group. There were no differences in heart rate between the hypertensive (101 ± 8.0 beats/min) and control (99 ± 4.0 beats/min) animals.

**Pathological Studies**

After the animals had been killed, the degree of hypertrophy was determined by comparing the LV free wall weight to body weight ratio in the normal dogs (3.34 ± 0.14 g/kg) with values from the hypertensive animals (4.98 ± 0.36 g/kg, *p < 0.01*). The 49% rise in this ratio indicates a moderate hypertrophic process accompanying the renal hypertension. The LV free wall weights from the hypertensive dogs were also significantly greater than those obtained in normal dogs. The normal dogs had an LV free wall weight of 83.4 ± 5.1 g and the hypertensive dogs had an LV free wall weight of 111 ± 7.8 g (*p < 0.01*).

**Muscarnic, Cholinergic Receptor Binding Studies**

Specific ²H-QNB binding to the myocardial membranes was saturable and best characterized by a single binding site according to the iterative nonlinear computer analysis of Munson and Rodbard.¹² The affinity of the normal and renal hypertensive hearts for ²H-QNB was similar (Kₐ = 0.30 ± 0.04, *n* = 6, versus 0.38 ± 0.04 nM, *n* = 8), whereas cholinergic receptor number was decreased in the renal hypertensive group (181 ± 19 fmol/mg, *p < 0.01*) as compared with the values obtained in the control group (272 ± 16 fmol/mg; Figure 2).

**Myocardial β-Adrenergic Receptor Binding Studies**

Specific ²H-DHA binding to the myocardial membrane preparation was saturable and yielded a single component.¹² Typical computer analyses of ³H-DHA binding to normal LV myocardial membranes and LV hypertensive membrane preparations are shown in Figure 2. The affinity for ³H-DHA was decreased in these membranes, as demonstrated by the increase in Kₐ (Kₐ = 10.4 ± 1.2 nM, *n* = 7) as compared with that of the normal LV preparations (Kₐ = 5.0 ± 0.7 nM, *n* = 15, *p < 0.01*). The density of binding sites, determined by the computer analysis, was significantly

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**Table 1** Comparison of Perinephritic Hypertension-Induced Left Ventricular Hypertrophy and Aortic Banding-Induced Left Ventricular Hypertrophy

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Normal (n = 15)</th>
<th>Perinephritic Hypertension (n = 7)</th>
<th>Aortic banded LV Hypertrophy (n = 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body weight (kg)</td>
<td>25 ± 1.4</td>
<td>23 ± 2.7</td>
<td>21 ± 1.6</td>
</tr>
<tr>
<td>LV weight (g)</td>
<td>83 ± 5.1</td>
<td>111 ± 7.8*</td>
<td>115 ± 12.0*</td>
</tr>
<tr>
<td>LV/body weight</td>
<td>3.34 ± 0.14</td>
<td>4.98 ± 0.36*</td>
<td>5.37 ± 0.20*</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>99 ± 4.0</td>
<td>101 ± 8.0</td>
<td>91 ± 4.8</td>
</tr>
<tr>
<td>LV systolic pressure (mm Hg)</td>
<td>126 ± 3.8</td>
<td>187 ± 10.4*</td>
<td>212 ± 13*</td>
</tr>
<tr>
<td>Mean arterial pressure</td>
<td>98 ± 3.4</td>
<td>156 ± 11*</td>
<td>98 ± 2</td>
</tr>
<tr>
<td>(mm Hg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>β-Adrenergic receptor density</td>
<td>68 ± 5.2</td>
<td>108 ± 10*</td>
<td>115 ± 14*</td>
</tr>
<tr>
<td>(fmol/mg of protein)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kₐ (nM)</td>
<td>5.0 ± 0.7</td>
<td>10.4 ± 1.2*</td>
<td>10.4 ± 2.2*</td>
</tr>
</tbody>
</table>

Values are means ± SEM.

LV = left ventricular, Kₐ = dissociation constant

*Different from normal, *p* < 0.01*
Catecholamine Studies

Before the animals were killed, plasma levels of norepinephrine (204 ± 29 pg/ml) and epinephrine (105 ± 19 pg/ml) in hypertensive dogs were similar to plasma levels of norepinephrine (244 ± 32 pg/ml) and epinephrine (110 ± 13 pg/ml) in normal, conscious dogs. In addition, in anesthetized dogs, LV norepinephrine levels were significantly less (266 ± 66 pg/mg wet weight; p < 0.05) in the renal hypertensive group than in the normal group (493 ± 50 pg/mg wet weight; Figure 3).

Comparison with Left Ventricular Hypertrophy Induced by Aortic Banding

When the groups with LV hypertrophy (perinephritic hypertension and aortic banding) with similar increases in LV free wall weight to body weight ratio were compared, similar increases in β-adrenergic receptor density and Kᵦ were observed in both models of LV hypertrophy (Table 1).

Discussion

The results from previous studies on the effects of chronic hypertension on β-adrenergic receptors are controversial. Even the same model of hypertension in the same species has produced opposite results.1-5 The majority of work in this field has been conducted in rodents, however, and no change or decreases in β-adrenergic receptor density have been found.1-2 4-7 9

The present investigation examined hearts from dogs with chronic perinephritic hypertension, a model that has been characterized extensively by other investigators.10-18 In contrast to what was observed by the majority of studies in rodents, the density of β-adrenergic receptors increased (57%) in the hearts from dogs with chronic perinephritic hypertension. The increase in β-adrenergic receptor number observed in the present investigation could not be attributed to a generalized reduction in sarcolemmal content of the membranes, as the level of other membrane markers (e.g., muscarinic receptors and Na-K-ATPase) actually fell.

It was considered that the upregulation in β-adrenergic receptor number could have been secondary to changes in catecholamines. Because the plasma levels of norepinephrine and epinephrine were similar in the control and hypertensive groups of conscious dogs before they were killed, the change in myocardial β-adrenergic receptor density cannot be attributed to differences in ambient levels of circulating catecholamines. Tissue levels of norepinephrine in the left ventricle were significantly depressed in the group with chronic perinephritic hypertension. This depletion in LV norepinephrine levels is similar to that seen in pressure overload hypertrophy secondary to aortic banding and may indicate that the normal adrenergic mechanisms are being exhausted or that in the hypertrophic process the adrenergic innervation has not increased proportionally to the increase in cell volume. It is conceivable that the increased density of β-adrenergic receptors is the reverse of the desensitization process whereby a downregulation of β-adrenergic recep-
tors is found with long-term exposure to high levels of catecholamines.22

Another major difference of the present investigation from previous work in this field was the finding of a decreased affinity for the β-adrenergic receptor; the \( K_d \) for \( \text{'H-DHA} \) rose from 5 0 ± 0 7 to 10 4 ± 1 2 nM. No other study on hypertension found a substantial change in affinity; however, a previous study from our laboratory that investigated the effects of LV hypertrophy induced by long-term aortic banding observed a marked increase in the \( K_d \) for \( 	ext{'H-DHA}.16 \)

Because the hypertrophy was more severe in that study, we compared the data from a subgroup of dogs with aortic banding with a similar level of LV hypertrophy to the dogs with perinephritic hypertension-induced LV hypertrophy (see Table 1). It was interesting to note that almost identical increases in β-adrenergic receptor number and \( K_d \) were observed in both groups of dogs when equivalent levels of hypertrophy were compared.

These data suggest that pressure overload hypertrophy in dogs, whether induced by mechanical obstruction (aortic banding) or perinephritic hypertension, results in similar increases in β-adrenergic receptor density and decrease in affinity. It is important to keep in mind that if plasma levels of catecholamines had been elevated, an increase in β-adrenergic receptor density might not have been observed. Although the change in receptor number could be due to the reduction in levels of LV norepinephrine, the change in affinity cannot be explained by decreased catecholamine levels in the heart. Another recent study from our laboratory investigated the effects of chronic cardiac denervation and found severe reductions (98%) in LV norepinephrine levels and increased β-adrenergic receptor density but no change in affinity.

It is speculative, but conceivable, that the hypertrophic process is associated with expression of a different form of the β-adrenergic receptor. This type of receptor microheterogeneity might explain the altered affinity in the hypertrophied heart.

In contrast to what was observed for the β-adrenergic receptor, muscarinic, cholinergic receptor density decreased from control values with no change in the \( K_d \) for \( 	ext{'H-QNB} \). The decrease in muscarinic, cholinergic receptor number could reflect a decrease in cholinergic innervation, a loss of parasympathetic modulation of sympathetic activity, or a decrease in membrane sarclemma content. In support of the last possibility are the measurements of Na-K-ATPase, which were found to be slightly depressed in the hearts from the dogs with chronic hypertension. In this connection, Lee et al.21 found depressed levels of Na-K-ATPase in hearts from spontaneously hypertensive rats. The decreased cholinergic receptor density could merely reflect a dilutional effect in response to the increase in myocardial cell size and cellular protein without a concomitant increase in cell membrane receptor content. Alternatively, the sarcolemmal preparation could be less pure because of contamination with non-myocyte elements. The only other study on muscarinic receptors in hypertensive dogs when equivalent levels of hypertrophy were compared because of contamination with non-myocyte elements.

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*Hypertension*. 1985;7:I55
doi: 10.1161/01.HYP.7.3_Pt_2.I55

*Hypertension* is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0194-911X. Online ISSN: 1524-4563

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